TYPE-SPECIFIC EVALUATION OF COMPONENT RELIABILITY FOR PREDICTING THE QUALITY OF SUPPLY IN DISTRIBUTION SYSTEMS

Uwe ZICKLER
E.ON Thüringer Energie AG – Germany
uwe.zickler@eon-thueringerenergie.com

Mirnes PLANIC
FGH e.V. – Germany
mirnes.planic@fgh-ma.de

Christoph KAHLEN
FGH e.V. – Germany
christoph.kahlen@fgh-ma.de

Armin SCHNETTLER
FGH e.V. – Germany
armin.schnettler@fgh-ma.de

ABSTRACT

The present paper addresses the topic of evaluating component conditions and reliability in medium voltage distribution systems. It explains the benefit and the need for detailed damage statistics to gain well-founded knowledge of the equipment aging behaviour and failure occurrence. In particular, the structure of the developed statistics, the applied prognosis model and current results of the investigation are described in detail.

INTRODUCTION

Due to the political objective of developing renewable energy sources in Germany the demands on electrical power supply grids increase continuously. Accordingly, the increasing utilization of deployed grid components as well as sudden changes in load due to the volatility of renewable energy sources are already observable effects that will have a negative influence on the failure performance of the equipment. In particular, fluctuating electrical stresses demand an improved approach for modelling the component reliability and to determine the resulting quality of supply. Another consequence of the development of distributed generation units will be a significant voltage variation in medium and low voltage distribution networks that requires the use of innovative technologies. The described issue will increase existing uncertainties in terms of operation and planning electrical supply systems and therefore the inclusion in asset management processes based on well-founded input data is indispensable.
Considering these aspects the strategic direction for renewal and maintenance of existing grid components must be revaluated. Although sophisticated asset management tools are common practice these days, fundamental modelling approaches are mainly based on simplified assumptions. The availability of resilient condition data determining the failure and aging behaviour of grid components is still insufficient in most cases. The impact of current decisions on the development of power quality needs to be estimated as exactly as possible, especially due to the introduction of the quality element as part of the incentive regulation in Germany [1].

In this context the aging structure of equipment resulting from the extensive network expansion in the 1970s aggravates the situation. However, the necessary documentation of historical, type-specific damage and failure events - as in other industries has been an integral part for a long time - was neglected or deficiently communicated in the past. Therefore, the influencing factors on the aging of grid components must be continuously examined for a concrete planning of counteractive measures.
In the following, a statistical approach is presented based on a comprehensive database which was supplied by several German network operators. The contribution results from a current IGF project[1] of the research institute Forschungsgemeinschaft für Elektrische Anlagen und Stromwirtschaft (FGH) e.V.

DAMAGE STATISTICS

Objective and scope of the statistics

The variety of components in distribution networks requires efficient methods in terms of condition assessment. For this purpose, statistical analyses of failures occurred during operation or discovered during maintenance measures can provide valuable information and conclusions to predict future equipment conditions [2].
Regarding equipment conditions it must be clarified that network failures in terms of supply interruptions are not to be considered but component failures influencing the functionality. The latter shall be called "damage" to emphasise the different meanings.

1 The IGF project 16391 N of the "Forschungsvereinigung FGH" was funded by the AiF under the program for funding of industrial research and development community (IGF) by the Federal Ministry of Economics and Technology based on a decision of the German Bundestag.

Federal Ministry
of Economics
and Technology

The component reliability is an appropriate characteristic representing the component condition which can be expressed by the frequency and duration of damage. These parameters can be determined by statistical evaluations and used as input data for asset simulations and reliability calculations. The knowledge on the detailed quantity structure of the components is a vital necessity for this purpose. Furthermore, the definition of component classes for certain components like circuit breakers, load interruption switches, transformers, cables and overhead lines ensures the necessary amount of data to achieve resilient results.
The consortium of the research project comprises more than 20 network operators, manufactures and service providers. It guarantees the data acquisition according to a specifically developed scheme as well as the experienced estimation of the results of the analyses. The aim is the derivation of type-specific prognosis models based on the empirically determined characteristics of age-related damage frequencies. Further subject of the investigation is the estimation of the factors influencing the equipment behaviour. Beside the age-related evaluation other criteria like cause and occasion of damages as well as corrective measures are considered. Additionally, the chronological order of executed and scheduled maintenance measures is taken into account and the resulting costs are recorded for the monetary estimation. Up to now, the developed statistic comprises about 33.000 data sets from 15 network operators.

Structure of data acquisition scheme

The currently applied data acquisition scheme is the result of a development process of several years considering the expertise of the network operators and the experience of previous research activities.
The data sets consist of five data blocks as listed below:

- Identification of the damage event; e.g. date, number
- Information on the subsystem containing the damaged component; e.g. identifier, type of insulation
- Information on the damaged component; e.g. year of manufacture, technology, manufacturer
- Description of damage details; e.g. cause, occasion, maintenance measures, damage potential, costs
- Description of network failure if relevant; e.g. condition, duration and type of failure

Most of the defined data fields are implemented as list boxes, so faulty entries are avoided and an efficient data analysis is guaranteed. In addition, information on the particular network are recorded like voltage level, neutral earthing, network configuration and percentage of cables.
The knowledge of the years of manufacture and technologies of the damaged components are of essential importance for the intended age- and type-specific condition modelling. Furthermore, in comparison to previous data acquisitions the level of detail was increased. For instance, the decrease of the electrical or mechanical properties has been the most recorded causes of damage. But this information is not exactly enough to identify weak spots or aging mechanism of the components. Therefore, a further differentiation was implemented allowing the determination of concrete measures.
Improving the benchmarking of performed maintenance the corresponding data acquisition was extended in terms of type and date of executed and scheduled measures. Additionally, experts of the network operators evaluate the damages regarding the period within damages could extend to network failures. For this purpose, typical damage patterns are considered.
The data acquisition scheme is realised in the software tool INTERASS which was primarily developed for the German statistics of failure and availability. In the following, a sophisticated modelling approach is described and applied to the collected data.

MODELLING APPROACH

The damage data provided by the network operators are checked for plausibility before they are used for the modelling approach. The proved data as well as the component quality structure and the information on maintenance are combined in a MySQL database. The calculation of the empirical damage frequency h_S follows equation 1 by the number of relevant events N_S related to the appropriate quantity of components M_S and the period under consideration T_B (usually one year).

$$h_S = \frac{N_S}{M_S \cdot T_B} \quad (1)$$

Depending on the type of components the quantity M_S corresponds to the number or length, so the frequency unit is 1/a or 1/a*km. The frequencies can be calculated for different criteria like component age, maintenance cycles, type of technology etc.
The simulation of the component aging behaviour is realised by the superposition of four basic functions to one model function as shown in Figure 1. The empirically determined frequencies are used as input data for the parameterisation of the model function. The aim is to find the best combination of the basic functions with the minimal deviation of the input data.
The basic functions represent typical phenomena influencing the component condition. They can be expressed by the following equations [3]:

$$h_{burn-in}(t) = b_1 \cdot e^{-b_2 \cdot t} \quad (2)$$

$$h_{wearout}(t) = b_3 \cdot (e^{-b_4 \cdot t} - 1) \quad (3)$$

$$h_{aging}(t) = b_5 \cdot t \quad (4)$$

$$h_{random}(t) = b_6 \quad (5)$$

$$h_{combination}(t) = b_1 \cdot e^{-b_2 \cdot t} + b_3 \cdot (e^{-b_4 \cdot t} - 1) + b_5 \cdot t + b_6 \quad (6)$$

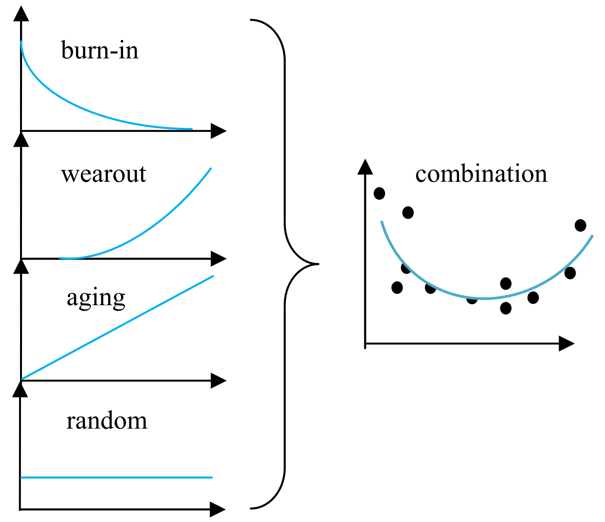

Figure 1: Modelling of the component reliability – basic functions and model function

The estimation of the parameter is based on a non-linear least squares method. The Levenberg-Marquard-Algorithm is used for the numerical solution of the problem. This algorithm works very stable and is fast converging, even with improper initial values.

CURRENT RESULTS OF INVESTIGATION

Data analysis

After a successful plausibility check the damage data are further analysed. For this purpose, suited ways of evaluation are considered, e.g. the age-related frequency of damages in combination with the types of technology. For instance, typical technologies of circuit breakers are low-oil-content, compressed air, vacuum or SF_6. Cables can be differentiated into paper-insulated, PE, XLPE, PVC and others. In some cases, especially for cables, the year of manufacture is not properly documented but an estimated value can be specified.
Another useful estimation is the cause of damage with the occasion of damage as parameter. So, the efficiency of applied measures like inspections can be proved and weak points can be detected. Similar analyses are applied to the data, so finally a satisfying data quality can be guaranteed in this way.

Modelling of failure occurrence

Impact of aging
The focus of analysis is on the evaluation of age- and type-specific damage frequencies where the modelling is based on. It allows the determination of the model functions describing the aging behaviour considering the technology and maintenance of the components. Figure 2 visualises the frequency per year of low-oil-content circuit breakers based on all damage events for an age range from 0 to 60 years.

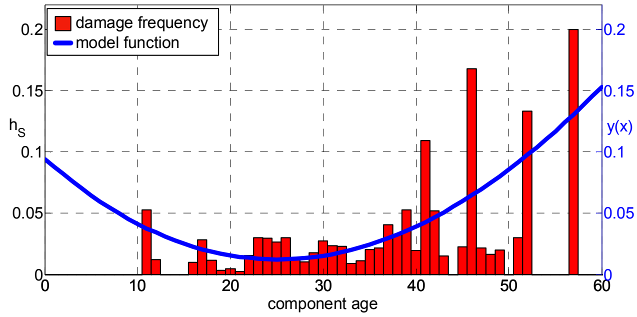

Figure 2: Age-related damage frequency per year and model function of low-oil-content circuit breakers

The blue curve represents the model function resulting from the approximation by the introduced approach. Due to the parameterisation of equation 6 consisting of the basic functions a continuous course is obtained for the entire age range. As a result a clear age dependence is identified with the typical characteristic of the so called “bathtub curve”. The extrapolation of the model function enables the description of the complete behaviour including burn-in failures, although new low-oil-content circuit breakers are not mounted anymore these days.

Impact of maintenance
Beside the component aging behaviour the failure occurrence regarding the network is of vital importance for network reliability calculations. Only actual failures in terms of supply interruptions affect the supply quality. As an example, the age-related failure frequency per year for load interrupter switches is shown in Figure 3.

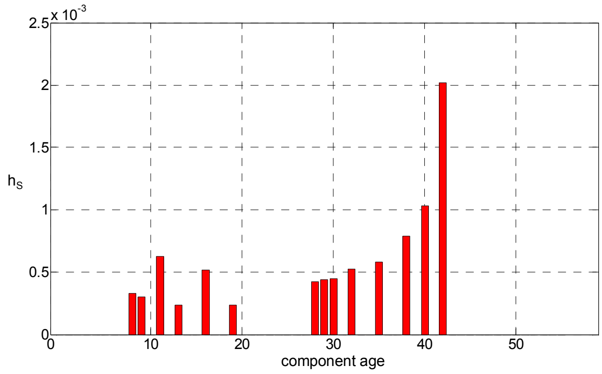

Figure 3: Age-related failure frequency per year of load interrupter switches

Furthermore, considering the optimisation of maintenance and renewal strategies the development of component damages to network failures is of interest to trigger the required measures right on time. For this purpose, the period within damages could extend to failures is estimated by experts of network operators. Figure 4 exemplarily shows the estimated times for load interrupter switches. Because a switchgear failure usually occurs during a switching operation the average time between two switching operations can be used as indicator.

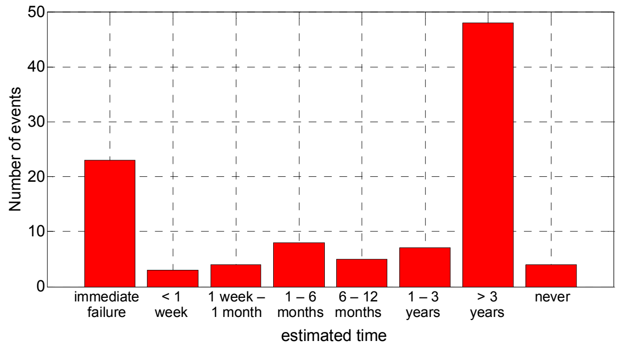

Figure 4: Estimated time for the extension of component damages to network failures for load interrupter switches

Therefore, most damages would extend to failures after more than three years as load interrupter switches are usually rarely used.
If the cycles of maintenance measures would be extended to a certain stage it can be assumed that damages with a lower estimated time will cause a network failure. Consequently, the failure occurrence would accordingly increase. The resulting frequency for load interrupter switches is visualised in Figure 5. In addition, the corresponding model function is included. In comparison to Figure 3 the different axis scaling has to be noted.

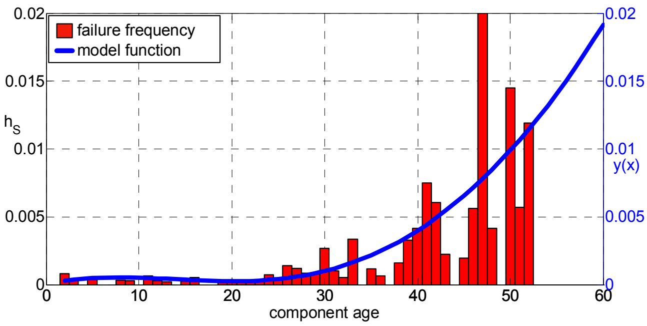

Figure 5: Age-related failure frequency per year and model function of load interrupter switches with the assumption of the described damage extension

In this case, the increase of the failure frequency appears mainly in the range of higher component age. This phenomenon is observable for other component types as well. In combination with reliability calculations the impact of extended maintenance cycles on the supply quality can be quantified.

CONCLUSION AND OUTLOOK

The presented paper explains the need und the benefit of a comprehensive damage statistics to achieve well-founded information on the conditions and aging behaviour of network components. Especially in medium voltage systems statistical analyses combined with sophisticated approaches provide additional knowledge as individual condition assessment and monitoring systems require too much effort. The developed statistics are used across network operators in Germany for the first time and present a well-engineered tool. Against the background of introducing the quality element in the context of the incentive regulation its importance will continue to increase.
The results of the investigation allow the evaluation of supply reliability depending on varied maintenance and renewal strategies which can be expressed by suited indices like SAIFI and SAIDI. The determined frequencies of damage events and the described extension to network failures close an essential information gap in existing asset management procedures. Additionally, further results give indication of weak spots of components and effectiveness of corrective measures.
In future works final results and the effects of changing component reliability on typical distribution networks as well as monetary evaluations will be presented. After completion of the current research project it will be surveyed if the statistical data acquisition can be extended to all German network operators in cooperation with the Forum network technology / network operation in the VDE (FNN).

REFERENCES

[1] Federal Network Agency of Germany (Bundesnetzagentur), 2010, "Eckpunktepapier zur Ausgestaltung des Qualitätselements Netzzuverlässigkeit Strom im Rahmen der Anreizregulierung", release date 15th Dec. 2010

[2] U. Zickler, M. Schwan, A. Schnettler, 2009, "Impact of Maintenance on Component Condition and System Supply Reliability in Distribution Networks" *Proceedings 20th CIRED Conference*, Prag, Paper No. 0839

[3] J. Moubray, 1997, "Reliability-centered maintenance", 2nd Edition, Industrial Press, Inc. - New York