AGEING BEHAVIOUR OF MEDIUM-VOLTAGE SUBSTATIONS

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ABSTRACT

The ageing infrastructure, in conjunction with incentives to improve power quality and reliability of supply, pose considerable challenges for distribution system operators (DSOs). More and more components of electric power grids are on the verge of reaching their assumed maximum service life. Today's DSOs apply modern and optimised maintenance, as well as replacement strategies based on the knowledge of the actual condition of the operating electrical equipment. This enables an efficient and fair distribution of the limited budget over the individual grid areas. In addition to the condition of medium-voltage (MV) substations, knowledge of their ageing behaviour is essential for long-term, well-founded replacement strategies. The asset simulation tools used by DSOs are mostly based on the bathtub curve, which is intended to describe the hypothetical failure rate in the distribution grid versus time. This paper presents a new and innovative approach to derive condition-dependent ageing curves as a valid basis for decision making from the results of inspection data of MV substations. The more than 100.000 inspection results, available from eleven different DSOs, serve as a basis for this. In order to verify the ageing behaviour determined from the inspection data, extensive additional laboratory tests have been carried out on 84 MV switchgears. For the first time, significant findings regarding the actual ageing behaviour of MV substations can be obtained from the collected data and used for well-founded asset management decisions.

INTRODUCTION

The liberalisation of the energy markets, as well as the ongoing incentive regulation, has fundamentally changed the regulatory framework conditions for DSOs. The distribution of electrical energy on the MV level is of particular importance, as the reliability of supply is significantly influenced by disturbances in the MV grid [1]. DSOs are therefore required to operate their grid efficiently while keeping up the current level of reliability.
In addition to the changed regulatory framework conditions, the existing age structure of the electrical components poses a further considerable challenge. Many electrical components have a greatly increased age and will reach their estimated lifetime in the next few years. Therefore, efficient and long-term maintenance is becoming increasingly important and optimised replacement strategies are being adopted [2].
Many DSOs make asset management decisions about maintenance and replacement measures based on input parameters such as age [3]. However, the actual condition of the electrical components is not taken into account, so that necessary measures may not be carried out at the right time. This, in turn, has a negative effect on the economic efficiency of the energy supply due to the high operational and capital expenditures. Although the individual electrical components in the distribution grid have significantly lower investment costs than the components in the transmission grid, the number of components increases disproportionately as the voltage level decreases.

Due to this large collection of individual components, the distribution grid represents a considerable share of the replacement value of the entire electricity grid. According to estimates, the replacement value of the German MV distribution grid amounts to approx. 20 billion euros [4].

MAIN PROJECT OBJECTIVES

DSOs are looking for ways to use their financial resources as efficiently as possible. In order to optimise maintenance and replacement strategies, the current condition and the actual ageing behaviour of the electrical components are becoming increasingly important. In order to increase cost-savings opportunities and to make investments at the right time, condition-orientated investment strategies should come into focus [2].
The approach of deriving the ageing behaviour from the fault events has proven to be unsuccessful. Disturbances in electricity grid are rare events, which, in combination with the age of the electrical components, lead to a non-valid database [4, 5, 6]. The present paper discusses the results of the research project on the derivation of the ageing behaviour of MV substations based on their condition. The derived condition-dependent ageing curves provide for the first time a valid basis for asset management decisions [2].

INSPECTION RESULTS

Data acquisition

DSOs are required to inspect their MV substations at regular intervals and to document and remedy any defects. For this purpose, most DSOs use inspection checklists, which contain operationally relevant inspection points that have to be assessed by the field service engineers when carrying out their inspections. The inspection checklists of eleven DSOs involved in this research project have a different level of detail. In recent years, the Chair of Power System Engineering at the University of Wuppertal has analysed numerous inspection checklists of various DSOs and found that these can be transferred into a uniform system [3, 7, 8]. Based on these findings, the individual inspection results were homogenised and thus made comparable. The up-to-72 ageing-relevant inspection points were aggregated into twelve major components, which in turn were aggregated into groups of four main components: Building, MV switchgear, Transformer, Low-voltage (LV) distribution equipment. The uniform assessment scheme used for the condition assessment of the electrical components is shown in Table 1.

Table 1 Assessment scheme

Maintenance requirements	Grading
No deficiency present	1
Deficiency to be remedied until next inspection	2
Deficiency to be remedied within one year	3
Deficiency to be remedied immediately	4

In addition to the inspection data, the master data of the main components (e.g. year of construction, design of MV switchgear etc.) and MV substation-specific data (e.g. types of MV substations, inspection date etc.) must also be taken into account in order to derive the ageing behaviour and conduct specific analyses. Based on the master data, a first analysis of the MV substations is already possible. Figure 1 shows the distribution of the different types of MV substations in relation to their year of construction.

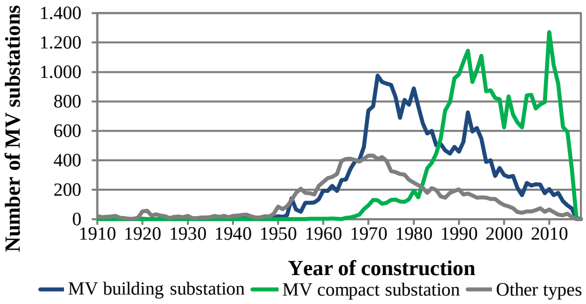

Figure 1 Distribution of the number of different types of MV substations for the different years of construction

As Figure 1 shows, more MV building substations were built in the 1970s and 1980s, while more MV compact substations have been built since the 1990s.

Aggregation scheme of the inspection data

The inspection points assessed according to the assessment scheme are first aggregated to major components, converted to a condition index, and then aggregated to the main components. The condition indices of the main components are aggregated via a weighted aggregation to the condition index of the entire MV substation. The main components have different weighting factors (G_i), since each main component has a different significance for the entire MV substation; for example from the point of view of the reliability of supply and the costs for the necessary maintenance and replacement measures. The formation of weighting factors, as described in detail in previous studies, results in the highest weighting factor for the MV switchgear [9]. The basic principle of the aggregation scheme of the inspection data is shown in Figure 2.

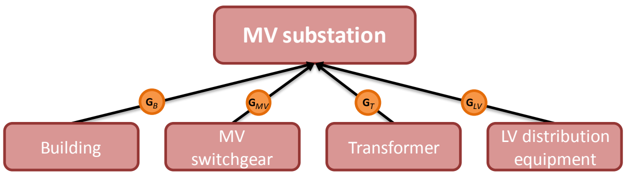

Figure 2 Aggregation scheme of the inspection data

A total of 102.899 inspection data sets are available for deriving condition-dependent ageing curves. Especially in the age-relevant and thus interesting area – MV substations with a service life of over 40 years – large amounts of data are available. Figure 3 shows the age distribution of the considered MV substations.

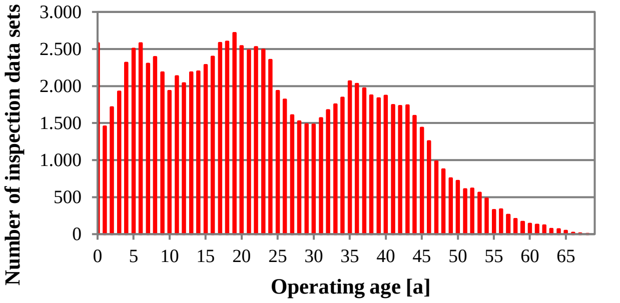

Figure 3 Distribution of the age structure of the MV substations of all eleven DSOs

As a result, 18.853 inspection data sets of MV substations with a service life of over 40 years provide a valid data basis for the determination of the ageing behaviour.

Analyses of the inspection results

In order to derive the ageing behaviour, the average condition indices of the MV substations are determined for each age. The results are shown in Figure 4. Based on the inspections, the MV substations show a deterioration of their condition with increasing age. The determined ageing behaviour can be described by a linear trendline.

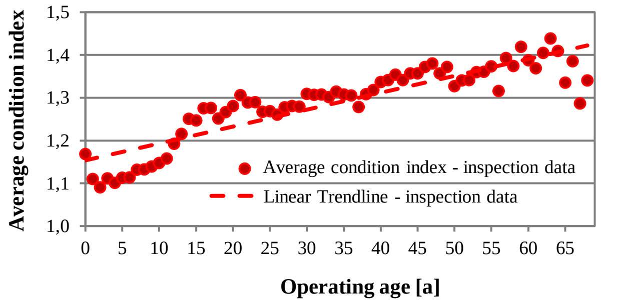

Figure 4 Ageing behaviour of the MV substations based on the inspection data

From the age of 63, the number of inspection data sets decreases. Individual MV substations that are in good condition despite their age, therefore, have a greater influence on the average condition index. This finding explains the better condition of the MV substations and the average condition index below the linear trend.

In addition, it must be taken into account that the MV substations have been maintained over the years or that some components may have been replaced. DSOs have different inspection and maintenance strategies. The maintenance cycles of all DSOs vary between 1 and 20 years. There is also condition-based maintenance. The average maintenance cycle is approx. 7 years. An interim improvement of the average condition index can thus be explained.

In order to gain a better understanding of the ageing behaviour of the MV substations, the conditions of the MV substations forming the average condition indices are also investigated. Figure 5 shows the percentage distribution of the MV substations by grading.

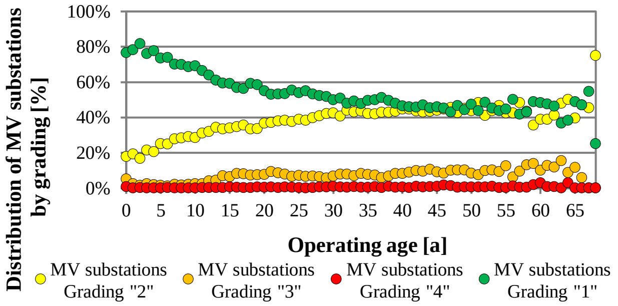

Figure 5 Percentage distribution of the MV substations by grading

The share of MV substations where no defects can be detected decreases, while the share where minor defects can be detected almost doubles within about 20 years.

A further approach for a better understanding of the ageing behaviour of MV substations is to determine the root cause of ageing. In this respect, the ageing behaviours of the four main components of the MV substations were also derived. These are shown in Figure 6.

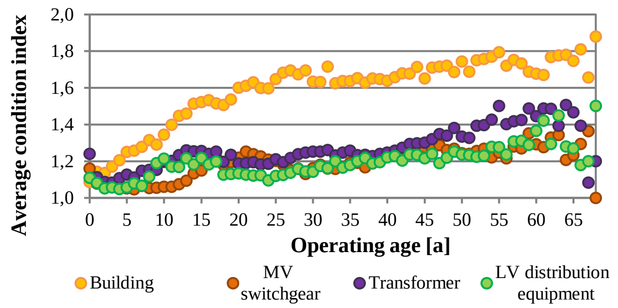

Figure 6 Ageing behaviour of the main components of the MV substations based on the inspection data

As Figure 6 shows, the electrical components have a similar ageing behaviour. The buildings, on the other hand, show a quite sharp rise in the first few years of service.

LABORATORY TESTS

DSOs usually only carry out visual inspections, although most electrical defects cannot be detected in this way. Thus, only structural defects can be detected and an evaluation of the electrical properties is only possible to a very limited extent. The findings from visual inspections must be supplemented by measurement results in order to be able to determine the validity of the ageing behaviour.

Laboratory data

In previous studies, the added value for an objective and realistic assessment of the condition of electrical components resulting from the use of measurement methods was presented [3, 10, 11]. In this respect, the conditions of 84 MV switchgears were tested in the high-voltage laboratory of the University of Wuppertal after their decommissioning. Figure 7 shows the age distribution of the tested MV switchgears.

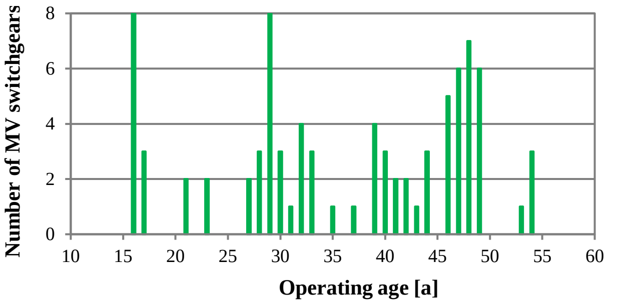

Figure 7 Distribution of the age structure of the MV switchgears tested in the laboratory

About 46 % of the tested MV switchgears are more than 40 years old. In addition, MV switchgears at a young age are also present in the data structure, which allows early indications of the first signs of ageing to be determined.

Test properties and measurement methods

The insulation strength, the load current capacity and the mechanical function of the MV switchgears were evaluated for the metrological condition assessment. For the assessment of the measurement values determined in the laboratory tests, limit values for the individual measurement results according to the requirements of DIN or IEC standards or from the reference values available at the University of Wuppertal (e.g. experiences of laboratory testing, field tests etc.) were used.

Insulation strength
Several measurement methods can be used to evaluate the insulation properties of MV switchgears.
The long-time appearance of partial discharge (PD) may lead to disruptive discharges, as insulating materials are eroded by PD and to a breakdown with a resulting supply interruption [12]. One measurement method to assess dielectric strength is *PD measurement.* It was performed in compliance with IEC 60270 or DIN VDE 0434 [13]. Since the insulating materials deteriorate with increasing operating age and PDs become more probable as a result, a statement can be made about the age-related condition of MV switchgear by analysing the detected PD level.

A further measurement method for evaluating the insulation strength was the *lightning impulse voltage test* according to DIN VDE 0432-1 [14]. In order to compare age-related results, lightning impulse voltage tests with standardised voltage curves according to DIN VDE 0111-1 [15] were carried out and the breakdown voltages were determined. Together with the lightning impulse voltage test, the *alternating voltage test* forms the insulation coordination of the MV switchgear in accordance with DIN VDE 0111-1 [15].

The *measurement of the insulation resistance* was performed in compliance with DIN VDE 0100-600 [16]. The MV switchgear must have at least a certain insulation resistance, which was measured and evaluated.

Load current capacity
The condition of the electrical contacts was evaluated for the property of the load current capacity. The measurement method used was the *measurement of the contact junction resistance*. By measuring the contact junction resistance, the increase in resistance of individual contact points or the change in contact resistance can be determined and the load current capacity of the MV switchgear can thus be assessed. Conclusions can be drawn about the condition and thus the ageing behaviour of the contact point.

Mechanical function
The switching times were evaluated for the property of the mechanical function since these can provide information about mechanical weak points and thus enable the derivation of the ageing behaviour. Therefore, the *measurement of the switching time* was carried out in accordance with DIN VDE 0105-1 [17]. The switchgear must enable the operating voltages to be switched off safely in order to be able to carry out switchover measures. Age-related changes to the drive system can lead to malfunctions and thus to a failure of complete contact separation or bounce of the switching contacts.

Aggregation scheme of the laboratory data

Based on the measurement methods a weighted aggregation at the level of the MV switchgear was carried out. The basic principle of the aggregation scheme of the measurement methods is shown in Figure 8.

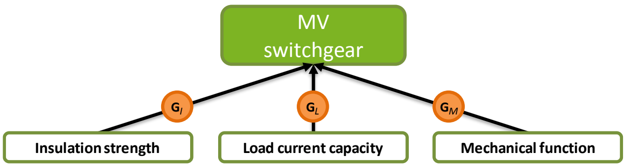

Figure 8 Aggregation scheme of the laboratory data

Similar to the inspection data, the average condition index was determined for each age of the MV switchgears. The results are shown in Figure 9.

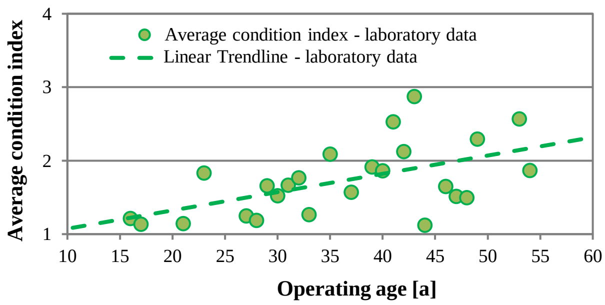

Figure 9 Ageing behaviour of the tested MV switchgears

It can be stated that the older MV switchgears have a significantly higher condition index. The use of measurement methods leads to a more realistic and reliable ageing curve. The determined ageing behaviour can be described by a linear trendline.

CONCLUSION AND OUTLOOK

The innovative approach of deriving condition-dependent and realistic ageing curves from the collected inspection data of MV substations with minimal effort was presented in this paper. By homogenising the inspection data of 102.899 inspection checklists, available from eleven different DSOs, a valid database was created which allows differentiated analyses to be carried out with regard to the ageing behaviour of different types of MV substations or of different inspection and maintenance strategies.

Overall, the ageing behaviour of the MV substations and their main components could be derived, providing the asset management of a DSO with a well-founded basis for making the right decision about long-term investments and budget planning. This results in a significant advantage for the asset management since realistic ageing curves of the MV substations can now be used as input parameters for asset simulation tools. The theoretically assumed ageing curves (e.g. bathtub curves) can thus be rejected.

In addition to the visual inspections, the results of laboratory tests on MV switchgears for the verification of the ageing curves were presented. By means of additional laboratory tests, conclusions can be drawn regarding the ageing behaviour of the electrical components of the MV switchgears. By a suitable combination of the laboratory results with the results of the visual inspections, which is still under investigation, the condition-dependent ageing curves of the MV substations based on visual inspections can be verified and adapted. Finally, the condition-dependent ageing curves will be extended to failure rate-dependent ageing curves.

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