ASSESSMENT OF REMAINING LIFETIME AND FAILURE PROBABILITY FOR NETWORK COMPONENTS – A PRACTICAL APPROACH

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ABSTRACT

The paper describes a methodology for estimating annual failure probabilities and remaining lifetime of network components, based on a simplified model of a component's deterioration curve, expert judgments on typical lifetimes and knowledge about its technical condition. In order to evaluate the method a case study based on deterioration mechanisms on circuit breaker sub-components (≥ 132 kV) has been performed. The case study shows that the methodology is an adequate alternative to methods based on more statistical analyses on fault data, due to the fact that such data very often is scarce.

INTRODUCTION

The power network infrastructure consists of a large number of components. In order to optimize maintenance and renewal, the network companies need better models and tools based on knowledge about expected residual lifetime and failure probability for critical components. The benefits of such models are most evident regarding the network asset management, and primarily in the maintenance and renewal planning.

This type of decisions is typically of the kind "should this component be renewed now or is it profitable to wait e.g. 5 years?", or: "How often should we perform condition monitoring (inspection) on this component?" This is a situation where the decision maker has to consider the technical capacity limits of the component as well as the probability of failure. A failure may result both in economical and non-economical consequences. The problem is, however, that we neither know for sure if or when a failure will occur, nor what the exact consequences will be. Probabilistic life models are a valuable support for the decision maker in such evaluations.

Various models were proposed over the past decades. Anders, Endrenyi and Leite da Silva presented in [1] maintenance optimization models based on a Markov chain and computer software for maintenance management. An often applied method to model deterioration is the use of the gamma process. A short overview about work on this topic is given by Kallen and Noortwijk in [2].

METHODOLOGY

Consider the general life curve (deterioration curve) for a component shown in Figure 1. The interpretation of the curve is as follows: The component may remain "as good as new" for many years, but as time goes, both constant and stochastic strain will degrade the component, which will (slowly) lose its original strength. At one point the component will be exposed to larger stress than its remaining strength, and a failure occurs.

It is important to bear in mind that a curve as the one shown in Figure 1 is applicable only for a single sub-component, and for a single failure/degradation mechanism.

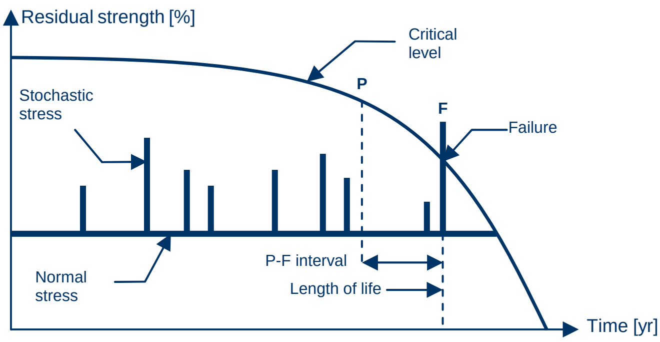

Figure 1 General life curve

If the exact life curve is difficult (or expensive) to reveal for a certain component, a simplification may be appropriate. The technical condition of a component can be characterized on a scale from 1 to 5 according to handbooks for condition monitoring of hydro power components, published by the Norwegian Electricity Industry Association (EBL Kompetanse) [3]. Here, the continuous degradation of a component is simplified by dividing its life into four states. The state description is given in Table 1 and these four states are denoted main states k. A component as-good-as-new is in state $k = 1$. When the condition is characterized as critical, the state is $k = 4$ and normally maintenance actions must be taken immediately in order to avoid state 5 (failure).

Table 1 Technical condition states (Main states)

State	Description
1	No indication of degradation.
2	Some indication of degradation. The condition is noticeably worse than "as good as new".
3	Serious degradation. The condition is considerably worse than "as good as new".
4	The condition is critical.
5	Failure

In addition to this general state specification, more detailed descriptions are given in the handbooks for different failure modes of all main components in a hydro power plant. Thus, the maintenance personnel have a guideline for the interpretation of different inspections and measurement results in order to define the condition of the component according to the five-state-scale. We have adopted the same methodology in a case study on circuit breakers (see description later in the paper).

Failure is always assumed to occur when there is a transition from state 4 to state 5 as indicated in Figure 2. The length T_k of each main state k may vary from several years (state 1) to only a few years or months (state 4). If the length of T_k is known, the concept of life curves can be applied and in principle the deterioration process can be sketched as shown in Figure 2. However, the length of the four main states has an element of uncertainty, which can be represented by a probability distribution. The gamma distribution is used to model T_k in this approach.

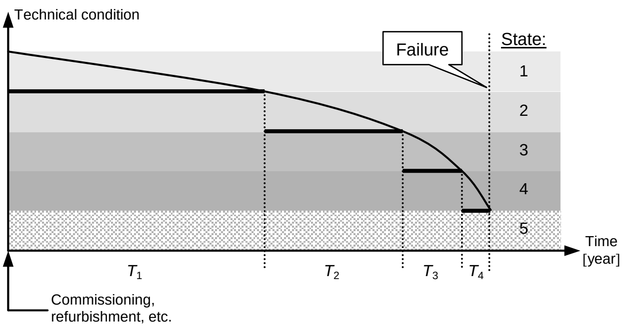

Figure 2 Technical condition levels and life curve

Preferably, the estimation of suitable probability distributions that describe the length of the four main states is based on analyses of reliability data and real observations. However, reliability data is often scarce. Hence, T_k has to be modelled by expert judgment.

There exist many proposals how expert judgment can be carried out [4]. In the example presented in this paper the expert has expressed his opinion about the four main state lengths by assessing the expectation $E(T_k)$ and the 10th percentile $t_{0.1,k}$ of T_k. A gamma distribution is then fitted to these values.

In the next step, the gamma distributed main states are transferred into a Markov chain. A theoretical result states that a sum of n identical and independent distributed exponential variables is gamma distributed with shape parameter n. In the methodology described in this paper, an approach is adopted for the approximation of each main state k by L_k exponentially distributed states. These exponentially distributed states are denoted sub states. The approach is further described in [5].

By modelling the transitions through the main states in Figure 2 by a Markov chain it is possible to calculate the annual failure probability, based on the technical condition of a component [5]. A prototype tool has been developed to execute such estimations, either based on previous expert judgements of the duration of each state, or by estimates of remaining life for a specific component entered by the user. The tool is based on the methodology described in the previous section as well as in [5].

Now consider a specific component of a certain type, age, etc. and with a dominant deterioration mechanism. Suppose that there exists an expert judgment on this deterioration mechanism on this kind of component, and that the technical condition of the component is known and in accordance with the systematics described in [3], i.e. the 1-4 states. The developed prototype tool can then be used to calculate the annual failure probabilities for this component based on the expert judgment and knowledge about the component's technical condition. This process is illustrated in the next section by a circuit breaker case study.

The relation between technical condition, failure and the consequences can be shown as in Figure 3. In addition it is indicated how preventive maintenance will affect the technical condition and how stresses and human behaviour influence the condition or may directly lead to a failure. Notice also the barriers indicated in the figure, which can be protection devices or simply making the equipment less available for people interference.

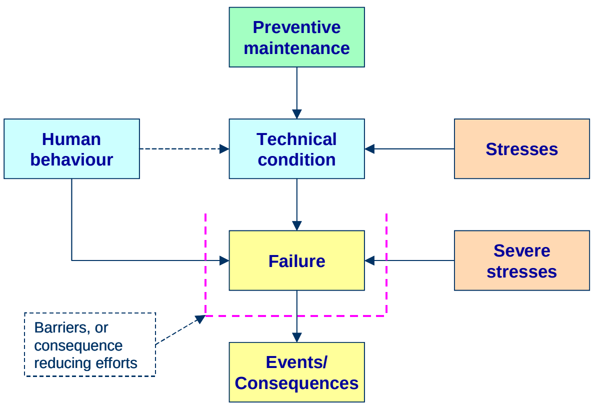

Figure 3 Relationship between different elements in the failure process

This failure model may be used as a framework for specifying the relevant failure mechanisms and their possible consequences for the chosen components. The probability of different consequences due to a certain failure can be found by the use of **event trees**, specifying the conditional probabilities for each branch given a specific failure and post-failure events. By this we have obtained a link between the deterioration speed of a component and the corresponding failure consequences, giving us the availability to analyse a variety of probability or consequence reducing measures in the network.

CASE STUDY: CIRCUIT BREAKER

In order to evaluate the methodology's applicability for network components a case study on circuit breaker sub-components (> 132 kV) has been performed. The adapted method makes use of expert judgements and knowledge about a component's technical condition with the purpose of estimating its remaining life and annual failure probability. Before we go further in describing the case study we take a closer look at the most common fault modes of the circuit breaker.

Working group 06 in Study committee 13 of CIGRÉ [6] has collected fault data for circuit breakers. The distribution of main fault modes according to CIGRÉ is:

- No contact movement 70 % of the faults
- Isolation failure 10 % of the faults
- Other 20 % of the faults

CIGRÉ differentiates between major and minor faults, where major faults are e.g. stuck breaker (corrective maintenance must be executed) and minor faults are e.g. a small oil leakage (where only small adjustments are necessary). The distribution of faults across the sub-component groups is (sum of major and minor faults):

- Operating mechanism: 40–50 % of the faults
- Control and auxiliary circuits: 20–30 % of the faults
- Component at service voltage: 20–30 % of the faults

Due to the fact that the operation mechanism has the majority of faults, our example is developed around a specific fault mechanism on a sub-component of this component, namely the mechanical transmission. An example of an expert judgement of the expected duration in each main state for this fault mechanism is shown here (together with the 10th percentiles):

- Expected values:
  T_1: 10 years; T_2: 10 years; T_3: 10 years; T_4: 5 years
- 10th percentiles:
  T_1: 5 years; T_2; 5 years; T_3: 5 years; T_4: 1 year

For other fault modes or more frequently operated breakers, it may be more relevant to specify the duration of states in terms of "number of operations" than "years".

Suppose now that we want to estimate the annual failure probability of a mechanical transmission of a circuit breaker with the technical condition "a bad state 3", denoted with the grade "3 minus" (3-) according to the classification given above, meaning that its condition is at the end of the interval defining state 3. The annual failure probability referred to the current year, can then be calculated, see Figure 4. In addition, MTTF is estimated to 5,9 years.

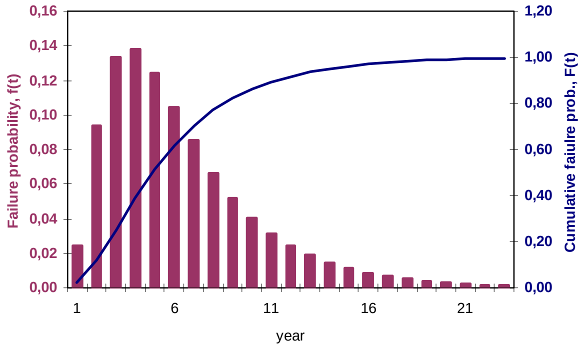

Figure 4 Annual failure probability for the test case

The network company is considering if they should perform preventive maintenance (PM) on the breaker in 2007 or wait another 5 years (2012). PM in this case means to bring this particular component back to "as good as new" condition, i.e. improving the technical condition from state 3- to state 1 (by replacement of defect parts).

Figure 5 shows the annual failure probabilities for the two alternatives. The blue bars represent the reference alternative (PM in 5 years), where the annual failure probabilities will be high until PM is performed and then are reduced to almost zero. The burgundy bars represent the alternative with PM in 2007, and the failure probability will then be close to zero the next 15 years or so.

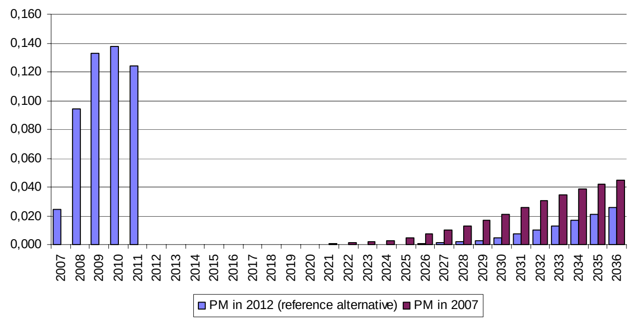

Figure 5 Annual failure probabilities for the two alternatives

The following information is used in the economical calculation in addition to the annual failure probabilities shown in Figure 5:

- Possible failure consequence no. 1:
  - Minor damage, smaller part(s) must be replaced
  - Repair cost: 20 000 NOK (1 € ≈ 8 NOK)
  - No customer interruption costs
  - Conditional probability of consequence no. 1: 50%
- Possible failure consequence no. 2:
  - Severe damage on the operating mechanism or other parts of the breaker
  - Repair cost: 200 000 NOK
  - No customer interruption costs
  - Conditional probability of consequence no. 2: 50%
- Cost of PM (replacement of mechanical parts): 20 000 NOK
- Period of analysis: 35 years
- Interest rate: 8 %

The differences in incomes and expenses between the two alternatives are shown in Figure 6, where the sign of the numbers should be viewed from the alternative with PM in 2007. The dark blue negative bar in 2007 is the PM costs and the burgundy bars represent the difference in expected cost of failure between the two alternatives. These bars are negative from 2012 because the failure probability of the reference alternative is smaller than the other alternative from that year, see Figure 5. At last, the yellow bar represents the avoided PM cost in 2012. So, the income bars in Figure 6 represent in reality the avoided (expected) costs by doing the work in 2007 instead of in 2012.

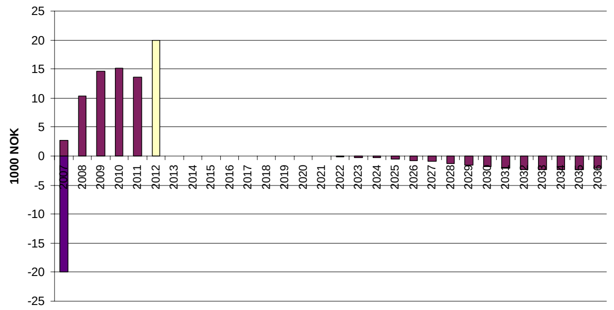

Figure 6 Income and expenses for the alternative of doing preventive maintenance in 2007 instead of in 2012

The net present value for the case of performing PM next year as opposed to in 5 years is 33 000 NOK. This means that it is profitable to do PM next year.

This example illustrates one possible application of the methodology described in this paper, showing the link between the technical condition of a component and the economical benefit of improving this condition at a given time. Through such calculations it is more convenient for the maintenance department to document their decisions in an "economical language", making it easier to argue for certain projects and to compare and rank individual projects within a larger maintenance portfolio.

CONCLUSIONS

The application areas for information about failure probability lie primarily within the topics "quantification of risk level" and "calculation of expected costs due to failures".

This information can be utilised as basis for many decisions in the maintenance and re-investment planning, e.g.:

- Answer to the basic question: What is the probability of failure in e.g. the next 5 years?
- Calculate the expected costs of undesired events
- Calculate economical utilitarian value of maintenance and re-investment projects
- Document a project's effect on various "qualitative" elements (health, environment, safety, PR, etc.)
- Quantify the effect of different maintenance strategies

This paper has described a methodology for forming the necessary basis for answering these questions, i.e. the annual failure probability and MTTF for a specific component that has a certain technical condition.

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