EVALUATION OF THE INFLUENCE OF REPAIR-JOINT NUMBER INCREASE ON THE OUTAGE FREQUENCY OF MEDIUM VOLTAGE CABLES

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ABSTRACT

A method for forecasting the outage frequency of cable sections including the influence of repair-joint increase is presented. Time series of joint numbers are processed by a computation procedure applying aging models for cable sections and joints. The methods were tested using data of a real-life medium voltage cable network. It could be shown that outage frequency of cable sections can be substantially reduced by appropriate maintenance measures.

INTRODUCTION

Outage statistics indicate that outages caused by cable and joint failures are becoming an increasing problem in medium-voltage network operation. Reasons for this effect are not only aging processes but also growing joint numbers being the result of repairs of cable faults. Thus, forecast methods for the future development of cable network outage frequencies become increasingly important tools for network operators. Application of such tools gives network operators the opportunity to take measures against an inadmissible deterioration of system reliability in time.

This paper presents a method for evaluating the increase of the number of repair-joints of a cable section as function of time. Time series of joint numbers and a special aging model constitute input parameters for evaluation of joint outage frequency. A similar procedure is applied for computation of cable outage frequency. The sum of joint plus cable outage frequencies yields total outage frequency of the cable line.

Aging models are based on component lifetime distributions. Effects of maintenance are introduced into the mathematical formulation of lifetime distribution by including maintenance intervals as additional parameters [1], [2]. Transformation of lifetime distributions into outage frequencies is performed applying renewal theory [1], [3].

In the first application case the time series of outage frequency is computed for different maintenance concepts (preventive maintenance and planned exchange). It serves as forecast of the development of reliability and cost as an effect of modifications of the maintenance concept. In the second application case a total cost function independent of time serves as object function for maintenance-interval optimization. A special feature of the presented methods is their ability to take technology changes of new components into consideration [4].

THEORETICAL BACKGROUNDS

Definitions

Lifetime distribution *F(t)* is the probability of not surviving lifetime t. **Lifetime density** *f(t)* is the probability for observing lifetimes of amount t (simplified definition, mathematically not quite exact). *f(t)* is the differential of *F(t)*.

A **cable section** is defined as part of a cable line terminated by stations or nodes connecting laterals to the main line. It is assumed that sections can be grouped into samples with small length dispersions. In the presented approach a cable section is thought to be subdivided into (fictitious) "**fragments**" with lengths equal to the average length of a piece of cable inserted during repair.

Maintenance comprises planned activities to increase lifetime expectation. **Exchange** is a planned activity to substitute worn-out component. It is assumed that maintenance and exchange affect whole cable sections and not only parts of them.

Renewal density

Renewal density is the statistical expectation of the number of renewals per time interval dt [1]. Neglecting repair times, outage and succeeding renewal (repair) can be treated as one related event. Thus, renewal density can be used as image of outage frequency. Under the assumption that time t is divided into intervals of dt=1 year, renewal density r(t) can be computed by recursive equation (1) [2].

$$r(t) = \sum_{\tau=0}^{t} rb(t-\tau).f(t-\tau,\tau) \qquad (1)$$

with

$$rb(0) = 1 + r(0); rb(t) = r(t), t > 0 \qquad (2)$$

In (1) *f(j,t)* is the lifetime density of a special component sample. Thus, *r(t)* describes outage frequency of a sample member as function of time. Parameter *(j)* of lifetime density *f(j,t)* is the year in which components were put into operation. The second one *(t)* is the classical time parameter of the density function. Components with different commencements of operation (different j-parameters) may have different lifetime densities. This feature is used to take technology changes, occurring at certain time instances *j*, into account.

Generally, not all components of the observed sample are put into operation at the same time. This is taken into account by an "operation-commencement" function inserted into a modified formulation of (1) [2].

Components with outage rates dependent on length

Equations defined above are valid for components with outage rates independent of length. To take length into account the cable section is divided into a chain of fragments with lengths equal to the average length of repair-fragments. Before occurrence of the first cable-fault these fragments are not really existing and thus fictitious ones. During each single-fault event one of the fragments is transformed from a fictitious to a real one by repair. Fragment number is given by the quotient between cable section- and fragment-length. Thus, the model implies that the crew performing repair is not quite free in the choice of the location of repair-fragments since fragment borders are pre-determined by the model structure. Although such a restriction does not exist in praxis, it is the author's opinion that this model constitutes a sufficiently accurate image of reality.

For application of this concept an expression for lifetime density of cable fragments has to be derived. Since the section forms a serial structure of fragments its probability of survival is given by the product of the survival probabilities of fragments. This equivalence leads to the following equation for fragment lifetime distribution [5]. Index "Sect" denotes section and "Frag" fragment.

$$f(t)_{Frag} = \frac{d}{dt}[1-(1-F(t)_{Sect})^{1/nr}] \quad (3)$$

nr is the number of fragments per section.

Since a cable section can be regarded as a sample of *nr* fragments, renewal density of the section is the product of the renewal density of fragments and the number of sample elements (4).

$$r(t)_{Sect} = r(t)_{Frag}.nr \quad (4)$$

During the operation period the increase of cable section outage frequency is retarded to a certain degree by inserting new fragments after each cable-failure. On the other hand the number of repair-joints increases as a consequence of failure events thus accelerating the growth of joint-failure numbers. In order to assess the influence of this effect a model for joint number increase has to be developed.

Model for the increase of repair-joint numbers

Development of repair-joint numbers per time is dependent on the number of installed repair-fragments. Consequently, at first a model for repair-fragment number increase has to be established. In (1) the term at the right hand side of the summation symbol can be interpreted as the frequency of failures occurring at time instant *t* on components with age τ [5]. The increase of the number of repair-fragments observed in time interval *dt* at time *t* is given by the frequency of failure-events occurring in cable section parts not yet affected by faults. (Failures in such regions are repaired by insertion of new repair-fragments. According to the adopted cable section model this action results in transformation of a fictitious fragment to a real one, thus increasing the number of real fragments). The age τ of these section parts is identical to the time *t* of the failure-event (τ=*t*). Thus, the frequency of events is given by

$$ra(t=\tau) = rb(0).f(0,t)_{Frag} \quad (5)$$

For a time interval dt = 1yr (5) expresses the contribution of one single fragment to total repair-fragment increase per year. To get repair-fragment increase for a cable section consisting of *nr* (fictitious or real) fragments (5) has to be multiplied by *nr*. The accumulated repair-fragment number N_{Frag} can be computed applying (6).

$$N_{Frag}(t) = rb(0).F(0,t)_{Frag}.nr, t < tl_{\max} \quad (6)$$

According to (6) the time parameter is restricted by the largest possible age tl_{max} which is reachable by the fragments. For this age the value of lifetime distribution $F(0,tl_{max})$ amounts to 1. Assuming that components do not fail immediately after operation commencement, identity $rb(0)=1$ is valid and (6) results in $N_{Frag}(tl_{max})=nr$. Thus, repair-fragment number of a cable section is developing in proportion to lifetime distribution and approaches to the number *nr* of fictitious fragments per section if cables are not exchanged by new ones in time.

In a cable section with only a small number of repair-fragments, insertion of a new fragment will increase the number of repair-joints by two. However, as the repair-fragment number rises, the probability that failures occur near already existing repair-fragments rises, too. In that case a new repair-fragment probably will border to an exiting one and the number of additional repair-joints necessary for its insertion will be less than two. Thus, the proportionality-factor for computation of repair-joint- as function of repair-fragment-increase is dependent on observation time *t* with a maximum value of 2 and a minimum of 0. The equation for proportionality-factor calculation is given in [5].

Total cable section outage frequency

During computation of renewal density of joints $r_m(t)$, repair-joint increase is treated like an operation-commencement function. In equivalence to (4) $r_m(t)$ has to be multiplied by the maximum possible repair-joint number $N_m(tl_{max})$. Combination of the renewal densities of the cable section and its joints results in total renewal density (7).

$$r_{sm}(t) = r_{Sect}(t) + r_m(t).N_m(tl_{\max}) \quad (7)$$

Models for maintenance and exchange

Effects of maintenance are taken into consideration by introducing maintenance interval as an additional parameter into the mathematical formulation of lifetime distribution [1], [2]. The approach for taking exchange into consideration is presented in [5].

Cost models

Since renewal density can be interpreted as an image of outage frequency, outage cost can be expressed as the product of renewal density $r_{sm}(t)$ and event-based societal outage cost $s(t)$. Including maintenance cost $M(t)$ and exchange cost $X(t)$, total cost is given by (8).

$$Ct(t) = r_{sm}(t).s(t) + [M(t) + X(t)].ls \quad (8)$$

Parameter ls is the cable section length. Formulae for $M(t)$ and $X(t)$ are presented in [5].

CASE STUDIES

Input data

The presented models are applied using data for 20-kV-cables with an average section length of 0.5 km. Because of the rather small number of available data no subdivision with respect to cable types could be performed. A parameter estimation procedure delivered the following lifetime distribution parameters for cables: Two combined normal distributions with (expectation/standard deviation/weighting factor):

1.) 50.0/6.42/0.72

2.) 33.1/4.25/0.28

For joints a single normal distribution with (55.0/11.0/-) was assumed.

Increase of repair-joint number

Fig. 1 visualizes the joint number increase for 1km cable section. It was assumed that the section contains 4 joints at the beginning of the observation period X. The joint number remains small till year number 40. Afterwards it begins to rise reaching a maximum of 87, hundred years later. As a consequence of the applied model, in a section partitioned into 100 fragments the highest possible joint number would be 100. However, the approach used for evaluation of joint numbers as a function of section numbers generally delivers lower joint numbers.

Time series of renewal density

In Fig. 2 *rsm* represents total renewal density for the cable section according to (7). Functions *rSect* and *rm* are the renewal densities due to cable and joint failures, respectively. The curves tend towards asymptotic values. The asymptotic value of *rsm* is represented by the horizontal line. It can be observed that during the first 80 years total renewal density is determined by cable faults. Subsequently, the influence of joint failures becomes visible. The time delay observed in joint renewal density *rm* is a consequence of the shape of joint number increase function, see Fig. 1: Although the joint number begins to increase already with year number 40, most of the joints responsible for this increase reach the end of life not before elapse of the next 60 years. Thus, it can be concluded that for an exploitation period of 60 years, repair-joint number increase does not constitute a severe problem.

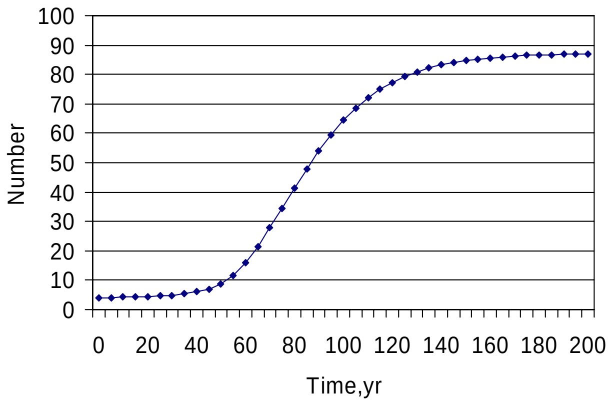

Fig. 1: Joint number increase

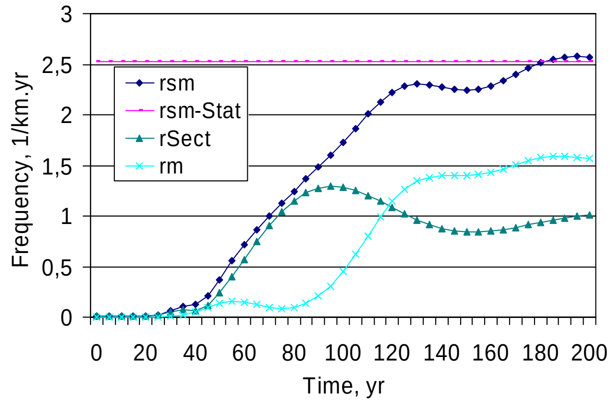

Fig. 2: Renewal densities for the cable section including effects of joint failures

In Fig. 3 the effects of maintenance activities are demonstrated. The applied model for simulation of maintenance intervals of 10 years leads to an increase of lifetime expectation of approximately 25% for cables and joints. Planned exchange is performed after an exploitation time of 40 years. In the figure "n.M." denotes the renewal density computed without any of the features mentioned above. Curve "w.M." represents renewal density with simulation of preventive maintenance. Influence of exchange is demonstrated by "Ex". Symbol "Stat" indicates asymptotic values.

It is demonstrated by Fig. 3 that maintenance can lead to a considerable reduction of renewal density provided that the assumed lifetime expectation gain of 25% can be reached in practice. Nevertheless, the more efficient measure to improve reliability is to exchange cable sections within a period during which renewal density increase is still smooth.

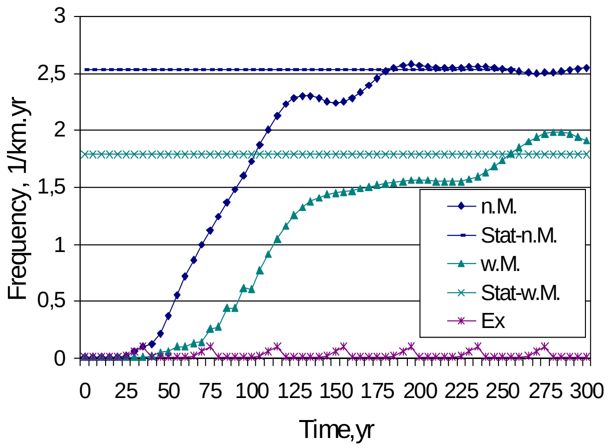

Fig. 3: Effects of maintenance activities and technology changes

Exchange interval optimization

The following specific cost values were used: Societal outage costs - 15.000€ per event; repair costs (personnel plus material) - 25.000€ per event; maintenance cost - 30.000€/km; exchange cost - 175.000€/km. Object function (8) is used for cost minimization. It can be observed in Fig. 4 that cost minimum is reached with exchange intervals of 40 years.

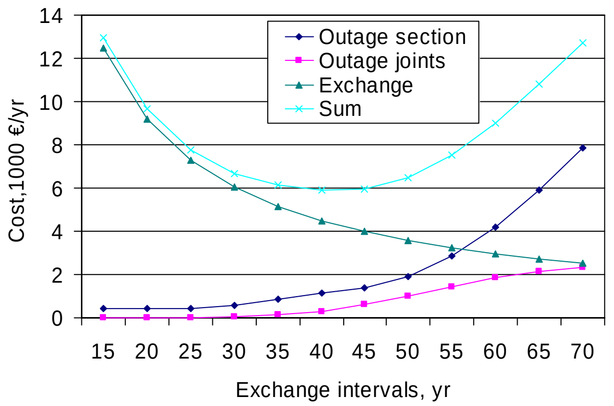

Fig. 4: Total cost as function of exchange intervals

CONCLUSIONS

The increase of joints inserted into a cable section during repair actions can be modelled as a function of lifetime density of the cable. Combination of the joint increase function with lifetime density of joints results in renewal density function of joints. By a similar procedure renewal density for failures occurring directly in the cable can be computed. The sum of these two densities represents the development of outage frequency of the cable section during its operation time.

Application of the presented concepts using data of a real-life medium voltage network resulted in following findings: A distinct increase of the outage frequency of a cable section can be observed when its exploitation time has passed lifetime expectation. The influence of repair-joint increase becomes visible in the time series of outage frequency with a delay determined by the sum of cable and joint lifetime expectation. Thus, for exploitation periods in the range of 40 to 50 years, increase of repair-joint numbers does not constitute a severe reliability problem.

The increase of outage frequency can be substantially reduced by maintenance. However, estimation of realistic maintenance model parameters still is an unsolved problem. Thus, an exact quantification of the gains reachable by maintenance is not yet possible. Despite of these uncertainties results indicate that the most effective measure to keep outage frequency and total cost (sum of outage, maintenance and renewal cost) within acceptable limits is periodical renewal of cable sections.

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