ASSET MANAGEMENT IN DISTRIBUTION SYSTEMS CONSIDERING NEW KNOWLEDGE ON COMPONENT RELIABILITY AND DAMAGE COSTS

Dipl.-Ing. Uwe Zickler*, M. Sc. Andrei Machkine,
Dr.-Ing. Michael Schwan, Prof. Dr.-Ing. Armin Schnettler
Forschungsgemeinschaft für Elektrische Anlagen und Stromwirtschaft e.V. (FGH)
Mannheim, Germany
* uwe.zickler@fgh-ma.de

Dr.-Ing. Xiang Zhang,
Prof. Dr.-Ing. Ernst Gockenbach
University of Hannover
Hannover, Germany

Abstract – In liberalised electrical power supply markets, asset management procedures have developed into a central element of network operation and planning. Asset management methods consider all relevant life cycle cost related to the network equipment and provide strategies for reinvestment, maintenance and fault elimination. However, the methods require information about the component reliability of the installed network equipment, as well as about costs arising in the case of damage. Further, the component reliability depends on component age, maintenance history and operational stresses – so, a prediction of the component reliability based on the asset management strategies has to be found. Up to now, only rudimental quantitative statements are available. In a current research project, data of historical damage events is collected in a special damage statistic to provide more detailed results.

In this paper, the approach for a comprehensive, risk-oriented asset management method in distribution networks is presented and possible applications are illustrated. Also, the developed scheme of the special damage statistic is described and intermediate results of the component reliability and their application in the corresponding ageing models to derive a prognosis of the component reliability depending on the chosen asset management strategies are presented.

Keywords: Asset Management, Medium Voltage Distribution Systems, Maintenance, Component Reliability, Damage Statistic

1 INTRODUCTION

In recent years, asset management methods have evolved into an integral part of planning and operation of electrical power supply networks in liberalised markets. The increasing cost pressure forces the utility companies to a more and more efficient use of the available funds, while preserving the high quality of supply at the same time. In this area of conflict between cost effectiveness and quality of supply, asset management procedures provide technical and economical information on the equipment and the entire network that form the basis for planning and entrepreneurial decisions.

Asset management methods in distribution networks have to consider some special aspects:

- The **number of installed equipment** is far higher in distribution systems than in transmission systems. Therefore, an individual condition monitoring would be very costly and time-consuming and considerations of individual cases are possible only in exceptions. In general, the application of statistical methods is necessary, where the devices are allocated to different type classes. Characteristic qualities of these type classes are considered in the input and output data of the methods.
- Though the value of the single devices is much less compared to transmission systems, due to the large number of installed units distribution systems represent a significant value. The **value of distribution systems** in Germany is estimated at approximately 20 billion €.
- The age structure of the equipment is coined by the systematic replacement after 40 years of operation in the past. Because of the strong expansion of the networks in the 50's and 60's, many components have reached the end of the assumed lifetime of 40 years today. Due to the limited means for reinvestments the **average component age** will increase, whereas sufficient operational experiences for many of these increasingly old components are not available.
- Today the central area of conflict for power utilities is defined between cost pressure and **quality of power supply**. This is of great importance to operators of distribution networks, since distribution networks have a significant influence on both the quality and the costs of power supply.

The aspects mentioned above clarify the necessity of a comprehensive asset management method especially in distribution networks. In the next chapter, such a method is introduced schematically from the point of view of the authors. Particular attention is paid to the meaning of the component reliability. Related models are presented in the third chapter.

Within the scope of a research project a novel damage statistic was defined to obtain a suitable database for the prognosis of the component reliability. This statistic is introduced in the fourth chapter. Finally, first intermediate results of the analysis of the data are presented. The participants of this research project are twenty power utilities, service providers and research institutes. The project is sponsored by the German Federation of Industrial Cooperative Research Associations "Otto von Guericke" (Arbeitsgemeinschaft industrieller Forschungsvereinigungen AiF) with funds of the Ministry of Economics and Labour (Bundesministerium für Wirtschaft und Arbeit BMWA) as well as by the German Research Foundation (Deutsche Forschungsgemeinschaft DFG).

2 ASSET MANAGEMENT IN DISTRIBUTION SYSTEMS

Asset management procedures pursue a comprehensive approach considering all resulting life cycle costs related to the network equipment. They aim at the minimization of the total costs of network operation.

There are different types of costs being relevant in the context of maintenance. The following costs segments are kept into consideration:

- **Deterministic costs**
  These costs are determined by the chosen strategies for inspections, servicing, reinvestment and fault elimination. Of course, also these deterministic costs can not be predicted exactly, but compared to the cost types described as stochastic costs, the uncertainties are on a far lower level. Deterministic costs are:
  - Costs for scheduled maintenance,
  - Costs for scheduled reinvestments,
  - Other fixed costs like costs for service personnel, capital costs etc.
- **Stochastic costs**
  These costs depend on the occurrences of damage and disturbance events with the components in the network and can be estimated only stochastically. Typically, these costs are subject to distributions with large dispersions. Stochastic costs are:
  - Costs for fault elimination,
  - Costs for repair or replacement,
  - Costs for penalties or compensations (if applicable).

The principle of such a comprehensive, risk-oriented asset management in distribution networks is described by the schematic diagram shown in **Figure 1** [1]. The network and component data, in particular the quantity structure and the age structure as well as the operational stresses of the components, are crucial for the asset management.

Based on the chosen strategies for maintenance, reinvestment and fault elimination, the deterministic costs can be evaluated directly. The stochastic costs result from a simulation of the system performance considering the damage events with the components.

Finally, the selected parameters are optimized, which corresponds to an adjustment of the strategies for maintenance, reinvestment and fault elimination.

This entire process is iteratively repeated until the cost minimum for the investigated network is found. The results are the optimal parameters for the maintenance, reinvestment and fault elimination strategies.

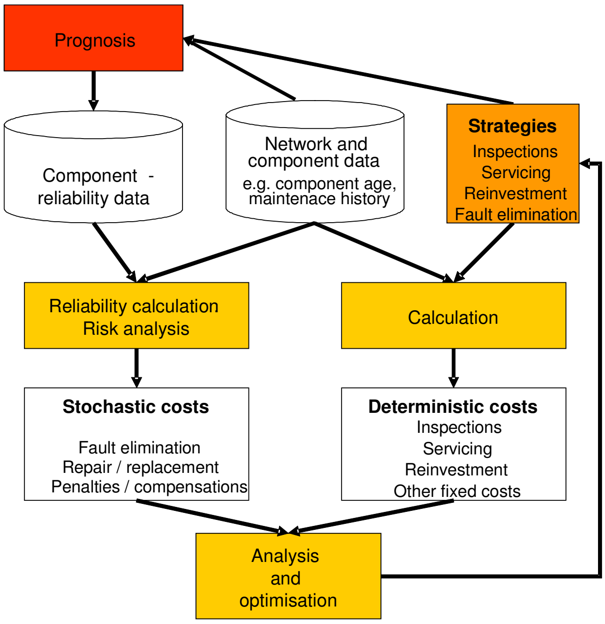

Figure 1: Principle of a comprehensive asset management approach [1]

The methods required for the described asset management approach are well-known in principle and applied successfully in economical or technical risk analyses for a long time. However, there are two problem fields:

- Meaningful statistics about the distribution of the costs caused by damages or disturbances at components of the network are not available. Up to now, only rough estimated values can be assumed.
- The parameters of the strategies for maintenance, reinvestment and fault elimination, as well as the component age and operational stresses have a clear influence on the expected component reliability. These effects have to be considered appropriately in the asset management method, as these parameters are changed in the optimization process.
  However, procedures for the prognosis of the disturbance and damage events for the different components are available only in a rare form or missing completely today.
  Thus, the description of the component reliability in a distribution network as a function of the component operating age and the maintenance history is a substantial but unresolved aspect.

The processing of both problem fields as well as the integration of the new solutions into the presented asset management procedure are essential parts of the above mentioned research project. For this purpose, a detailed damage statistic and adequate component failure models are required.

Both the statistic and the failure modelling are described in the following chapters.

3 MODELLING OF COMPONENT RELIABILITY

3.1 Theoretical models

The failures in the electrical components are often found to contribute to the ageing of materials due to the presence of degradation stresses, such as electrical, thermal, mechanical and ambient (due to the associated environment) stresses. Thus it becomes necessary to do basic research in material analysis (i.e. ageing tests), in order to assess the technical life times of the electrical components.

The ageing of insulating materials is estimated by the time to the occurrence of an electrical breakdown in the electrical component. From a statistical point of view, the probability of electrical breakdown is described by a probabilistic failure model, which can be identified as a consequence of breakdown tests. Along with the life model, the probabilistic failure model regarding possible time to failure give the related statistical variances for the observed variables (in terms of probability, failure rate, reliability of the electrical components, etc.).

Such a system of models helps to predict the failure events of electrical components and the networks under various operating conditions, and thus helps to provide a timely implementation of a strategy for the replacement of electrical equipment and the related investments. This contributes to the prevention of electrical faults and allows scheduling and integrating reinvestments into the overall development plan for the network.

The typical ageing processes of the electrical components are considered to be partial discharge, electrical breakdown, formation of water trees, electro- and thermo-chemical processes as well as mechanical stresses. A chance for the development of a thorough electro-thermo-mechanical life model is given by the phenomenological theory of ageing [2]. If a generic combination of stresses is applied to an electrical component, a suitable life function L of the electrical component can be established according to the following relationship:

$$L = L_0 \, (S / S_0)^{-n} \cdot e^{-BT}, \quad T = 1/\vartheta_0 - 1/\vartheta \tag{1}$$

where n is the stress endurance coefficient, S_0 is the lower limit of stress (below which the ageing can be neglected), B is proportional to the activation energy of the main thermal degradation reaction, T is the conventional thermal stress, ϑ is the absolute temperature, ϑ_0 is a reference temperature and L_0 is the corresponding life at the reference temperature.

The proposed electro-thermo and mechanical life model comes from a suitable combination of single-stress models, which can be represented by the Inverse-Power-Model and the Arrhenius-Model, respectively. This can be done by simply assuming that the ageing rate under combined stresses is the product of the ageing rates under each single stress.

When a failure occurs in an electrical component under the applied stresses, the failure has to be specified by the so-called stress withstand strength which is assigned to the event “non-failure” at the highest stress strength but derived from the event “failure”. Therefore, an accepted statistical model of determining the likelihood of failure at given stresses is compared with the shape of an exponential function and can be described well by

$$p\,(S) = 1 - \exp\left[-\left(\frac{S}{S_{63\%}} \right)^{\beta} \right] \tag{2}$$

where p is the failure probability of an electrical component, β the shape parameter, which can be obtained by failure tests, and $S_{63\%}$ the stress withstand strength of the Weibull-distribution according to the failure probability of 63%.

A failure would occur if a stress is applied or an electrical component is aged by thermal stress, electrical stress, mechanical stress or time. Therefore a criterion for the failure is consistent with the electrical, mechanical and thermal lives. As an estimation of the electrical withstand strength $E_{63\%}$, (1) is applied in (2) to determine the failure probability of an electrical component under the influences of all stresses:

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

If a shape-parameter α is defined by $\alpha = \beta/(n-bT)$, (3) is simplified into:

$$p\,(S,T,L) = 1 - \exp\left[-\left(\frac{L}{L_0} \right)^{\alpha} \cdot \left(\frac{S}{S_0} \right)^{\beta} \cdot e^{\alpha BT} \right] \tag{4}$$

As a multi-stress model the Weibull-function (4) provides a probabilistic failure model giving the failure percentiles for each pair of stresses.

3.2 Practical application

It is known from the statistical theory of failure, that the density of failure probability and the failure rate are determined by the gradient of failure probability.

As a practical application, certain investigations on early XLPE-insulated cables are presented. These cables suffered from rapid ageing of the insulation due to water trees, caused by the manufacturing technology. So, these cables are very problematic in network operation, and thus an unusually extensive database on damages of these cables is available. Of course, these problems were quickly remedied by the cable manufacturers by a technology change.

Figure 2 shows the failure rates of an XLPE-insulated medium voltage cable derived from the VDEW statistic on outages [3] and the calculated values for the year 1975. For a calculation, the characterised parameters of (4) have been determined on a sample of a model cable. It can be seen in Figure 2, that the failure rate rises over the years according to the increasing right wing of the well-known bathtub curve. In the case of an earth fault the reason of failure is usually the water tree correlating strongly to the age of the cable. During the first years of a cable's lifetime the failure rate is constantly low. But after about already 8 years of operation the ageing phenomenon causes an increase in the failure rate of the cable at the end of life, thus indicating an impending failure and showing the strong influence of the age on failure probability.

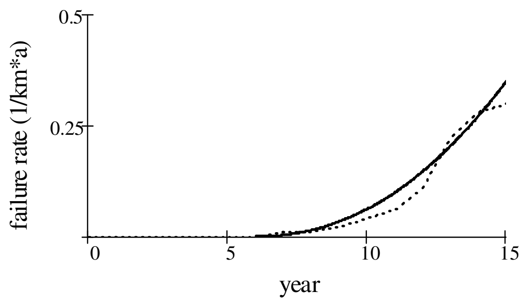

Figure 2: Calculated (full line) and statistical failure rates

However, characteristics of failure rates like the one shown above are not available for most types of equipment. A detailed description of the different influences of maintenance history, ageing and operational stresses are not known in most cases. Therefore a novel damage statistic was defined as presented in the next chapter.

4 DAMAGE STATISTIC

4.1 Introduction

The novel detailed damage statistic shall provide information on the costs caused by damage and disturbance events and enable the modelling of the component reliability as a function of operating age, operational stresses and maintenance history. Even in the rare cases where certain models for a component type are available, they can often not be parameterized with actual data derived from practical operation. For most component types adequate models as well as suitable parameterizations still have to be developed.

Due to the statistical description similar equipment can be combined to type classes. Therefore the amount of data compared to the consideration of individual components is reduced and the data collection is simplified by the formation of collectives. The large number of installed components in distribution networks allows assuming a high precision of the results when using statistical methods.

The required information is gained by the analysis of historical damage events from the networks of the operators participating in the research project. All damages of a considered network in a given observation period are acquired, whether they led to an actual disturbance of network operation or not.

The damage statistic is based on a database. Because of time and financial constraints no independent database was developed. Instead, the existing client-capable database system MABI is used. The database was modified to meet the required demands and was set up on a central server for this purpose. The data is entered by the project participants via internet.

Due to the high confidential character of the acquired data a special information coding method is used, so that no relation between individual events and the network operators can be established. Only the project scientists of FGH have access to all unencrypted data for evaluation purposes.

4.2 Scheme of Data Acquisition

In cooperation with the participating network operators a special scheme of data acquisition according to the demands of the research project was created [4]. Thereby the following subsystems are distinguished:

- MV switchgear stations,
- Secondary substations,
- Cable systems,
- Overhead lines.

Transmission transformers are allocated to the MV switchgear stations and distribution transformers are allocated to the secondary substations.

The design of the input masks for the four subsystems is basically the same. Most of the data fields of the input masks are realized as selection fields with accordant pre-defined selection lists. For each subsystem, information is grouped into five data blocks:

- Identification of the damage event,
- General data of the subsystem,
- Network data,
- Description of damage,
- Description of disturbance (if applicable).

The damage costs, information on maintenance strategies and, of course, the location of damage are collected as part of the damage description. Locations of damages are component types like transformer, circuit breaker, load interrupter switch, disconnecting switch, busbar, voltage or current transformer etc. Depending on the damage-affected component type, additional subforms are retrieved to obtain more detailed information like damage-affected subsystem, manufacturer, year of manufacture / installation, construction type.

The costs caused by damage events at a component are separated in:

- **Damage costs**:
  Costs to re-establish the function of the damage-affected component itself. This refers solely to the implemented action (repair / replacement / withdrawal from service) in the concrete case of damage under consideration.
- **Consequential costs**:
  Costs to recondition other components damaged by electrical or mechanical overstresses (e.g. arc) caused by the initially damage-affected component.
  If the stresses are in line with the operating conditions and further damages occur nevertheless (e.g. double-line-to-ground fault due to voltage in-

crease), it is a considered as a separate, consequential event. These events are acquired on their own and do not belong to consequential costs of the primary damage.

In addition to the data of damage events, information on the component quantity structure, including the age, of the considered networks in the observation period are required.

The final definition and level of detail of the component classes considered in the evaluation depend on the number of damage events, since every class needs a sufficient number of events for statistical evaluation.

4.3 *Evaluation*

The level of detail of evaluation of the damage statistic depends on the quantity and quality of the acquired data to a high degree. The aim is the determination of the failure probability of the investigated components as a function of component operating age, maintenance strategy and component type. Furthermore well-founded data concerning the costs caused by component damages and their statistical dispersion shall be found.

In addition the damage statistic provides the basic possibility to combine the entries of all data fields and to prove them for possible correlations.

The introduced damage statistic focuses on events with actual component damages being relevant to maintenance. In particular these are damage events occurring without a recognisable external reason. Further aspects, e.g. atmospheric disturbances or disturbances without damages, have to be added to gain component reliability data which are input data of the asset management procedure. These data can be achieved from the German VDN statistic on outages and availability [5].

5 EVALUATION EXAMPLES

5.1 *General Information*

At the time this paper was written about two thirds of the expected input data were delivered. Therefore, the results introduced in the following have to be considered as examples for the possibilities of evaluation of the statistic. The discussed aspects are **purely qualitative** at the present time. The numerical values are not sound yet and will certainly change until the data entry is complete. Not all of the participating network operators have finished the data entry for the considered components yet and, in particular, not for the respective observation period. Therefore the presented results are partly limited to subsets of the collected damages.

In the following several evaluation examples for components of different subsystems are visualised.

5.2 *Age Related Damage Rate*

The investigation of the dependence of the component damage rate on component age is an essential topic of the research project. Apparently the damage rate of many components clearly depends on their operating age, but concrete practical experiences for this purpose are hardly available so far.

The age related damage rate h_S is evaluated for five-years-intervals. The undifferentiated damage rate $\bar{h}_S$ is included additionally in the presented figures.

Figure 3 shows the age related damage rate for distribution transformers in secondary substations. After a first peak, representing initial faults, the curve shows a rising characteristic up to an age of 40 years, so a distinct dependence on age is observable. Due to regular visual inspections of the considered transformers an extreme increase of the damage rate can be avoided. So the gradient reaches a maximum between 25 and 30 years and even becomes negative after 40 years of operation.

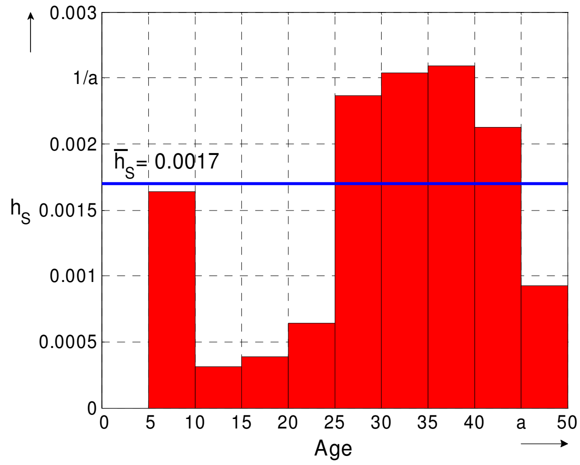

Figure 3: Secondary substations, distribution transformers: age related damage rate, 70 events in total

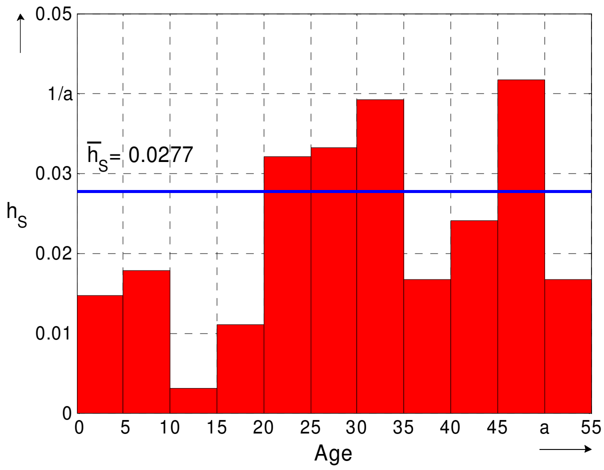

Figure 4: MV switchgear stations, circuit breakers: age related damage rate, 200 events in total

Another example for the age related damage rate is represented by **Figure 4**. It shows the characteristic for circuit breakers of medium voltage switchgear stations, which has an obvious dependence on age as well. In this case the influence of corrective maintenance after a certain time can be clearly seen. Apparently the damage rate – which is not the failure rate describing effects on network operation – increases until a servicing takes place and then it falls back again to a lower value.

5.3 Cause of Damage

This chapter contains two examples for investigations of the cause of damage. Fourteen causes of damages are distinguished in the damage statistic, but in the following diagrams only the causes that have actually occurred are considered.

Figure 5 shows the causes of damages for load interrupter switches of secondary substations with the occasion of damage information as additional parameter. The most frequent causes are the decrease of electrical and mechanical quality. But in most cases the damage was detected on the occasion of a maintenance action, so that network operation was not affected directly. About one fourth of all events occurred as electrical faults or with switching actions during operation, so that the supply of electrical energy was at risk in these cases.

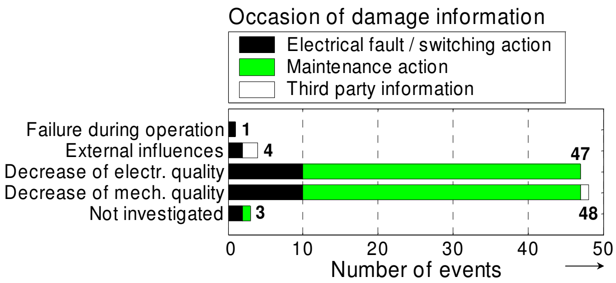

Figure 5: Secondary substations, load interrupter switches: cause of damage – parameter occasion of damage information, 103 events in total

The causes of damages for overhead lines with the parameter damage effect are visualised in **Figure 6**. Here external, especially atmospheric influences are the most frequent causes. But also one case of mechanical overstressing was found. In most cases an immediate action was necessary to clear the damage. Only once no unscheduled action was performed.

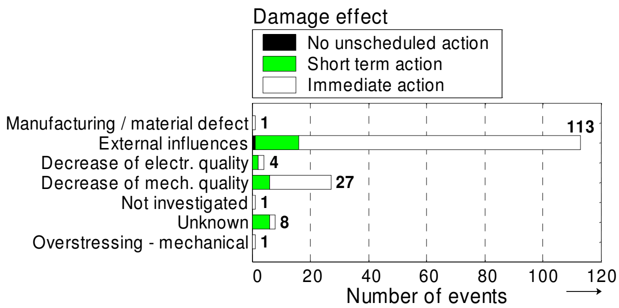

Figure 6: Overhead lines: cause of damage – parameter damage effect, 155 events in total

5.4 Damage Costs

The determination of damage related costs – separated into damage costs and consequential costs as described in section 4.2 – is another main topic of the statistic.

Figure 7 shows the damage costs of each event for distribution transformers sorted by amount. The visualised characteristic consists of a small number of events with low costs, a broad field of costs around the mean value and a few events with very high costs. This is also typical for other components.

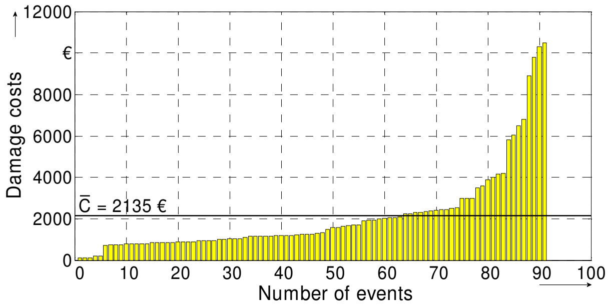

Figure 7: Secondary substations, distribution transformers: damage costs, sorted, 91 events in total

Another kind of illustration of the damage costs is shown in **Figure 8**. It represents the relative frequency and the relative cumulative frequency for certain intervals of damage costs for buildings and enclosures of secondary substations. In this example, the characteristic of the values is similar to the one shown in Figure 7. The cumulative frequency distribution e.g. directly indicates, that the costs are maximum 2000 € in 80 percent of the damage events.

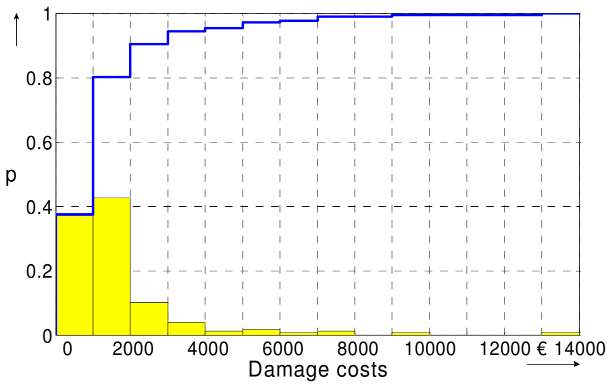

Figure 8: Secondary substations, building/enclosure: damage costs, relative frequency and relative cumulative frequency, 176 events in total

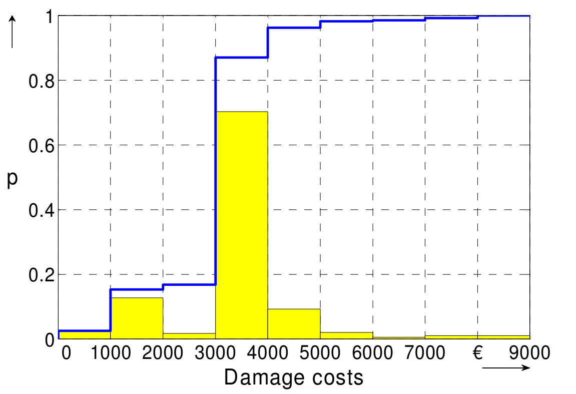

Figure 9: Cabel systems, joints: damage costs, relative frequency and relative cumulative frequency, 251 events in total

A nontypical distribution of damage costs is exemplarily shown in **Figure 9**. Here, the values for joints of cable systems are visualised. The damage costs – the costs for the replacement of a damaged joint – are between 3000 and 4000 € in 70 percent of all cases. So, the costs for the replacement of damaged joints are obviously quite uniform for different cable types and for different network operators.

5.5 Consequential Costs

Finally, the intermediate results for consequential costs of cables are introduced. **Figure 10** shows the values sorted by amount. Consequential costs arise only in a smaller part of the damage events. Therefore the validity of the results is impaired.

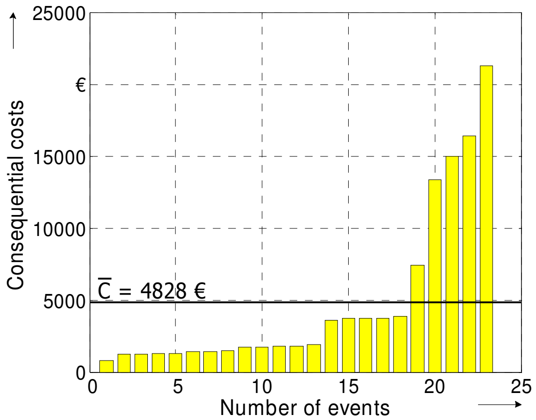

Figure 10: Cable systems, cable: consequential costs, sorted, 23 events in total

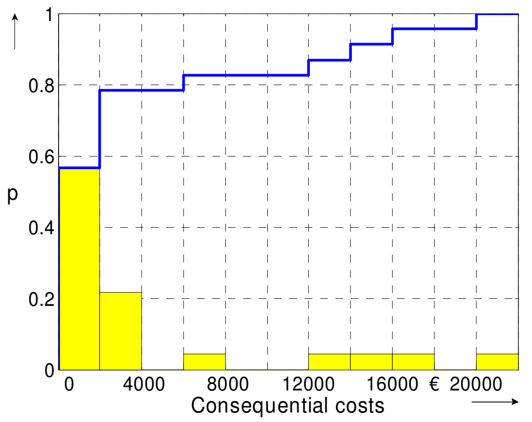

Figure 11: Cable systems, cable: consequential costs, relative frequency and relative cumulative frequency, 23 events in total

Figure 11 shows the corresponding relative frequency and the resulting cumulative frequency. Due to the different effects of consequential events the corresponding costs can reach a high dispersion. In the given example the majority of the consequential costs are below 4000 € but they can also exceed 20000 €.

6 CONCLUSION

The fundamental algorithms of asset management methods are well-known and applied to planning and operation of electrical power systems. But, especially for distribution networks, the availability of the required input data is not satisfactory in all fields. Therefore a research project was initiated to find new solutions for the modelling of the component reliability and the costs arising in the case of damage. The high importance of this data was motivated in the paper.

The evaluation examples given in this paper clarify that appropriate models can be derived if sufficient data is available. E.g. the damage rate of distribution transformers in secondary substations depends clearly on the operating age and the influence of maintenance can be seen at the damage rate of circuit breakers of MV switchgear stations. The illustrations of the costs show that the damage costs of distribution transformers can be estimated by a mean value and the damage costs of cable joints are quite uniform, whereas the consequential costs of cables have a high dispersion.

The results clearly show the dependency of component damage rates on component age and on the maintenance history, thus again underlining the importance of an appropriate prognosis of component reliability in asset management methods.

The final results of the research project, expected for mid-2005, will be a sound contribution to the elimination of the described lack of models and data for comprehensive asset management methods.

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