STATISTICAL APPROACH FOR COMPONENT STATE EVALUATION IMPLEMENTED IN ASSET MANAGEMENT OF DISTRIBUTION SYSTEMS

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ABSTRACT

The main intention of comprehensive asset management procedures is the optimal use of the assets of a network by means of best maintenance and replacement strategies. Although such methods have been applied in praxis for several years, certain information on specific input data - especially for medium-voltage distribution systems - are hard to acquire or even not available today. In particular, appropriate condition assessment, aging models and failure probabilities of the components are most critical aspects. This crucial information gap was explicitly addressed in a broad research project conducted in Germany[1].

The paper focuses on present challenges on implementing asset management processes within the utilities and an appropriate solution. A developed statistical approach combined with a probabilistic method to evaluate the component state is introduced and applied to several component classes. Finally the results of reliability calculations for a distribution network using the derived input data are discussed.

INTRODUCTION

In an electrical power system, asset management is introduced mainly to cut the complementary costs and to use the electrical equipment and the networks in a more efficient way. Thus the policy, in a comprehensive economic view, is to look for a complete solution which gives maximum profit at minimum costs and is applicable to the whole network for a long time period [1].

Therefore it is the asset manager's task presented in Fig. 1, to quantify the parameters of medium-voltage networks (equipment inventory, network topology, etc.), as well as the technical operating conditions (voltage level, working load, operating time, etc.), and to manage their correspondence with each other (reliability, maintenance, etc.). With the assessment of conditions (network parameters, and operating conditions), the multiple models (life model and probabilistic failure model) with the time-sequential Monte Carlo simulation allow a calculation of the consequences in terms of failure probability, failure rate, system reliability, etc. These issues estimate the behaviors of electrical equipment, and medium-voltage networks as a whole. Based on the assessment of reliability and technical lifetime, the deterministic costs, and the maximal economical lifetime can be achieved by an optimization of the actions and procedures of maintenance [2].

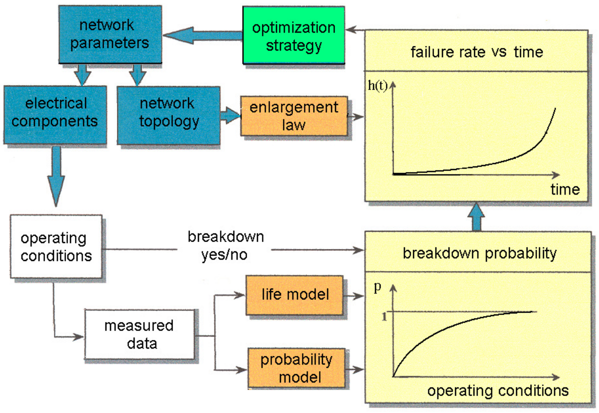

Fig. 1 Technical asset management

COMPREHENSIVE FAILURE MODEL

From the general degradation properties of the electrical components, it is known that the aging of insulating materials in electrical components often contribute to the failure due to the presence of degradation stresses such as electrical, thermal and environmental stresses. The typical aging processes of insulating materials are considered to be partial discharge, formation of water trees and electro- and thermo-chemical processes as well as wear-out processes.

On the basis of the investigations, a thorough electro-thermal life model [2] derives from a suitable combination of single-stress models, e.g. the Inverse-Power-Model and the Arrhenius-Model. This can be simply done by assuming that the aging rate under these combined stresses is the product of the aging rates under each single stress:

$$t = t_0 (E / E_0)^{-(n-bT)} \cdot e^{-BT}, \quad T = 1/\vartheta_0 - 1/\vartheta \qquad (1)$$

where E, T and t are the electrical, thermal stresses and lifetime, respectively. E_0 is the scale-parameter for the lower limit of electrical stress (below which the aging can be neglected) and t_0 is the corresponding lifetime. n and B are the voltage-endurance coefficient and the activation energy

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of thermal degradation reaction, respectively. b is the correct coefficient which takes into account the reaction of materials due to combined stress application. ϑ and ϑ_0 are the absolute temperature and the reference temperature.

With regard to the aging of insulating materials which are subjected to combined electrical and thermal stresses, the Weibull function to determine the likelihood of failure P at given stresses is compared with a shape parameter α and can be well described by

$$P(t) = 1 - \exp\left[-\left(t / t_{63\%}\right)^{\alpha}\right] \tag{2}$$

where $t_{63\%}$ is the failure time for the failure probability of 63% as a function of the lifetime t, at which a fraction ($1 - e^{-1}$) equal to 63% of the electrical components have failed.

The failure of an electrical component may occur if over-voltage stress is applied, or if the electrical component is aged by temperature or time. Therefore, a criterion for the aging of electrical components is consistent with the electrical and thermal stress. Thus the lifetime $t_{63\%}$ can be explained by the appropriate life model (1). For the estimation of $t_{63\%}$ in equation (2), the lifetime t for the failure probability of 63% in equation (1) is substituted to determine the failure probability of an electrical component under the influences of aging and electrical stress:

$$P(t) = 1 - \exp\left[-\left(\frac{E}{E_0}\right)^{\alpha(n-bT)} \cdot \left(\frac{t}{t_0}\right)^{\alpha} \cdot e^{\alpha BT}\right] \tag{3}$$

In this way, equation (3) becomes the probabilistic failure model for combined stresses. That is, a functional relationship between the failure distribution and the applied stresses provides life lines at different probabilities.

It is a more reliable approach to determine the parameters of equation (3) directly through aging tests and breakdown testes, respectively. One part of the parameters of equation (3) can be accepted as shown in Table 1 which is found in [2].

Table 1. The Parameters of Equation (3)

n	b (K)	B (K)
7.0	6000	17000

The other parameters of equation (3) may be significantly changed by different service conditions. For this purpose, the specific failure statistics [3] from the historical failure events have been especially evaluated, by which those parameters can be optimized as reported in Table 2.

Table 2. The Parameters of Equation (3)

component	α	E/E_0	T(1/K)
circuit breaker	0~100	2.5	1.5×10^{-4}
transformer	0~100	2.0	1.5×10^{-4}
VPE-cable	0~100	1.0	3.5×10^{-4}

Although these parameters are carefully chosen to match up with the actual data, every component has a wide characteristic range which is hard to address explicitly the component type. This reflects the wide range of values, e.g. found in the shape parameter α.

STATISTIC ON COMPONENT DAMAGES

Medium-voltage distribution systems consist - in comparison to transmission systems - of a multitude of equipment. The general condition assessment of their components can be realized effectively by statistical evaluation of damage events occurring during operation [4]. The usage of diagnostic tools or monitoring techniques is recommended only in certain circumstances like a particular degree of degradation or high importance of a component. Therefore one major objective of the mentioned research project was the development of a novel statistic on component damages [3].

Damage is defined as an undesired, enduring degradation of the component as a result of a particular influence or cause entailing repair actions in a certain time. Damage may or may not lead to a total component failure with a possible disturbance of network operation.

In cooperation with a total of 20 network operators, service providers and academic institutions a specific data acquisition scheme was created to obtain the required information. The considered subsystems are MV switchgear stations, secondary substations, cable systems and overhead lines. Transmission transformers are assigned to MV stations and distribution transformers are assigned to secondary substations. Besides data of the relevant subsystem and of the network, specifications of the damage itself are acquired. The damage description includes information on the affected component like year of manufacture, functional or technological classification. Furthermore data on applied maintenance, on arising costs, causes and effects of damages as well as other relevant criteria are collected. For some component classes, further details on the location of damage are differentiated. In total nearly 3500 protocols were collected in the specially designed database.

The analysis of the collected data allows conclusions e.g. on the interaction between damage occurring and maintenance activities, on the costs caused by component damages and their statistical dispersion as well as on failure probabilities depending on component class and age. The calculation of the failure probabilities - introduced in the following chapter - requires also information on the quantity structure and the age structure of the components of the investigated networks.

APPLICATION EXAMPLES

Failure Probability

The estimation of the component failure probability is one essential benefit of the developed approach providing information on component condition dependent on relevant criteria. At this, the impact of component age is of special concern to reproduce and predict the aging behavior respectively. The generalization of statistical results requires the application of suitable models. On the other hand, models derived from theory need the data from praxis to be parameterized. The presented approach is a combination of these two aspects. Hence the introduced probabilistic method is applied to the evaluated values from the statistic. The statistic delivers failure frequencies depending on component class and age [5]. They are calculated by the number of events referring to the appropriate quantity structure and the length of the observation period. The chosen width of time intervals amounts five years to reproduce the dependency on age. The quantity of equipment is specific to the years of manufacture and clustered to 5-year-groups as well. Therefore the determination of the failure frequency has to consider the correct assignment of a damaged component of a certain age to the quantity of its year of manufacture.

The sought failure probabilities can be determined by means of the presented model from the component failure frequencies. For this purpose the probability density function – which is achieved by deriving the distribution function with respect to time – is approximated on the relative frequencies from the statistic using a least squares fit method. It has to be noticed that a failure of a component is not stringent the end of its life time but can be remedied by repair actions in most cases.

Fig. 2 shows the resulting failure probabilities of medium-voltage circuit breakers and transmission transformers depending on time. All of the considered transformers are oil-insulated and the circuit breakers comprise mainly low-oil-content, but also vacuum and SF_6 types. Future analyses aim at the type specific determination of failure probabilities which the currently existing database allows only in a rudimental manner.

The probability functions are visualized for regularly maintained and not maintained equipment. As expected, for both component classes the characteristics move to much lower expectation values and achieve decreased dispersions if maintenance is omitted. They were obtained due to the following assumptions: The “maintained regularly”-curves can be derived directly from the data of failure events leading to a disturbance of network operation. The “not maintained”-curves result from the evaluation of all collected data, whether damages were detected by maintenance activities or not. So, damages would lead to component failures after a certain time if there is no maintenance applied at all. As the involved network operators perform time and/or condition based maintenance most of the damages were discovered during maintenance activities.

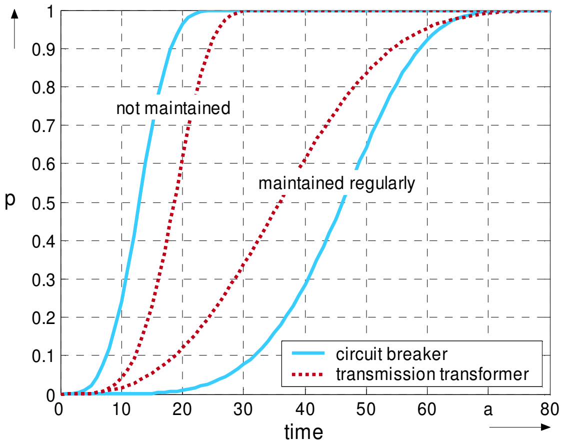

Fig. 2 Failure probabilities for MV circuit breakers and transmission transformers - influence of maintenance

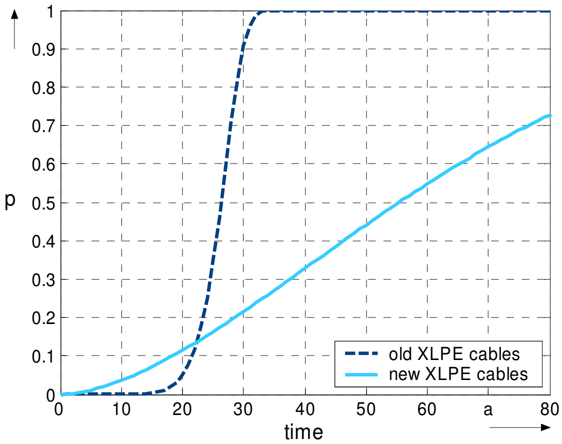

Fig. 3 Failure probabilities of old and new XLPE cables (curing measures not considered)

Another example is given by Fig. 3 for XLPE-insulated cables. It shows the failure probabilities for old and new cables as there was a substantial change in manufacturing technology at the beginning of the 1980ies. Early XLPE cables suffered from rapid aging of the insulation due to water trees. Now the quality of XLPE cables manufactured with improved technologies has been increased significantly. Nevertheless, the experiences with new XLPE cables are at early stages. This is visualized by the high dispersion of their failure probability. External influences are not considered as they are not caused by aging processes.

The gained failure probabilities are of high importance as input data of asset management methods including risk analysis respectively. The parameters for electrical and thermal stresses included in the failure model were kept constant as no reliable data is available for their exact estimation yet. Of course, the effects of these stresses to the failure probability can be investigated by variation of the appropriate magnitudes.

Reliability Calculations

The reliability calculation is an essential element of modern asset management processes [6]. The developed statistic enables the determination of component reliability data as the required input information being usually hardly available today. The following example presents the effects of component aging and maintenance on supply reliability of a medium-voltage system.

The simulation is performed on the base of a subnetwork of a rural distribution network. It comprises one central HV/MV substation with a double bus bar and two transformers, 60 km of cables and 60 km of overhead lines with 152 secondary substations. It is operated in open loops with radial-line connections and neutral point compensation. The mean values of the component age amount 15 years for cables, 28 years for overhead lines and 21 years for secondary substations.

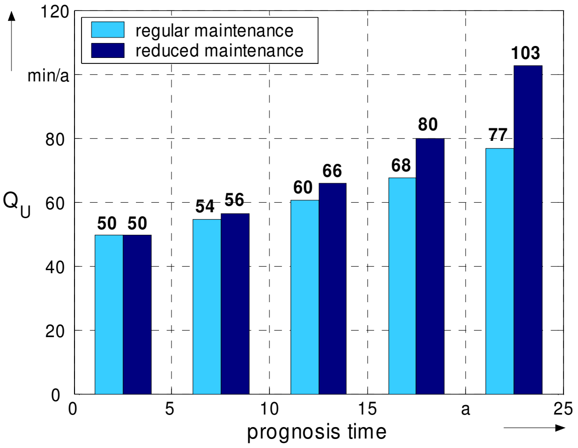

Fig. 4 Average supply unavailability per customer, scenarios with regular and reduced maintenance

Of course, the age structure and configuration of the network have a strong influence on the results of the reliability calculations shown in Fig. 4. It represents the prognosis of average supply unavailability per customer in min/a as a common criterion of supply reliability for two scenarios: At the first, regular maintenance is applied to all components as usual. At the second, all preventive maintenance activities were omitted from the second prognosis interval (5 year intervals) except for overhead lines which were retained unchanged due to security reasons. It has to be emphasized that no replacements were simulated at both scenarios. The results clearly demonstrate the impact of both investigated factors, the aging and the maintenance of components, and provide useful information for maximizing the exploitation of the assets.

CONCLUSION

The introduced approach is a valuable contribution to the integration of asset management methods within the utilities. It provides essential information to facilitate the decision process on choosing efficient strategies for maintenance and replacement.

The developed statistic on component damages allows the assessment of component condition in dependency of relevant parameters. The application of the presented comprehensive failure model to the evaluated data from the statistic enables the determination of the failure probability of the components with respect to age and maintenance. Moreover, the prognosis of supply reliability of a system can be performed respectively. Of course, the financial aspect, not reflected in this paper, always has to be considered as a vital part of the aspired optimization.

Further investigations will distinguish between different technological features of components on the base of an extended database. For this purpose, the data acquisition scheme is readapted and the data collection is continued. The evaluations will result e.g. in concrete failure probabilities for low-oil-content and vacuum circuit breakers. In addition the impact of maintenance has to be explored more detailed. For the comparison of different strategies, a harmonization of terms and contents of maintenance measures between the involved utilities is indispensable and will be part of future studies.

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