CONDITION ASSESSMENT OF DISTRIBUTION GRIDS USING UNCERTAINTY THEORY

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ABSTRACT

The basis of all optimized maintenance strategies, which are also widely adopted on the distribution system level, is the most objective and realistic condition assessment of the various electrical grid components. In this paper a simple, cost-efficient but reliable method for systematic condition assessment of medium-voltage substations is presented. It is based on periodic visual inspections. However, visual inspections are subject to personal influence and therefore the method is supplemented by suitable simple measurement methods. These different information sources are combined to an overall statement. To represent the subjective influence and the credibility of the sources this paper will describe the theoretical foundations of the theory of evidence and the systematic adaption to the condition assessment. Therefore, the paper focuses on the first practical experiences of field tests to determine the subjective influence and the first application of this new developed methodology in practice. As a conclusion a significant and realistic condition assessment is achieved by taking the significance and subjectivity into account. The influence of individual experiences must be kept in mind.

INTRODUCTION

German distribution system operators are forced by the regulator to fulfil continuous efficiency enhancements in maintenance and operation of their electrical distribution grids. Referring to this cost reduction and optimization is crucial. Therefore the distribution system operators use optimized maintenance and replacement strategies for the grids like reliability centered maintenance (RCM) or risk based maintenance.[1] Basis of all optimized strategies is the most objective and realistic condition assessment of various electrical equipment of the distribution grid.

For a systematic condition assessment of medium- and low-voltage components a suitable method, presented in [2] by the example of medium-voltage substations, has been developed in cooperation with several German distribution grid operators. Since the condition assessment of medium- and low-voltage components has to be as cost-effective as possible without additional effort, the procedures are based on continuous visual inspections. Uniform inspection checklists are to be used as the basis for condition assessment. The individual inspection points will be evaluated on-site by the maintenance staff based on a predefined scheme of classification. For on-site data entry it is possible to use a classic method e.g. paper and pencil, a digital pen or a mobile solution for laptop/tablet. Then the evaluated inspection points are aggregated via an evaluation model to an overall condition index for the substation and for its main inspection components like transformer, medium-voltage switchgear etc.

Even additional simple measurement methods are used to objectify the condition assessment to get a more valid basis of decision-making in asset management. In addition, guidance for power supply operation is given. Simple measurement methods support the maintenance staff because not all issues and conditions can be detected by human sensory organs. It is especially difficult for electrical equipment. The combination of visual inspections and simple measurement leads to a well-founded and comprehensible condition assessment of medium-voltage substations.

SYSTEMATIC CONDITION ASSESSMENT

Evaluation model

Maintenance staff uses various methods of sensory perception for detecting potential equipment failure or for condition assessment, such as visual identification, system indicators or acoustic detection. With these methods the maintenance employees evaluate every single inspection point during an inspection by using the scheme of classification (B_i). But each individual and main inspection point has a different relevance for the condition index. Because of their different influences on reliability of supply, danger to personnel and environment or maintenance costs, different weighting factors have to be generated (G_i). The following figure 1 shows the process which is used for the determination of the overall condition index (Z) in simplified form.

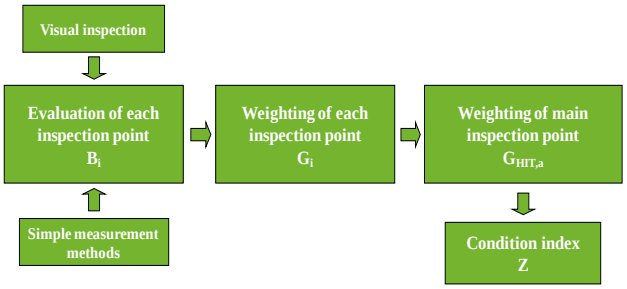

Figure 1: Determination of overall condition index

The aggregated overall condition index allows a classification and prioritization of a variety of medium-voltage substations of a distribution system operator for optimized asset and maintenance strategies.
The developed condition assessment model has been tested in practice by various distribution system operators and this paper will present the main results.

Subjectivity of condition assessment

During a first field test it has been indicated, as expected, that the evaluation results from visual inspections are very subjective because of the individual wealth of the employees' experience. The evaluation may not provide identical results (despite of a unified checklist and a suitable weighting procedure). The comparability of the results is limited because of different approaches and evaluation bases of the maintenance staff. The subjectivity has been reduced through systematic approach and evaluation, but the condition index is still strongly influenced by the experiences and preferences of the maintenance staff. But it is precisely the intention of the developed method that the experience of the maintenance staff should be incorporated in the decision-making process in the asset management. So the results have to be objectified.

To objectify the results, a number of countermeasures to reduce the subjectivity have been implemented and tested in practice.
One effective countermeasure is to train employees intensively to standardize their evaluation principles. Furthermore the use of a catalogue with exemplary faults is recommended. Deficiencies can be classified better by using a reference catalogue and the maintenance staff will be supported by the catalogue.
A further reduction of subjective influence and also an enhancement of information value are accomplished by using several simple measurement methods that have been identified in laboratory and field tests. Measurement methods generate objective values for a classification. By combining visual inspection and measured values it is possible to achieve an actual comprehensive and substantiated condition assessment.

Results of Field tests

As mentioned before, the developed condition assessment model has been tested in extensive field tests by various German distribution system operators. Random substations, which represent a cross-section of substations in the grid area, have been inspected by using the developed checklist. And several people have carried out the assessment of same substations independently. For example, in two field tests the visual inspection was carried out by six people for a substation to specifically examine the subjective influence of the assessment.

The Results of numerous field tests illustrated a massive influence of individual experiences and preferences of the maintenance staff on the assessment. In further field tests the effectiveness of the appropriate countermeasures has been confirmed, too.

The results obtained from the first field test were not satisfactory because the deviation of the six independent assessments made by the maintenance staff among each other was too high. The determined index is not person-neutral and there is no valid basis for decision-making. That is why the described countermeasures have been developed. In subsequent tests they were applied and were able to confirm their effectiveness.

Figure 2 sums up the influence of all additional effort to objectify the condition assessment.

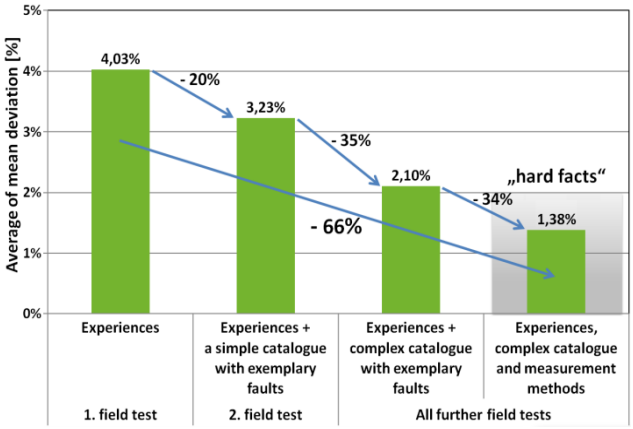

Figure 2: Summary of the different countermeasures to reduce the subjective influence

Without either a catalogue or measurement methods the mean deviation was about 4 percent. If a first simple version of a catalogue is used, the mean deviation has been reduced by 20 percent. Using the complex catalogue the mean deviation is again 35 percent lower. If you rely on additional hard facts, based on simple measurement methods, the mean deviation will be reduced as well. These hard facts are combined with the visual inspection to achieve a comprehensible condition assessment.

All in all, the mean deviation can effectively be reduced minus 66 percent by supporting the inspections with a catalogue of exemplary faults and including simple measurement methods into the evaluation model. Hence, a more valid basis for decision-making in the asset management is created - with a huge decrease of subject influence.

However, it has to be noted that the subjective influence cannot be completely reduced and remains to exist because within certain limits the assessments continue to be influenced by the experiences and preferences of the maintenance staff.

EVIDENCE MODEL

As a consequence the expression of the still remaining subjective influence is essential. For that reason the evaluation method is extended to the mathematical principles of the theory of evidence. This is a fundamental new approach for condition assessment of medium- and low-voltage components and will be described in the following.

Theoretical foundations

The Dempster-Shafer theory was introduced by Dempster [3] and developed by Shafer [4]. It is a mathematical theory of evidence which can be interpreted as a generalization of Bayes' probability theory. One important feature is that the model is designed to cope with varying degrees of precision, regarding to the input data and can combine information gathered from disparate sources to an overall statement. The credibility of these sources is taken into account in the calculation. As a result the model is able to express the uncertainty of the underlying data.

The Dempster-Shafer theory differentiates between three important functions: the basic probability assignment or mass function (bpa or m), the belief function (Bel) and the plausibility function (Pl).

The basic probability assignment expresses the level of support and quantifies to which extent an event is credible. Based on the available information, each mass function may be assigned a degree of belief and ranges between 0 and 1, where 0 represents no belief and 1 represents complete belief. The basic probability assignments can be interpreted as key elements of the upper and lower bounds of an interval. The lower bound is called belief function (Bel) and the upper bound is called plausibility function (Pl). This distinction is significant because a light or uncertain evidence for compliance of a statement (Bel(A)) do not necessarily mean a strong evidence for the complementary statement (Bel($\bar{A}$)). The following figure illustrates this distinction compared to the Bayesian theory of probability:

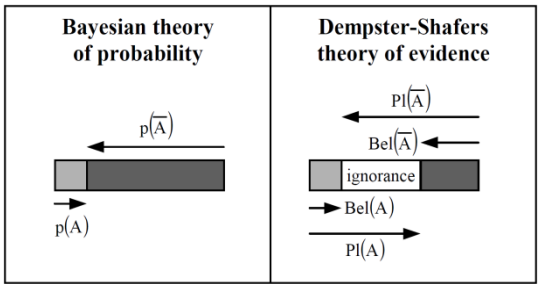

Figure 3: Basic idea of the theory of evidence [6]

The "true" belief of the event A can be assumed to lie somewhere within the interval [Bel(A);Pl(A)] and the distance can be considered as ignorance of the event A. The more reliable the underlying evidence is, the smaller the ignorance will be.

Furthermore, the Dempster-Shafer theory provides a mathematical formalism for the combination of several distinct evidences over the same frame of discernment. This rule is called Dempster's rule of combination and compute a new belief function based on the combined evidence.

The following equation shows the linking of two evidences:

$$m_1 \oplus m_2(A) = \frac{\sum_{B_1 \cap B_2 = A} m_1(B_1) \cdot m_2(B_2)}{1 - \sum_{B_1 \cap B_2 = \varnothing} m_1(B_1) \cdot m_2(B_2)}$$

Even more than two evidences can also be combined. Any further information of an event (for or against) will reduce the ignorance and the sum of the belief function will increase.

Systematic adaption to condition assessment

For condition assessment the frame of discernment consists only of the one hypothesis, whether there is a maintenance requirement or not. The positive event A denotes "There is a need for maintenance requirement" and the associated counter-event $\bar{A}$ denotes "There is no need for maintenance requirement". Because of this, every different input data, like visual inspection of the several inspection points or measurement methods, can be considered into the model and make a contribution to the overall condition assessment of the whole substation. This approach with two statements is also used in [5] and [6].

Every input data has three characteristic basic probability assignments:

- m(A) for the event "There is a need for maintenance requirement"
- m($\bar{A}$) for the counterevent "There is no need for maintenance requirement"
- m(Θ) for the ignorance

These basic probability assignments will then be combined by the Dempster's rule of combination, if hints of different information sources are available.

One indication of a maintenance requirement results through the visual inspection of the maintenance staff. But this assessment is under a subjective influence and that is why the uncertainty has to be considered. The results are presented above.
Furthermore, the effectiveness of the inspection is different. In [7] a large number of malfunction data of the distribution grid have been examined. It was also analysed how the malfunction was detected. 90% of the

recorded damages of the building of a substation are detected during a visual inspection. Malfunctions of electrical equipment (in the study switches) could only have been discovered in 60% of all analysed cases during an inspection. This shows that the effectiveness of a visual inspection mainly depends on the considered component. If maintenance staff detects and evaluates a damage the assessment is very reliable but will be influenced by the different approaches and evaluation bases. If they do not detect damage and evaluate no need for maintenance requirement, there is the additional question to answer as to whether the visual inspection is suitable to detect the malfunction.

Further indications of a maintenance requirement result by the values generated with simple measurement methods. Each measurement method like thermography, acoustic detection of partial discharges, detection of transient earth voltages (TEV) or earth-loop testing can only be used for different components of the substation and will selectively support the visual inspection. The significance of the assessment will increase highly, especially for electrical equipment. To determine the uncertainty for each measurement method they were tested and verified in laboratory and field tests. Thereby, selected measurement instruments established their effectiveness [8] and the uncertainty was derived from the extensive findings which resulted from measuring inaccuracies. Even the systematic inaccuracies of the measurement devices were considered.

The model for the condition assessment must also handle imprecise and missing datasets. During an inspection all inspection points cannot always be assessed. Therefore, if an inspection point is not assessed by the maintenance staff - but this assessment is necessary for the condition index - the uncertainty is assigned to the value 1. The basic probability assignment of this information represents no belief for or against the event whether or not there is a maintenance requirement.

Then these several different indications (translated in individual basic probability assignments) will be combined by the Dempster-Shafer-theory for each single inspection point. Each indication about a component provides information on the maintenance requirement of the individual component. But each individual and main inspection point has a different relevance for the condition index (G_i). Because of this the new calculated quantities of the combination (Bel(A), Bel($\bar{A}$), Bel(Θ)) handed over to the model which is illustrated in figure 1 and then the overall indices are computed.

Using the Dempster-Shafer theory the margin of deviation regarding the condition parameters can be determined. In addition to the condition index now the quality of the underlying data base is expressed and respectively quantified by using this developed procedure. For the first time this is possible for medium-voltage components.

Besides that, operational requirements needing immediate corrective action will be put out separately in an uncoupled form from the assessment scheme. Few individual but critical operational requirements do not get lost in the condition index and become apparent.

Presentation of results

Figure 4 shows the principal results of the novel developed method. The green area represents the percentage of the ensured condition "No maintenance required" and the red area the percentage of the certain condition "maintenance required". The grey area expresses the uncertainty as a result of insecure knowledge. The orange line finally represents the calculated overall condition index, which is generated from the three quantities and includes the uncertainties of all input parameters. The condition index can be influenced by the asset manager because it depends on the risk taking of the asset manager. This is adjusted once and then should be consistent for an analysis. If the asset manager is rather risk-seeking he will accept uncertainty and the condition index will move in the direction of the red area. The index decreases and all in all it is tolerated that a supply interruption appears than if the asset manager is risk-averse.

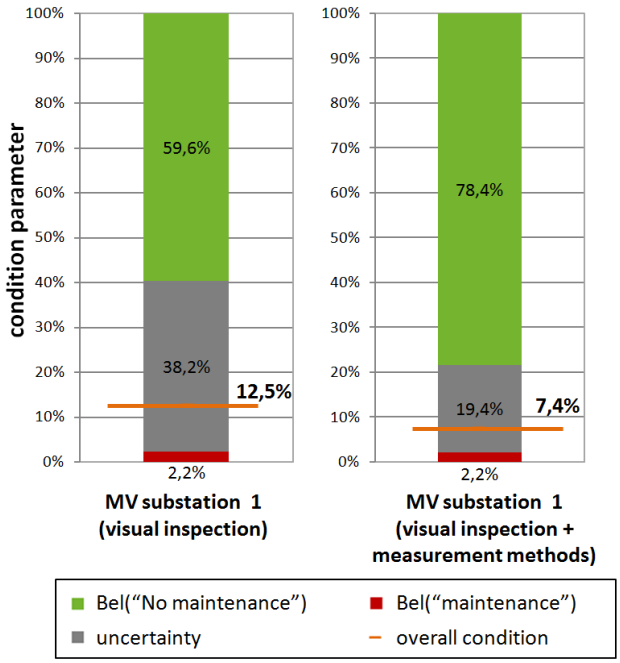

Figure 4: Exemplary results of a substation using the extended model

On the left side in figure 4 the condition assessment of the MV substation is based on visual inspection. Only a few minor deficiencies like cleanliness of several components were found. On the right side the same MV substation is shown. In addition to visual inspections simple measurement methods were used for the condition assessment. Here the uncertainty was significantly

reduced and the results become more reliable as stated before. Furthermore, the index of ensured condition "No maintenance required" increases, because no deficiencies were found by the used measurement methods. As a result of reduced uncertainties and because no other deficiencies were found, the overall condition index decreases. The red area remains unchanged because this index represents the noted deficiencies.

CONCLUSION AND OUTLOOK

In this paper the practical experience with the developed method for an objective condition assessment of distribution grids is presented using medium-voltage substations as an example.

It has been seen that the subjective influence cannot be neglected if only the on-site experience of employees is used for the condition assessment. Several countermeasures have been presented, which are developed to reduce the subjective influence, confirming their effectiveness in practice by several German distribution grid operators. Especially the use of simple measurement methods is an effective way and can further objectify the condition index.

However, due to the requirements which are needed for the input data in the distribution grids, a remaining subjective influence, respectively uncertainty must be considered. Regarding this the assessment model is extended to the mathematical principles of the theory of evidence. As a main result an additional value for the condition assessment is gained, considering the not avoidable uncertainty caused by imprecise and missing datasets, measuring inaccuracies or uncertain information (subjective influence). The extended model does not only generate an aggregated index for the whole substation but delivers information about the uncertainty of the outcome and thereby its credibility, too. In addition to the condition index now the quality of the underlying data base is expressed and respectively quantified as well. The extended model and the determined basic probability assignments will be further validated in field tests.

Due to the experiences of extensive field tests and the enhancement of the condition assessment model a well-founded and comprehensible condition assessment of medium-voltage substations is achieved. Prioritized lists can be generated to provide an established basis of decision-making for asset management and maintenance measures required.

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