IMPACT OF MAINTENANCE STRATEGY
ON RELIABILITY

Final report by the IEEE/PES Task Force on
Impact of Maintenance Strategy on Reliability
of the
Reliability, Risk and Probability Applications
Subcommittee

July 1999

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IMPACT OF MAINTENANCE STRATEGY ON RELIABILITY

1 Mandate and Scop

A Task Force on the effect of various maintenance strategies on reliability has been established by th IEEE Subcommittee on Application of Probability Methods (presently Reliability, Risk & Probabilit Applications SC). The mandate of the Task Force was set at the TF's meeting during the PES Winter Meeting in New York, January 1995. It contains the following agenda.

1. Define the area of investigation. Propose terminology where ambiguity exists.

2. Review literature on maintenance methods and rank them for applicability in power systems. Include an assessment of the recently developed methods commonly called reliability-centered maintenance (RCM) which appear mostly heuristic but may contain useful observations or models.

3. Review the major maintenance policies presently practiced in electric utilities.

4. Review the data needs of maintenance programs and discuss data collection methods.

5. Discuss the interpretation of diagnostic tests, and the ways of determining the stage of ageing in which a device is found during inspection.

6. Describe approaches to developing a maintenance program which could increase the cost and reliability benefits from those gained when using traditional policies. Discuss the costs to be included.

7. Survey present efforts of developing such approaches.

8. Produce a document which summarizes the findings and offers recommendations. Assess the need for further refinements such as considering the effects of load levels or cost optimization.

The structure of the present report closely follows the mandate. The focus of the work is on providing clear concepts, identifying needs and criteria (particularly about costs) for maintenance in the electric power industry, and discussing approaches which can best satisfy the needs. The report is not aimed at developing a comprehensive maintenance program; rather, it is restricted to the evaluation of factors to be considered in such a development. The goal of the report is to increase the industry's awareness o this tool for improving system reliability, a tool which has not been fully exploited in the past.

2 Terminology

In the following, definitions will be given of a few fundamantal concepts discussed in this report. While the terms below will be used throughout the report, it must be understood that there is no standard nomenclature in this field, and the literature has been employing a variety of terms for some of the concepts. In the notes to the definitions, several alternative terms are listed which are frequently used in power system reliability studies or in the component and circuit reliability literature; in proposing the definitions below, an attempt is made to offer a consistent set which may be acceptable to most users.

Failure - The termination of the ability of a device to perform a required function.

Random failure - A failure whose rate of occurrence (intensity) is constant, and independent of the device's condition.

> *Note 1:* In other words, the chances of a failure occurring in any short time interval, assuming that the device has been working up to that time, is always the same. In the more precise terminology of reliability theory, a failure is random if the density of the conditional probability that it occurs in the interval $(t, t + \Delta t)$, given that the device was in a working condition at t, is constant (independent of t). In general, this density is called the *hazard function,* and if it is constant, the *hazard rat* or *failure rate.*
>
> *Note 2:* In a broader sense, failures whose origins are not well understood and therefore are perceived as being able to occur at any time are often said to be random. If for easier mathematical modeling it is assumed that such failures can occur at any time with equal probability, then the broader concept is reduced to the above definition.
>
> *Note 3:* The rate of random failure may depend on external conditions. For example, the rates of lightning or ice storms, and the rates of resulting random failures, would b different in each season.

Deterioration (*wear* or *wear-out*) - A process by which the rate of failure increases due to loss o strength, the effects of usage, environmental exposure or passage of time.

Note: The term is also used to describe the accumulated results of the process.

Deterioration failure - A failure resulting from the deterioration of a device.

Restoration - An activity which improves the condition of a device. If the device is in a failed condition, the intent of restoration is the re-establishment of a working state.

Replacement - Restoration wherein a device is removed and one in better condition is put in its place; if the device is failed, it is replaced by a working one. It is often assumed that the device so installed is new.

Repair - Restoration wherein a failed device is returned to operable condition.

> *Note:* It is common to use the term *corrective maintenance* for both replacement and repair.

Minimal repair - Repair of limited effort wherein the device is returned to the operable state it was in just before failure.

Maintenance - Restoration wherein an unfailed device has, from time to time, its deterioration arrested, reduced or eliminated.

> *Note:* It is common to call this concept *planned maintenance* or *preventive maintenance*. These terms are meant to contrast with *corrective maintenance* (see *Repair*). They are redundant by the above definition, and are not used in this report.

Scheduled maintenance - A maintenance carried out at regular intervals (rigid schedule).

> *Note:* Another term often used for this activity is *preventive maintenance*. This usage of the term contradicts the one mentioned in the Note to Maintenance above. In this report, the term is not used.

Predictive maintenance - A maintenance carried out when it is deemed necessary, based on periodic inspections, diagnostic tests or other means of condition monitoring.

Emergency maintenance - A predictive maintenance that must be carried out immediately, or with the shortest delay possible, after condition monitoring detects a danger of imminent failure.

Minor maintenance - Maintenance of limited effort and effect.

> *Note:* If deterioration is modeled in discrete stages and the intent of maintenance is to improve conditions by just one stage, the maintenance procedure is often called *minimal.*

Overhaul - Maintenance or repair requiring major effort and resulting in a significant improvement o the device's condition.

> *Note:* Occasionally the terms *maintenance-overhaul* and *repair-overhaul* are used to indicate the distinction. In most cases, however, this is not necessary and these terms will not be used in this report.

Minor overhaul - An overhaul of substantial effort yet involving only a limited number of parts, whose effect is a considerable improvement of the equipment's condition.

Major overhaul - An overhaul of extensive effort and duration which involves most or all parts of the equipment and results, as far as possible, in the "good as new" condition.

> *Note:* A major overhaul usually involves complete disassembly and maintenance of all parts of the equipment, and replacement of some.

3 Introduction

The purpose of maintenance is to extend equipment lifetime, or at least the mean time to the next failure whose repair may be costly. Furthermore, it is expected that effective maintenance policies can reduce the frequency of service interruptions and the many undesirable consequences of such interruptions. Maintenance clearly impacts on component and system reliability: if too little is done, this may result in an excessive number of costly failures and poor system performance and, therefore, reliability is degraded; done often, reliability may improve but the cost of maintenance will sharply increase. In a cost-effective scheme, the two expenditures must be balanced.

Maintenance is just one of the devices for upkeeping or, if necessary, improving the level of reliability of components and systems. Others include increasing system capacity, reinforcing redundancy and employing more reliable components. At a time, however, when these approaches are heavily constrained, electric utilities are forced to get the most out of the devices they already own through more effective maintenance routines. In fact, maintenance is becoming an important part of what is often called asset management.

Electric power utilities have always employed maintenance programs to keep their equipment in good working condition for as long as it is feasible. Traditional maintenance approaches mostly consisted o pre-defined activities carried out at regular intervals (scheduled maintenance). However, such a maintenance policy may be quite inefficient: it may be overly costly (in the long run), and may not extend component lifetime as much as possible. In the last ten years, therefore, many utilities replaced their maintenace routines using fixed schedules with more flexible programs based on an analysis of needs and priorities, or on a study of information obtained through periodic or continuous conditio monitoring (predictive maintenance). Some of these routines are named Reliability-Centered Maintenance, commonly abbreviated to RCM. In an RCM approach, various alternative maintenance policies can be compared and the one most cost-effective for sustaining equipment reliability selected. RCM programs have been installed by several electric power utilities as a useful management tool.

The implementation of RCM programs represented a significant step in the direction of "getting the most out" of the equipment installed. However, the approach is still heuristic, and its applicatio requires experience and judgement at every turn. Besides, it can take a long time before enough dat are collected for making such judgements. For this reason, several mathematical models have been proposed to aid maintenance scheduling. In fact, the literature on maintenance models has become quite extensive. In the following Section, a short review is given of the most important approaches and models proposed and in the subsequent Section, power system maintenance practices are discussed.

4 Review of Maintenance Approaches

In Figure 1, a classification of the various maintenance approaches is presented. Note that maintenance is shown as part of the overall asset management effort. Clearly, maintenance policy is one of the operating policies and, in a given setting, it is selected to satisfy both technical requirements and financial constraints.

Much of the literature concerns itself with replacements only, both after failures and during maintenance, and disregards the possibility of the kind of maintenance where less improvement is achieved at smaller cost. The oldest replacement models are the age replacement and bulk replacement policies [1, 2]. In the first, a component is replaced at a certain age or when it fails, whichever comes first. In the second, all devices in a given class are replaced at predetermined intervals, or when the fail. The last policy is easier to administer (especially if the ages of components are not known) and may be more economical than a policy based on individual replacement. Newer replacement schemes are often based on probabilistic models [e.g., 3, 4] and can be quite complex. In most electrical utilit applications, however, maintenance resulting in limited improvement is an established practice and replacement models have only a secondary role.

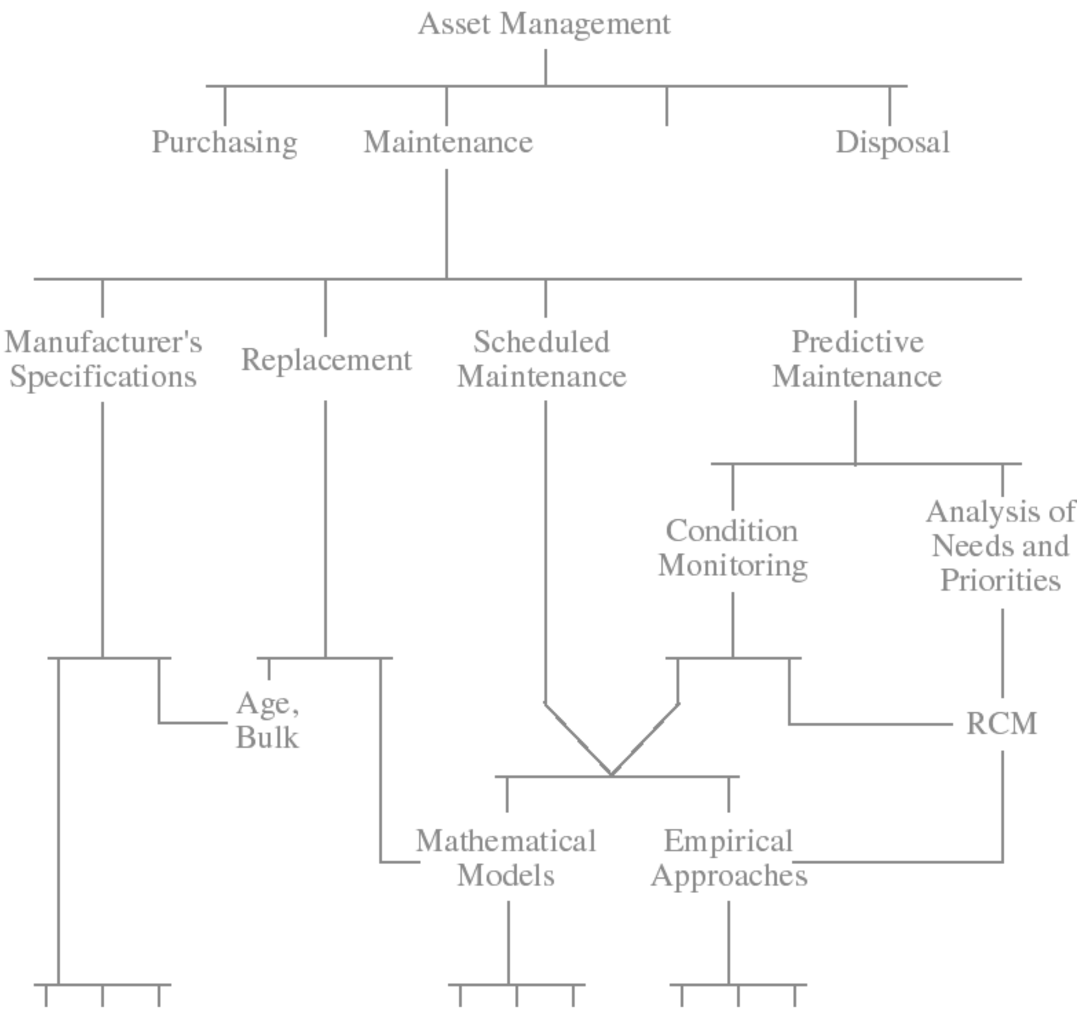

Figure 1 - Overview of maintenance approaches

Maintenance models range from the very simple to the quite sophisticated. Perhaps the simplest plan is to adopt a rigid maintenance schedule where pre-defined activities are carried out at fixed time intervals. Whenever the component fails, it is repaired or replaced. Both repair and replacement ar assumed to be much more costly than a single maintenance job. The maintenace intervals are selected on the basis of long-time experience (not necessarily an inferior alternative to mathematical models). To this day, this is the approach the most frequently used.

For a complete evaluation of the effects of a maintenance policy, one would have to know how fa such a policy would extend the lifetime of a component, measured in, say, mean time to failure. To find this out, the deterioration processes of components have to be modeled, and of late, several suc models have been proposed [5, 6, 7]. They provide the link missing in earlier approaches: quantitative connection between reliability and maintenance. By incorporating assumptions about the improvements resulting from maintenance one can optimize the process with regard to changes in one or more of the variables.

The simpler such models are essentially still based on fixed maintenance intervals, and optimization will result in identifying the least costly maintenance frequency. More complex models incorporate the idea of condition monitoring, where decisions with regard to the timing and amount of maintenance are dependent on the actual condition (stage of deterioration) of the device [5, 8, 9]. Thus, some kind of monitoring (e.g., inspection) must be part of the model [10]. Optimization can include many variables, from the frequency of inspections to the resulting choices made. Note that many condition-monitoring schemes are empirical.

The RCM approach referred to in the Introduction is heavily based on regular assessments o equipment condition and, therefore, does not apply rigid maintenance schedules. It should be observed that RCM is a somewhat fluid concept, defined differently in various sources [11, 12, 13]. It is not always based on condition monitoring, but on other features such as failure modes and effects analysi and an investigation of operating needs and priorities. The approach is almost always empirical. As an example, the RCM program used at the Consolidated Edison Company of New York [11] consists o the following procedure.

- System identification, and the listing of critical components and their functions

- Failure mode and effects analysis for each selected component, the determination of failure history, and the calculation of the mean time between failures.

- Categorization of failure effects (by using appropriate flow charts) and determination o possible maintenance tasks.

- Maintenance task assignment.

- Program evaluation, including cost analysis.

Another approach, claimed to be more efficient than RCM, was recently described in Reference 14. Called Preventive Maintenance Optimization (PREMO), it is based on extensive task analysis rathe than system analysis, with a capability of drastically reducing the required number of maintenance task in a plant. Programs such as RCM and PREMO have been very useful in ensuring the economic operation of power stations. However, they will not provide the full benefits and flexibility of those based on probabilistic models

Good surveys of the literature on maintenance are given in References 15 and 16. A probabilistic model developed for applications in the electric power industry with a number of features to enhance the realism of the model is described in References 17 and 18.

5 Present Maintenance Policies in Electric Utilities

To form an overview of present maintenance practices, a questionnaire was prepared and, with the help of the Task Force membership, distributed among a number of utilities, both in North America an overseas. Since maintenance protocols vary from equipment to equipment and to review all would have required an unwieldy effort, it was decided to select three typical components of different sizes and quantities in the system as representative in the hope that basic trends can already be observed o this sample. The equipment selected are: (A) hydrogen-cooled steam-turbine driven generators, (B) substation transformers, 100-161 kV primary, 4-20 kV secondary, and (C) distribution system indoor circuit breakers, 15 kV. Accordingly, the questionnaire was structured into three parts. As an example, Part B is appended.

Replies were received from 6 countries, Austria, Canada, Germany, Italy, Saudi Arabia, and the U.S. A total of 53 completed questionnaires were returned, 19 of Part A, and 17 each of Parts B and C. Thus the returns form comparatively small samples, but even so, the conclusions can be stated with some measure of confidence. In the following, the findings are listed.

5.1 General

- The answers to many questions display a considerable spread. This is not only the consequence o different practices, but also of different interpretations of some of the concepts introduced.

- Most utilities do scheduled maintenance only, or a modified form of it where additional corrective actions are taken if required by inspection results. The following Table indicates the number of utilities where scheduled, modified or predictive maintenance is performed.

	A: Generators	B: Transformers	C: Breakers
Scheduled only			
Modified scheduled	13	12	11
Predictive only			

5.2 Scheduled maintenan

- The intervals and durations reported for scheduled maintenance show considerable spread. The following Table lists their most frequent values.

	A: Generators		B: Transformers		C: Breakers	
	Interval	Duration	Interval	Duration	Interval	Duration
Minor maintenance	1 yr	1-2 wk	1 yr	1 day	1 yr	1 day
Minor overhaul	5 yr	4-5 wk	5 r	3 days	5 yr	3 days
Major overhaul	8-10 yr	6-8 wk	7 yr	4-8 wk	8-10 yr	2 wk

- Cyclic routine (e.g. a major overhaul following 3 minor overhauls) is rare (6 cases reported).

5.3 Predicti (as needed) maintenan

- The most often used device to establish the need for maintenance is periodic inspection. The inspection intervals vary widely and are also different for different tasks. For example, in Part intervals ranging from 1 week to 5 years were reported, with the most frequent entry of 1 month. Same for Part C. In part A, yearly inspections were the most frequent.

- Another device for detecting maintenance needs is continuous monitoring. This was mentioned most often in Part A (oil leakage, vibration, bearing temperature) and to lesser degree for smalle equipment (tap changer condition, corrosion, discharge voltage).

- The most effective diagnostic tools were found to be, in Part A, gas and oil analysis, surge testing, vibration monitoring; in Part B, gas and oil analysis, power factor tests, thermal tests, dielectri tests; in Part C, contact resistance tests, hi-pot tests.

5.4 Reliability-centered maintenance (RCM)

- This procedure is not generally used, and particularly rarely applied outside North America. However, nearly half of the correspondents are considering its introduction. At the present, only 1 in Part A, 2 in Part B and 1 in Part C reported that the procedure is fully used.

- Those who consider using RCM are expecting to gain the following benefits: longer up-times, lower costs, better control and decisions, better use of labour.

5.5 Probabilistic model

- Probabilistic approaches are not used in maintenance planning by any of the respondents. Some report on pilot applications and “tests”, others have hired external consultants who may include such methods.

- Many do, or wish to, compute such indices as unavailability, failure frequency and duration (or mean time to failure); in Part A also forced outage rate (FOR) or equivalents

5.6 Data requirement

- For generators (Part A), present maintenance policies are primarily based on historical records These may include performance indices, inspection records and maintenance data. In addition, generator manuals are used and experience and memory were frequently mentioned as important resources.

- For transformers (Part B), the more frequently mentioned data used were test reports, data o windings, failure data, maintenance protocols and maintenance history.

- For breakers (Part C), the replies included operation logs, maintenance history, failure statistics, faulty operation counts vs. total number of operations, results of oil and hi-pot tests.

5.7 Contracting out maintenance work

- The majority of respondents do contract out at least part of the maintenance activities. Some do it on an “as needed” basis or only for special tests. Others contract out major maintenance work.

6 Ageing and Maintenan

6.1 Classification of failures

It is widely accepted that component failures can be divided into two categories, random failures and those arising as a consequence of deterioration (ageing). Simple failure-repair models in the two cases are shown in Figure 2. Note that these are state models, not Markov models as there are no assumptions made about the time-distributions of the individual transitions. The various stat designations are explained in the legend of Figure 2.

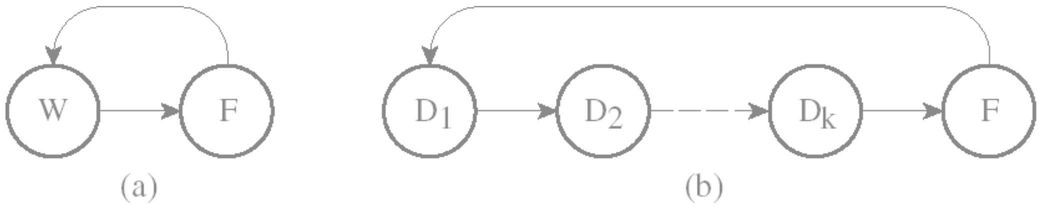

Figure 2 - State diagrams for (a) random failure and (b) deterioration failure
W: working state, F: failure state, $_1$, D_2 *. . . : stages of deterioration*

In some cases, failure is declared when wear reaches an unacceptable level even if no actual equipment breakdown occurs. Such failures may allow for some flexibility in the timing of repair or replacement. Simple modifications of the model in Figure 2(b) will account for this possibility.

The mean time to failure from the instant the device is "new" - that is, the moment of entrance into the W state in case (a) and into the initial deterioration state D_1 in case (b) - is the mean time spent in W in the first case, and the sum of the mean durations of the deterioration states in the second. As alread mentioned, the purpose of maintenance is to increase the mean time to failure. One way of adding maintenance states to the models in Figure 2 is shown in Figure 3. In diagram 3(b), it is assumed that maintenance will bring about an improvement to the conditions in the previous stage of deterioratio (minimal maintenance, [6]). This contrasts with many strategies described in the literature, wher maintenance involves replacement - that is, a return to the "new" conditions.

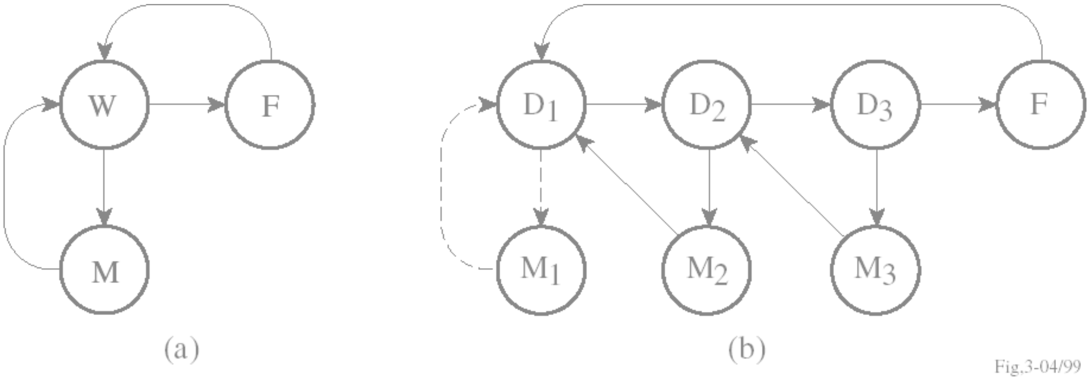

Figure 3 - State diagrams including maintenance states for (a) random failure,
(b) failure following a three-stage deterioration process

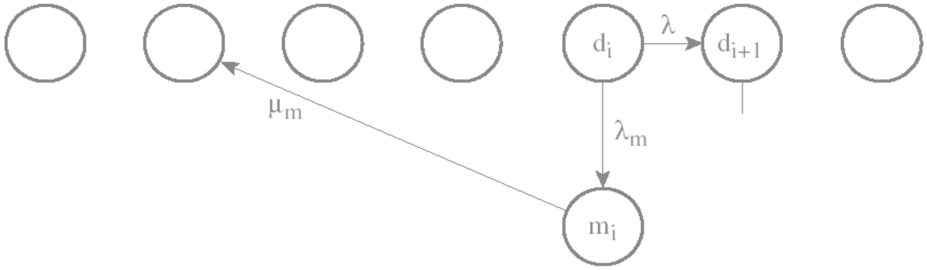

Figure 4 - The number of deterioration states is so selected that the average wear in an state d_i equals the amount occurring between two subsequent maintenances ($\lambda = \lambda_m$)

In Figure 3(b), the dotted-line transitions to and from state M_1 indicate that maintenance out o D_1 should really not be performed because, as noted before, it would be meaningless. The implication is, however, that when maintenance is due the maintainer would know if the deterioration process was still in its first stage. If this is not the case, maintenance should be carried out regularly from the beginning, and state M_1 must then be part of the diagram.

The computed effect of maintenance depends on the mathematical model chosen. The more realistic is the model, the closer are the computed and real consequences of maintenance. It can be often assumed, for example, that the uptimes (the durations in state W or the times of stay in the various deterioration stages) are exponentially distributed. In the case of random failures, this assumption would lead to the result that maintenance cannot produce any improvement, because the chances of a failure occurring during any future time-interval are the same with or without maintenance. This follows from a property of the exponential distribution, but also agrees with experience; it gave rise to the widely known piece of wisdom: "if it ain't broke, don' fix it!" The situation is quite different for deterioration processes, where the times from the new condition to failure are not exponentially distributed even if the times between subsequent stages of deterioration are. In such a process, maintenance will bring about improvement independentl of the types of distributions between stages [7]. Hence the rule: conditions cannot be improved by maintenance for random failures, but maintenance has an important role to play when failures are the consequence of ageing.

6.2 How many stages of deterioration should be modeled?

Deterioration is a continuous process in time and only for the purposes of easier modeling is it considered in discrete steps. The number of deterioration stages may vary, and so do thei definitions. There are, essentially, two ways of defining deterioration stages: either by duration (the second stage is reached, on the average, in three years, the third in six, and so on), or by

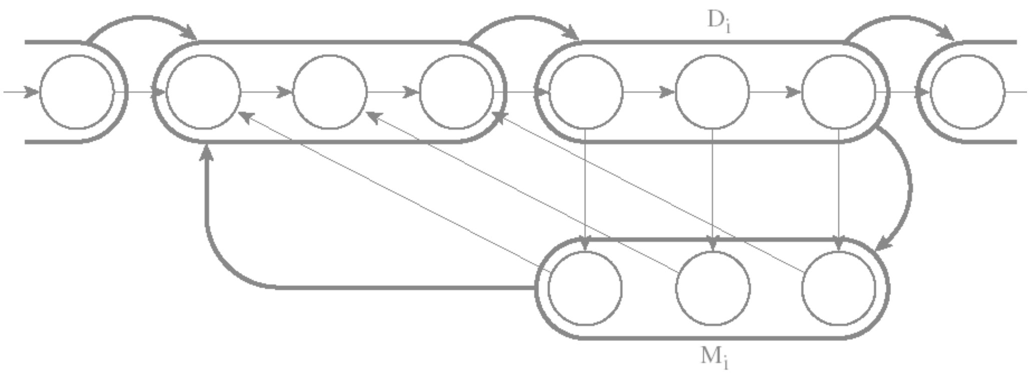

Figure 5 - Combining deterioration states so that maintenance will improve condition by one stag (heavy lines: combined states and their transitions)

physical signs (corrosion, wear, etc.) and appropriate milepost . In practical applications, the tendency is to favour the second way which, of course, makes periodic inspections necessary to determine the stage of deterioration the device has reached. If this course is taken, the mean times between the stages are usually uneven, and are selected from performance data or by judgement based on experience. The maintenance routines in the various stages may also differ.

To further explore the situation, first let the definition by duration be considered. Assuming scheduled maintenance routine (yearly, for example), one could select the amount of wear occurring between every two consecutive maintenances (the amount of deterioration occurring every year) as a stage of deterioration. This way, however, one may end up with a very large number of states. Under the circumstances, it would be reasonable to expect that every maintenance will result in a set-back o several stages in the deterioration process (Figure 4). Assuming now that the improvement in deterioration is the same (in terms of the magnitude of set-back) after every maintenance, groups of d and m states of the size equal to the amount of set-back can be combined as shown in Figure 5. The resulting outcome is the same as the arrangement in Figure 3(b).

While the deterioration stages in Figure 5 are still defined by their durations, there is nothing in the scheme of Figure 3(b) which actually requires this. If the requirement that maintenance out of any d state must have the same setback is relaxed, and only the assumption made that maintenance in an state in D_i will bring about an improvement resulting in a state in D_{i-1}, than the mean durations of D_i may be different, and the stages may be identified by the status of recognizable physical signs of deterioration. This agrees with the second definition of deterioration stages above. But even the last assumption above may be questionable and should be relaxed in a practical model. It must be remembered that Figure 3(b) shows a conceptual model rather than a prototype. Several features that will have to be incorporated before it can be considered ready for practica applications are listed in Section 8.3.

6.3 Other model

The model described in Sections 6.1 and 6.2 represents just one of several ways of accounting for the effect of maintenance on reliability. Many other approaches have been developed; of these, at least two are concerned with power system applications [20, 21]. In [20], a maintenance model is derived for parallel branches of components in series as often found in transformer stations, and in [21], the maintenance and reliability of standby devices are studied. Both are, in essence, replacement models where repair and maintenance are assumed to result in "as new" conditions.

As already mentioned, the identification of the deterioration stage a device finds itself in at any given time is a significant part of the methodology and models. The next Section deals with approaches to this task.

7 Identification of the Deterioration Stages

7.1 Diagnostic test

Under a predictive maintenance policy, maintenance is carried out as needed. There are no schedules to follow. The need for maintenance is established through periodic inspections.

To perform meaningful inspections, diagnostic routines and techniques are required which help to identify disorders that call for maintenance. While the maintenance activities are performed as needed, inspections should be carried out regularly to initiate maintenance before equipment break-down. I addition, predictive maintenance may allow for:

- better outage scheduling,
- operating flexibility,
- better fuel use,
- improved efficiency,
- more efficient spare part management.

Commonly used diagnostic methods include visual inspection, optical inspection, neutron analysis, radiography, eddy current testing, ultrasonic testing, vibration analysis, lubricant analysis, temperatur analysis, magnetic flux leakage analysis and acoustic emission monitoring. Each of these method have advantages and limitations. Examples of diagnostic systems currently implemented by the electric power industry are given below.

Electrical equipment
Visual inspection
Temperatures
Insulating oil tests - to detect transformer oil and insulation condition
Megger tests - to measure insulation resistance
Protection system tests
Winding resistance tests
Drop load tests and dry wicket gate open/close rates - to ensure that governor operation is within limits
Transformer ratio check - to probe for short circuits in winding
Rotor voltage drop check - to probe for short circuits in the rotor
Partial discharge analysis - to predict the condition of stator winding
Thermography tests - to detect high-resistance joint
Double insulation tests

Mechanical equipment
Lubricating oil testing - to look for metallic parts as sign of wear
Vibration monitoring - to detect wear, broken rotating component, hydraulic instabilit
El-Cid and core flux test - to detect stator damage
Auxiliary motor operating currents - to check general motor conditio

Structural equipment
Among civil engineering structures, large dams are the most prominent. Typical dam surveillance programs are the following:
routine dam safety inspections,
monitoring of strategically installed instrumentation
periodic reviews of design procedures

As production equipment becomes more sophisticated, the instrumentation required to diagnose it condition becomes more complex. Implementation of new diagnostic technologies may incur hig equipment costs and necessitate the often difficult task of analyzing the data that has been gathered. On the other hand, with further refinements predictive maintenance techniques and technologies may become cheaper and easier to use. As this occurs, their benefits to economic operation and maintenance could be quite extraordinary.

It is not the mandate of this report to make recommendations for diagnostic tests applicable in specific cases. In this Section simply an overview is given of the tests that may be required during inspections, and their importance and diversity is highlighted.

7.2 Continuous inspection

Continuous inspection, or condition monitoring, is the ongoing inspection and surveillance of th operation of an equipment to ensure proper performance and to detect abnormalities indicative o approaching failure. Condition monitoring is preferred where it is not possible to predict wear-out trends through periodic inspections with reasonable accuracy, given that the associated costs are not prohibitive; also, where off-line inspections are not desirable and where the criticality of a failure justifies keeping constant vigil on a device or process.

Numerous condition monitoring and non-destructive testing techniques have been developed and utilized in the past two decades. These techniques, many based on high-technology devices, differ in applicability, accuracy, and cost. Most schemes provide continuous readout or at least informatio obtained from frequent observations, and many will automatically alert the operator when critical levels are reached. In other cases, the operator will have to take readings of the monitoring instruments at regular intervals.

In the following, a few typical applications are listed.

Electrical equipment
- On-line intelligent automatic monitoring
- Zero Outage On-Line Monitoring (ZOOM) - used for hydraulic generator

Mechanical Equipment
- Rotor-mounted scanner
- Vibration monitoring

Structural equipment
- Monitoring of leakage quantities
- Monitoring of uplift pressures
- Monitoring of deformations/displacements
- Monitoring of temperatures and precipitation

The parameters that require monitoring are defined during the process of planning or during a general inspection. At the same time, the degree of automatic operation needed in the given case is also established. It should be noted, however, that automated instruments do not generally remain reliable sources of data over extended periods. They need to be equipped with means for checking calibratio and/or with redundant manual readout instruments [19].

The economy of condition monitoring depends on its costs. If the costs are not excessive, it may be more economical than maintenance based on regular inspections [18].

8 Mathematical Models Based on Ageing

8.1 The use of mathematical models

As mentioned in Section 4, the simplest maintenance policies consist of a set of instructions taken from equipment manuals or based on long-standing experience. There are no quantitative relationships involved and the possibilities are very limited for making predictions about the effectiveness of the policy or carrying out any sort of optimization. For the latter, at least one variable is necessary whose numerical value can be freely chosen, and the costs and benefits associated with the different values of the variable are known. This then leads to the use of mathematical models where optimization can be carried out either analytically or through a series of sensitivity tests.

Mathematical models can be deterministic or probabilistic. Both can be put to good use in appropriate maintenance studies, and many applications are described in the literature [10]. However, where quantities are involved whose values can vary randomly, the associated future uncertainties can be properly handled only through probabilistic models. In the following, a simple comparison will be made of the two approaches.

8.2 Deterministic or probabilistic approach?

As mentioned before, maintenance can increase the time to failure only if failures do not happen at random but are the consequences of deterioration occurring as a device ages. Therefore, any mathematical model to represent the benefits of a given maintenance policy must relate the results o maintenance to the process of deterioration. A simple state space diagram where such a link is established was shown in Figure 3(b); its properties were discussed in Section 6.2. The diagram can be converted into a probabilistic mathematical model and, under certain restrictions, this becomes a Markov model with the transitions represented by their rates. Well-known techniques exist for the solution of such models. A prominent feature of the model is that its solution can be readily optimized either for the highest reliability or for the lowest cost. Examples are given in many studies reported in the literature.

While many deterministic maintenance models have been proposed, a simple one could be devised by using roughly the same approach as that used in the development of the probabilistic model earlier. An example is shown in Figure 6(a), based on the assumptions that without maintenance, the device would fail after exactly 10 years, the (rigid) maintenance interval is 3 years and the effect o maintenance is a 1-year improvement in deterioration (a questionable assumption; more of which later). The horizontal line serves as a scale of deterioration; otherwise the diagram in Figure 6(a) is self-explanatory. Deterioration and maintenance are still linked in this representation through an algorithm based on the above diagram; this algorithm takes the place of a mathematical model. It can be seen that the time to failure is now extended to 14 years as a result of the four maintenances carried out in the interval.

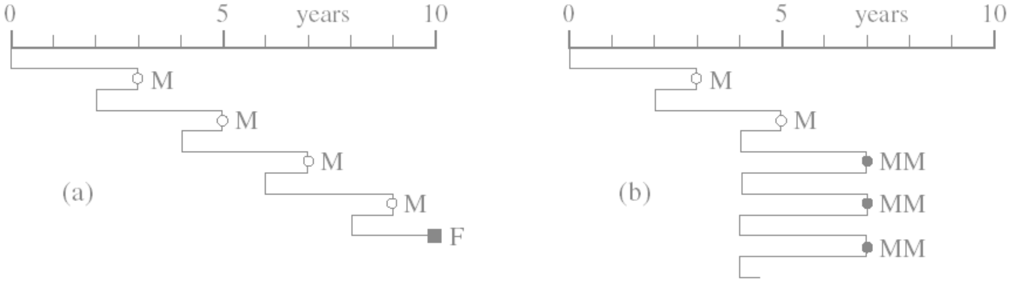

Figure 6 - Maintenance every 3 years, resulting in (a) 1-year improvement, (b) 3-year improvement if total wear is 6 years or more, otherwise as in (a)
M - maintenance MM - overhaul F - failure

While it is conceivable that the improvement due to a maintenance activity is less than the deterioration between two consecutive maintenances, especially early in the life of a device when only minor maintenances are performed, later the effect of maintenance should equal or exceed the deterioration occurring between maintenances. This can be ensured by scheduling overhauls (major maintenances) beyond a given stage of deterioration. If, for instance, in the example of Figure 6(a) overhaul is required at or after the deterioration stage 6, and if the effect of overhaul is a 3-yea improvement in deterioration, the diagram will change to that shown in Figure 6(b). Note that no the expected time to failure is infinity.

The problem with this deterministic representation (and many others) becomes obvious in the last example. It is easy to visualize that if the setback effected by maintenance is less than the maintenance interval the process will tend “to the right” and end in failure. However, in Section 6.2 this was considered an unlikely case. Every time the setback equals the maintenance interval, the process will oscillate within a given range, as in Figure 6(b), and if it exceeds the maintenance interval, the process will move “to the left”. In both latter cases the implication is that failure will never occur. This is a false conclusion and is entirely due to the assumption that all quantities involved have fixed values. I variability is allowed as in a probabilistic model, the failure state will sooner or later always b reached. This agrees with experience and can be proven rigorously.

In conclusion, it appears that while deterministic approaches may be simple to follow, some can lead to erroneous results. Probabilistic models produce much more credible conclusions but, unfortunately, their more complex structure will often mask the fact that they can in many applications better describe real conditions.

8.3 *Model extensions*

In general, probabilistic models can accommodate extensions and refinements easier than deterministi models. In the following, a few examples are given of desirable features that ought to be built into maintenance models.

If the rates of transitions from the D_i to the M_i states are the same for all i, the model in Figure 3(b) will represent a situation where maintenance is scheduled; that is, performed at regular intervals. It is fairly obvious that better economy can be achieved with a predictive maintenance policy wher maintenance is performed only when needed. The model in Figure 3(b) can be further developed to accommodate such a policy [18]. A simple solution is to insert inspection states before proceeding to maintenance; during inspections decisions are made as to the necessity of carrying out maintenance at that time. The probabilities of the possible decision outcomes must be chosen in advance; clearly, the more elaborate is the model, the more input data are needed.

Further development is required for enhancing probabilistic models so that they can accommodate, for example, the following:

- maintenance schemes based on continuous condition monitoring instead of periodic inspection;
- several deterioration processes taking place concurrently;
- the impact of load changes, or cycling loads, on ageing;
- the possibility that maintenance, if not done with care, can damage rather than improve the condition of a device; in fact, the effect of maintenance in terms of the resulting adjustment in the deterioration process should be considered a rando variable, including the possibilities of no set-back and “set-forward”;
- recognition of the necessity of postponing maintenance, particularly for generating units, if load conditions do not allow the removal of a unit from service;
- Recognition of the effect of obsolescence which may result in spare part unavailability at some time during the device’s active lifetime.

The claim may be made that the effect of the break-in/debugging period at the beginning of a device’s operating life, when failure rate is possibly quite high, should also be recognized in a practical model. However, maintenance during this period is usually covered by special instructions which are apart from the long-term maintenance policy, the subject matter of this report.

Many of the above refinements are presently under study. Several probabilistic models dealing wit some of these concerns are already described in the literature [e.g., 10, 18, 20, 21].

9 Conclusions

From the limited survey of maintenance practices in electric utilities described in this report it has become evident that many utilities in North America and overseas have not yet adopted practices beyond those of scheduled maintenance or empirical forms of predictive maintenance based on periodic inspections. However, many are interested in introducing reliability-centered maintenance and while this may mean different things to different people it is certain that in most cases it would result in significant savings.

Mathematical models, deterministic or probabilistic, are as of yet rarely used. They lack the simplicit required for evaluations which are often carried out in the field; besides, they require a multitude o input information which may not be readily available.

For all their advantages, probability-based maintenance policies are particularly slow in being considered for implementation. It cannot be denied, however, that optimized probabilistic maintenance models would provide the highest savings and also the highest flexibility in exploring and utilizing the effects of changes in any of the parameters. Therefore, there is little doubt that the final development in utility maintenance policies will be the introduction of such models, however complex they first appear to be. This is particularly true in a competitive environment where it is a prime necessity to find optimal solutions in complicated situations. A good example is generator maintenance where, as mentioned above, the questions are not only of minimizing maintenance and repair costs but also of appropriate scheduling.

In the past, the practice of electric utilities and power pools was to centrally plan and coordinate the maintenance of generating units. Maintenance was done during low-load seasons and the timing was influenced by such considerations as system risk and production cost. In the deregulated scenario it is unlikely that maintenance will be centrally planned or even coordinated. Generator owners will ten to keep the units running when the market clearing price of electric energy is high and perfor maintenance only when the market price is low. In addition, they may wish to sell energy in a neighbouring control area in which the periods of high load (and high market price) may be different from those in the area where the generator is located. Under such circumstances the decision when to maintain a generator will be driven by profit incentives rather than by the optimal cost of maintenan and repair.

Since it is unclear at the time of this writing how energy markets will operate, it is not possible to examine the effect of generator maintenance policies on risk in the deregulated industry. Therefore this report does not address these issues. But it should be noted that for equipment other than generating units and some generating station components, findings in this document are applicable even when utilities operate in competition. Work is being carried out in several centers to develop program packages for both the probability-based maintenance approaches discussed in this report, and the analysis of risk under deregulation and how the risk is influenced by various maintenance strategies.

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APPENDIX

Sample Questionnaire

Note: The definitions of terms at the end of the questionnaire are essentially the same as those in Section 2. Minor differences in wording can be attributed to the effort to make the definitions mor compact for the questionnaire, and also to the fact that the questionnaire was issued half-way throug the project while there was more time to review Section 2.

IEEE Questionnaire
on Maintenance Policies
Respondent Company No. ....

Part B.
Substation Transformers,
100 - l6l kV Primary, 4-20 kV Secondary

As you complete the Questionnaire feel free to provide
more detailed or supplementary information on separate sheets.
If you need any clarifications in completing the form,
please contact: .... at ....

For definitions of terms, see Appendix.

1. Please indicate the number and MVA size range (on a 3 phase basis) of such transformers.

   Number:................. .... MVA to .... MV

2. What type of maintenance policy do you employ? Please check all that apply.

   Scheduled maintenance activities at fixed time intervals. (Sometimes called "preventive" or “cyclic” maintenance).
   Maintenance activities based on evaluating the condition of the equipmen while it is in service. (Sometimes called "predictive" maintenance.)
   Emergency maintenance/overhaul as needed.

3. Is replacement of the entire transformer a part of your policy? ....
   If so, what criteria would prompt consideration of this alternative?

   ……………………………………………………………………………….
   ……………………………………………………………………………….
   ……………………………………………………………………………….

Part B - continued

4. If you schedule some or all maintenance activities at fixed time intervals for these transformers, how often are the following performed.

Minor maintenance...	weeks / months / years
Minor overhaul..........	weeks / months / years
Major overhaul	weeks / months / years
Other	weeks / months / years

5. Do you employ a cyclic routine such as an overhaul following 3 minor maintenances

…………………………………………………………………………………
…………………………………………………………………………………

6. What is the average duration of the following maintenance alternatives

	Duration
Minor maintenance	
Minor overhaul	
Major overhau	

7. The terms used in questions 4, 5 and 6 are defined in the Appendix. Are you comfortable with this terminology or is your company using different terms for the same concepts

………………………………………………………………………………..
………………………………………………………………………………..
………………………………………………………………………………..

8. If you schedule some or all maintenance activities based on evaluating the condition of t evaluation? (If you do not use predictive maintenance, skip to question 11.)

Periodic inspection or testing at intervals of.................... weeks / months
Continuous monitoring.. ....
Other technique (please describe)..

9. Have you found any diagnostic tools or techniques particularly effective
If yes, which

………………………………………………………………………………..
………………………………………………………………………………..

Part B - continued

10. If your policy is to carry out maintenance as needed, what criteria do you use to perform the following levels of maintenance

    No maintenance
    Minor maintenance
    Minor overhaul
    Major overhau
    Emergency maintenance/overhaul

11. In what percentage of the cases evaluated under your predictive maintenance strategy do you decide to select each of the following alternatives

    No maintenance........................ % Major overhaul......... .... %

    Minor maintenance................... % Emergency maintenance/overhaul.......... %
    Minor overhaul......................... %

12. Are you using a Reliability-Centered Maintenance (RCM) program for transformers

    If yes, how long has it been in use?
    ……………………………………………………………………………………

    If not, are you considering adopting one?
    ……………………………………………………………………………………
    ……………………………………………………………………………………
    ……………………………………………………………………………………

13. If you are using, or considering to use, an RCM program, what benefits do you see in employing this technique

    …………………………………………………………………………………….
    …………………………………………………………………………………….
    …………………………………………………………………………………….

Part B - continued

14. Are you using any technique to predict the effect of your maintenance policy and to see if improvements can be made

....

....

If yes, please describe.

……………………………………………………………………………………

……………………………………………………………………………………

Are you using probabilistic models for the purpose, and if yes, what models

……………………………………………………………………………………..

……………………………………………………………………………………..

……………………………………………………………………………………..

15. What measures of transformer reliability do you use to evaluate your maintenance policy?

Unavailability
Failure frequency
Mean time to failure
Other

(explain)..

16. For what components do you collect historical data? What type of data is being collected

……………………………………………………………………………………..

……………………………………………………………………………………..

……………………………………………………………………………………..

17. What historical data are available to you in providing the estimates required in questions 4, 6, 10 and 11?

……………………………………………………………………………………..

……………………………………………………………………………………..

……………………………………………………………………………………..

……………………………………………………………………………………..

18. Do you contract out any maintenance work (e.g., major overhaul) ? ....
If yes, what type and what percentage ? ....%

……………………………………………………………………………………..

……………………………………………………………………………………..

……………………………………………………………………………………..

IEEE Questionnaire
on Maintenance Policies

APPENDIX: DEFINITIONS

Repair - An activity restoring equipment which has failed to operable condition. (Often called *corrective maintenance.*)

Deterioration - The effects of usage, environmental exposure, or the passage of time which cause an increase in the probability of failure for a surviving unit.

Maintenance - An activity to arrest or reduce deterioration of equipment which is still in operable condition. (Often called *preventive maintenance*).

Scheduled maintenance - A maintenance activity carried out at regular intervals (rigid schedule).

Predictive maintenance - A maintenance activity carried out when it is deemed necessary, based on inspections, diagnostic tests or other means of monitoring.

Minor maintenance - A maintenance activity of limited effort whose effect is a minor reduction of its accumulated deterioration.

Overhaul - Maintenance or repair requiring major effort and resulting in significan improvement of the equipment’s condition.

Note: In this Questionnaire overhaul always represents a maintenance activity.

Minor overhaul - An overhaul affecting considerable improvement yet involving only a limited number of equipment parts (for example, rewedging a generator).

Major overhaul - An overhaul involving most or all parts, whose effect is to restore the equipment, as far as possible, to like-new condition. The equipment may be completely disassembled, either on site or after removal to a shop or the factory

Emergency maintenance/overhaul - A maintenance or overhaul carried out with a minimum of delay after its necessity is detected.

Reliability Centered Maintenance (RCM) – A maintenance process incorporating continuous or periodic condition monitoring, failure effects analysis, and evaluation of operating needs and priorities to sustain the most cost-effective level o equipment reliability.