COMBINED MAINTENANCE AND INSPECTION MODELS FOR APPLICATION IN CONDITION- AND RELIABILITY-CENTERED MAINTENANCE PLANNING

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ABSTRACT

Maintenance models will be presented by which effects of imperfect maintenance on system condition can be simulated. Using these models a maintenance-intensity dependent cost function consisting of maintenance and societal outage costs is derived and applied to the evaluation of optimal maintenance intervals for 20-kV-wood poles.

INTRODUCTION

To increase the efficiency of maintenance planning strategies, an adequate compromise between maintenance intensity and resultant network component reliability has to be found. A powerful approach to a solution of this problem constitutes the application of cost oriented models. While the evaluation of maintenance expenses seems to be a rather trivial task, modeling the influence of maintenance intensity on costs of not supplied energy (outage costs) evidently is a more complex problem. Outage cost is dependent on the outage frequency of network components and on event-based outage costs, which represent the societal cost of not delivered energy occurring as a consequence of one single outage of a certain component or a pool of components with similar outage effects. Provided the event-based outage costs are known, the problem is reduced to modeling the influence of maintenance intensity on component outage frequency by an adequate maintenance model. Thus, the central topic of the paper is the development of maintenance models and their application in maintenance planning.

The presented maintenance models are based on lifetime and time-to-failure density functions. In the basic model [1] the density function reproduces itself after each maintenance action, so as if components would be fully restituted to their initial state by maintenance. Since this is not realistic in practice, model extensions for taking irreversible system degradation into account will be presented. Since in condition-oriented maintenance strategies inspection findings play an important role, the probability of defect detection during inspection is included as additional parameter into the presented model.

On the basis of the extended maintenance model a cost function consisting of maintenance cost and maintenance-intensity dependent outage cost is derived. This function delivers a forecast for the development of cost during a given observation period as a consequence of maintenance concept modifications and thus serves as object function for the evaluation of optimal maintenance intervals.

THEORETICAL BACKGROUNDS

Basic maintenance model

In this context maintenance comprises planned activities performed to keep the system in working state and to maintain an as large as possible lifetime. No distinction between minor maintenance and major maintenance is considered.

The outage behavior of a component (network facility like transformers, switches, cables, towers etc.) is represented by the statistical density function f(t) for lifetime or time between repairable failure (cycle-time). Lifetime distributions are used for representation of maintenance activities which are performed for increasing lifetime, cycle-time distributions are used for simulation of maintenance which aims at preservation of component operability.

In the model presented in [1] maintenance times are of deterministic nature. Additionally, it is assumed that the system can be fully restored to its initial condition by maintenance (perfect maintenance). Thus, after having performed maintenance the density function starts with its initial value f(t=0). For simulation of imperfect maintenance the following extensions are introduced into the model of [1]: The density function is shifted towards the left by the time tv as shown in Fig. 1.

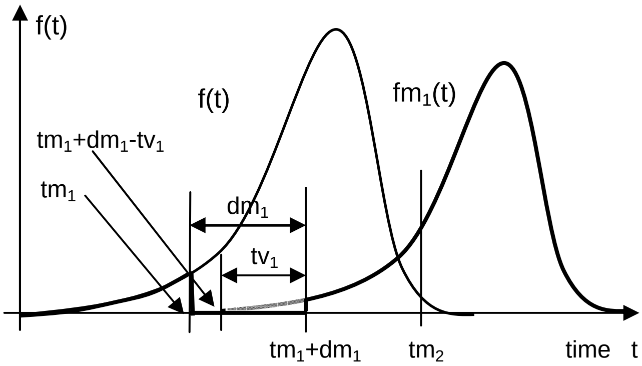

Fig. 1: Lifetime density function for one maintenance action, imperfect maintenance

By that way immediately after having finished maintenance the (time-dependent) outage probability starts with a value greater than 0 thus representing a degradation residue which cannot be canceled by maintenance. In the figure *tm* and *dm* are maintenance time and maintenance duration respectively. For the general case of n maintenance actions performed during component lifetime the density function consists of n+1 segments $fm_i(t)$, see (1) [2].

$$fm_i(t) = K_i\, f(t - tm_i - dm_i + tv_i), i = 0....n \quad (1)$$

Segment i = 0 to n-1:

$$tm_i + dm_i <= t < tm_{i+1} \quad (2)$$

Segment n:

$$tm_n + dm_n <= t < \infty \quad (3)$$

$$K_i = \prod_{j=1}^{i} \frac{1 - F(tm_j - tm_{j-1} - dm_{j-1} + tv_{j-1})}{1 - F(tv_j)} \quad (4)$$

$K_0 = 1, tm_0 = 0, dm_0 = 0, tv_0 = 0.$

F(t) is the original lifetime or cycle time distribution function without maintenance effects.

If the degradation parameter *tv* is smaller than the maintenance interval (tm_j - tm_{j-1}), maintenance results in an increase of lifetime (cycle-time) expectation, otherwise expectation is decreased. If *tv* is equal to the maintenance interval, maintenance has no effect.

For a constant parameter *tv* degradation frequency increases/decreases with the number of maintenance actions performed during the observation period. Intuitively, this approach is not in coincidence with reality. To relax coupling of degradation to maintenance frequency, *tv* can be put up in proportion to maintenance interval length [2].

Maintenance model with simulation of inspection

Purpose of inspection is to check whether maintenance activities have to be performed or not. In the presented model inspection is taken into account by the so called defect detection probability *pi* which introduces a stochastic aspect into the maintenance model. It is a measure for the ratio of the number of maintenance actions performed after inspection (*nm*) and the number of inspections performed during the observation period or system lifetime respectively (*ni*), see (5).

$$pi = \frac{nm}{ni}, nm <= ni \quad (5)$$

As a result of inspection two cases have to be distinguished: Maintenance is necessary with probability *pi* or maintenance is not necessary with probability *1-pi*. Thus, for the period after the first inspection the density function $fmi_1(t)$ forms a combination of the original density *f(t)* and the density including the effect of maintenance $fm_1(t)$ given by (1) and (4) for i=1, see (6).

$$fmi_1(t) = pi \,.\, fm_1(t) + (1 - pi)\,.\, f(t) \quad (6)$$

Recursive formulae for a deliberate number of inspections are given in [2].

The defect detection probability can be modeled either as constant which is evaluated on the basis of system operation statistics or as function of the lifetime or cycle-time distribution [2].

COST MODELS

Outage cost

Cost accruing during the observation period by outages of a component or a collective of similar components is given by the product of outage frequency with event-based societal outage cost. Representing outage frequency by renewal density [3], outage cost per component for a time interval of 1yr. at time instant t can be formulated by (7).

$$R(t) = s(t).r(t) \quad (7)$$

s(t) mean value of societal cost of one component outage for components of the observed collective

r(t) value of renewal density function at time instant t

Event-based outage costs are evaluated by reliability computations of the observed system [4]. The renewal density is a function of the lifetime (cycle-time) density function *f(t), fm(t)* respectively [1]. Its basic equation is given in (8), more complex formulations, e.g. including times of facility installation, can be found in [3], [5].

$$r(t) = f(t) + \sum_{\tau=0}^{t} r(t-\tau)\,.\, f(\tau) \quad (8)$$

Since lifetime or cycle-time densities are formulated as functions of inspection/maintenance interval and defect detection probability, maintenance intensity becomes an independent parameter of renewal density and outage cost respectively.

Maintenance cost

For a certain component maintenance is performed as soon as it has reached the age for which maintenance activities have been assigned by the actual maintenance concept.

Thus, maintenance cost can be mathematically formulated by combining the age-density function with the time series of event-based maintenance cost. Age-density is a function of renewal density and lifetime (cycle-time) distribution [3].

Total cost

Total cost *Ct(t)* is given by the sum of outage cost *R(t)* and maintenance cost *M(t)*. If the cost models are based on lifetime distributions, event based outage costs have to be completed by costs for replacement of damaged facility *e(t)*.

$$Ct(t) = (s(t) + e(t)).r(t) + M(t) \tag{9}$$

PARAMETER SENSITIVITY ANALYSIS

The presented maintenance models are applied to the lifetime distribution/density of 20-kV-wood poles. The density function was computed by parameter estimation by processing the lifetime histogram for a sample of 16000 components. The resulting density is a normal distribution with an expectation of 26 years and a standard deviation of 9.9 years [6].

For application of the presented maintenance models the influence of external effects (e.g. adverse weather or exchange due to security considerations) as well as the influence of maintenance should be extracted from the original lifetime density. Since the raw data material of this sample did not contain any information about the reasons for which the components were taken out of operation such effects could not be eliminated. Thus, the presented results are not suitable for practical use but only for demonstration purposes.

For simulation of irreversible aging which cannot be influenced by maintenance, a second lifetime distribution is used by which an additional cost term is introduced into the total cost function. With reference to [5] this distribution is formulated as normal with an expectation of 50 years and a standard deviation of 11 years.

The cost ratio of societal outage cost to maintenance costs amounts to 8.8 : 0.2.

Maintenance with high efficiency

In Fig. 2 the lifetime density functions with inspection intervals of 10 years, a shift *tv* of 2 years and a defect detection probability of 0.7 is shown. It can be observed that the assumption of a rather small time shift results in a model with almost perfect maintenance by which components are restituted to a large degree to their initial "as new" state. As a consequence lifetime expectation increases from 26 to 65 years.

It does not seem to be very realistic to reach a lifetime increase of a factor two to three merely by intensive maintenance. Thus, this model will rather not be adequate for practical application.

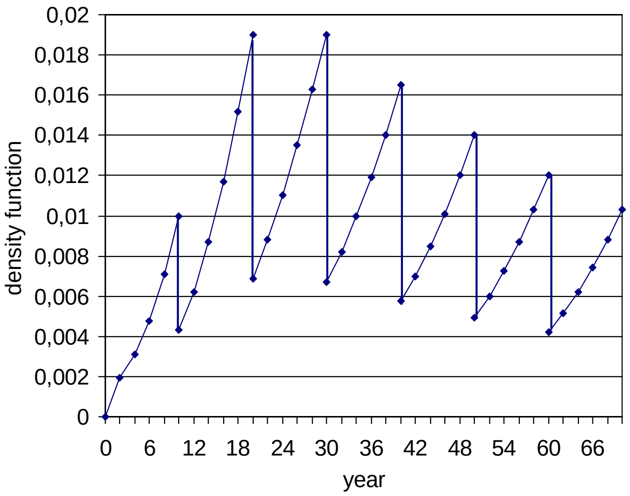

Fig. 2: Lifetime density for high efficient maintenance

Maintenance with reduced efficiency

The time shift parameter *tv* is modeled as a linear function progressing with the number of inspections performed during the observation period [2]. In Fig. 3 the lifetime density function for inspection intervals of 10 years and a defect detection probability of 0.7 is shown. Lifetime expectation is increased by maintenance from 26 to 40 years.

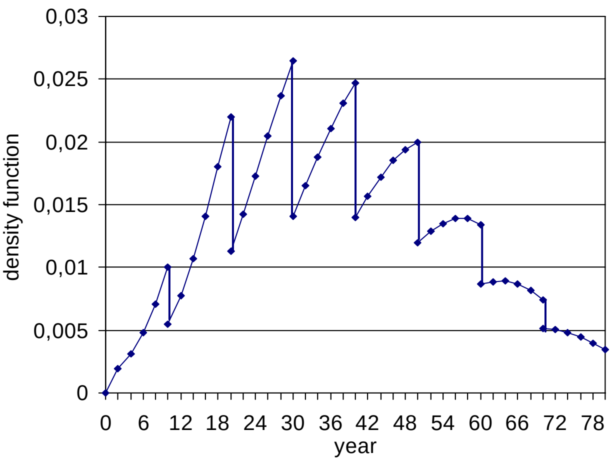

Fig. 3: Lifetime density for reduced maintenance efficiency

In Fig. 4 the development of cost units per component and year with respect to variation of defect detection probability is shown. Inspection intervals of two years are assumed, the time shift parameter is modeled in the same way as in Fig. 3. Components are exchanged after a lifetime of 42 years irrespective of their state.

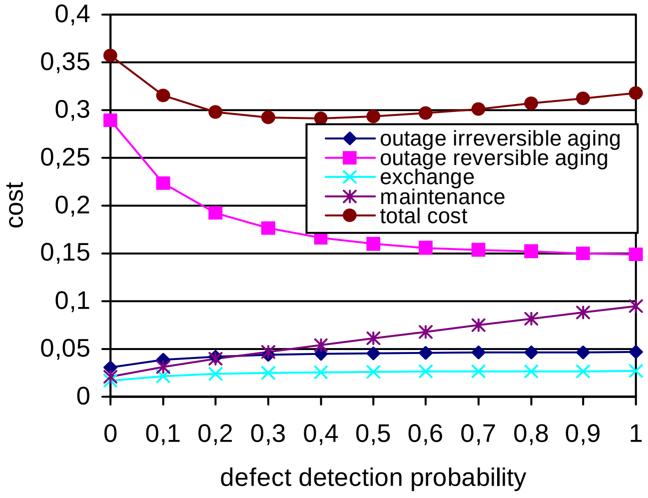

Fig. 4: Cost function versus defect detection probability

Since defect detection probability represents the probability for undertaking maintenance activities as a consequence of inspection findings, maintenance cost increases with growing defect detection probability, whereas outage cost decreases with increasing maintenance intensity. Total cost reaches a minimum at a defect detection probability of 0.4 which results in a mean maintenance interval of 0.2/0.4 = 5 years.

In Fig. 5 cost as function of inspection intervals is shown. Defect detection probability is now modeled as function of lifetime distribution.

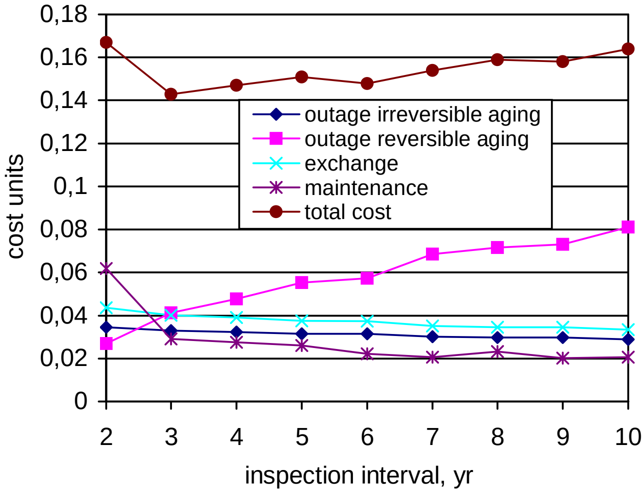

Fig. 5: Cost functions versus inspection interval

It can be observed that total cost has some local minima. This is a consequence of the formulation of the time shift parameter as discrete value with a step length of 1 year. The global optimum is located at an inspection interval of 3 years. The mean value of defect detection probability amounts to approximately 0.6 for this example which again results in a maintenance interval of 5 years.

CONCLUSIONS

Adequate maintenance models constitute crucial elements within the development of maintenance planning methods. It could be shown that simple deterministic models by which system state is restituted to the initial "as-new" state do not always deliver realistic results. Applying the proposed extended maintenance model, component condition and irreversible system degradation (independent of maintenance activities) can be simulated in a more realistic way than by the basic model.

The extended inspection and maintenance model was applied to maintenance optimizations on the basis of a cost function including maintenance and societal outage costs.

Provided adequate information for model parameter evaluation and adaptation is available the proposed maintenance model constitutes a valuable tool for maintenance optimization.

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