SYSTEM-APPROACH FOR REALISTIC CONDITION ASSESSMENT OF HIGH-VOLTAGE GAS-INSULATED SUBSTATIONS

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ABSTRACT

To ensure a solid basis for maintenance strategies a realistic condition assessment of the considered electrical equipment is crucial. With respect to their enclosure realistic assessing of gas-insulated substations is very difficult. Solely "soft facts" based on visual inspections cannot provide objective and credible data. Reliable "hard facts" emerged by measuring techniques are needed. The present paper deals with combining hard and soft facts in the context of non-invasive condition assessment of 123 kV high voltage gas-insulated substations. A system-approach, developed in cooperation of Westnetz GmbH and Wuppertal University, and its field application results are presented. The aggregation scheme for the various soft and hard facts is described, regarding specific uncertainty and probability numbers of hard and soft facts by the use of the theory of evidence.

INTRODUCTION

High voltage (HV) gas-insulated substations (GIS) are used in electrical power supply systems for several decades, in Germany as well as in many other countries. 50 GIS are operated by Westnetz GmbH, Germany's largest distribution grid operator and grid service provider. The assets consist of 14 different types. Several of them are in the second half of their life cycle.

Representative for GIS is their high reliability in combination with low maintenance effort. Some GIS will reach their estimated lifetime soon. Hence, the asset management of the operator is forced to evaluate the actual condition of the GIS and act within technical and economic constraints where necessary. In this context, a realistic condition assessment is crucial.

With respect to the substation's enclosure, the acquisition of relevant and reliable assessment data is complicated. In conclusion, condition assessment cannot exclusively be done by visual inspections. These so-called soft facts are not able to provide objective and credible data. Consequently, hard facts based on metrology are essential for a realistic condition assessment. These measuring techniques differ against the background of different types of substations, for instance because of various coupling devices for partial discharge (PD) measurements.

To cope with that problem a system-approach for realistic condition assessment of HV gas-insulated substations was developed in cooperation of Wuppertal University and Westnetz GmbH. This approach combines hard and soft facts and observes respective validity of the overall result. Thus a condition interval is generated next to the condition index. The range represents uncertainty. A narrow interval means a reliable result.

SYSTEM-APPROACH

Previous investigations [1] identified important components with influence on the substation´s reliability: the insulation system, load current capacity and overall mechanical performance. Evaluation and assessment of these components is done by visual and metrological items included in the approach. Primarily, non-invasive methods are taken into account. However, processing data emerged by invasive measuring techniques is possible as well.

For determining a realistic prediction about the substation´s condition soft and hard facts, i.e. visual inspections and measuring techniques, are combined in a first step, considering specific uncertainty of corresponding assessment method.

Several layers were formed to handle data. The first layer scores incoming information by evaluating parameters and assigning validity – respectively uncertainty – of the methods. The upper level combines parameters observing specific uncertainty. Therefore elements of the theory of evidence are used. With assistance of probability masses the substation´s functions are evaluated. Finally the condition assessment is done for the switch bay and the entire substations. Figure 1 illustrates the operating principle.

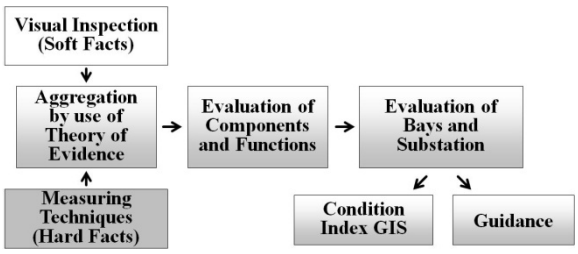

Figure 1: Operating principle of system-approach for realistic condition assessment

In conclusion the system-approach consists of a functional orientation with particular attention to the insulation system, the load current capacity and the

overall mechanical performance. Condition indices for the bay´s functions, the entire bays and the substation are created stating specific validity. In the case of detected defects, affected substation components and bay functions are displayed separately.
This analytic procedure enables the identification of affected bay functions. Hence, crucial guidance for asset management can be deduced in an uncomplicated way. In that case, guidance does not exclusively mean maintenance tasks. Moreover, further investigations may be an upcoming task originated by low validity of the overall result.

INPUT DATA

For processing metrological and visual data in the system-approach knowledge about its validity is crucial. This information is combined by using the aggregation scheme presented in the next chapter.

Soft Facts

In this context soft facts mean the evaluation of components and their functionality based on visual inspections. These facts are important and "easy to gather", but their validity is quite differing. Most of them can only make a small contribution to the asset´s condition because of restrictions caused by the GIS enclosure. However validity might be at a high level, especially if a defect is detected.
Through the combination with measuring techniques they make condition assessment more valuable. Therefore they were adapted to the bay´s functions assessing those parameters that cannot be evaluated by measurements.

Hard Facts

Prior to the implementation of measurements important parameter sets for assessing substation´s reliability were identified: the insulation system, load current capacity and overall mechanical performance [1]. On this basis appropriate measuring devices were selected and laboratory tests in combination with field trials were done [2]. The following paragraphs present results in the context of the system-approach. Gas analysis is also used as a hard fact. That method is not considered separately in the present paper.

Insulation System

This parameter set consists of measuring techniques for evaluating the dielectric strength. Several methods were investigated. In conclusion UHF and acoustic partial discharge measuring techniques provide most reliable non-invasive data. Both methods cannot detect all types of insulation defects [2; 3]. The UHF–method provides more reliable data. Nearly 80% of relevant insulation defects can be identified, but the sensitivity of the method is not constant [2]. In relation to internal sensors, sensitivity can be reduced up to 45% by using flange sensors. In laboratory sets more than 80% of defects measured by UHF-PD-measurement could be detected by the acoustic method on average – depending on the type of defect. Since the acoustic sensors can be used on the whole enclosure their sensitivity can be considered as constant [2].
Field tests pointed out that determining the failure location can straightforwardly be done by assembling the acoustic signal´s amplitude. Time-of-flight measurements with the UHF method are not feasible regarding the relevant assets because of missing coupling devices and error-proneness of the method [2].
For interpretation of measured signals a risk assessment is essential. This is done by evaluating the defect characteristics: type, location, time dependencies, voltage and its impact on the gas [2; 3; 4].
In conclusion the methods feature high sensitivity. The defect can be localized and its risk can be evaluated. Their validity was determined so that they can be used in the context of the system-approach.

Load Current Capacity

This category considers the condition of electrical contacts inside the GIS. Thermal measuring techniques like thermography or RFID-thermo-observation are used to express the current condition [2; 5]. Therefore abnormality of the enclosure temperature is inspected. An average temperature is assigned to each gas-filled compartment by measuring techniques and compared to other compartments such as identical structures of other phases. The method is primary limited due to the actual load, its duration and the presence of compartments for comparison [2].
Practical application enables generally to detect an increase of the conductor resistance of more than 50 µΩ by using this method. Depending on the accepted temperature rise and the current load this limit value can vary [2]. Regarding data evaluation and effort, operators should set minimum temperature rises for using thermal methods. Field tests illustrated the unprofitability of very small temperature rises. Expert knowledge is required to avoid misinterpretation. Knowing about these restrictions allows defining sensitivity for this method [2].
Risk assessment is done by limit values for resistance increases which are defined by the average temperature rise concerning reference gas-filled compartments.

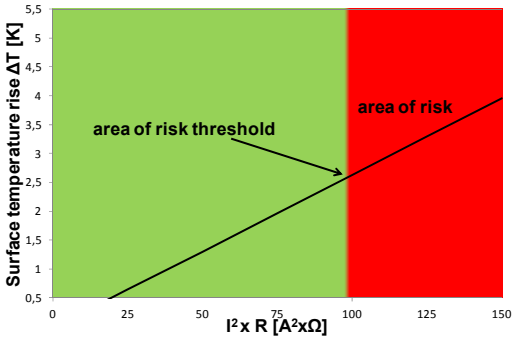

Figure 2: Surface temperature rise among identical gas-filled compartments range

Figure 2 illustrates the surface temperature rise of the enclosure concerning identical gas-filled compartments, e.g. those of different phases, as a function of relevant parameters. The area of risk means overheating of the conductor. Using that figure allows identifying resistance increase by measured surface temperature rise [2]. Furthermore operators can assess the method sensitivity considering the current load. In conclusion relevant defects of the load current capacity can be identified, localized and valuated [2].

Overall Mechanical Performance
This class includes metrology for evaluating the switchgear operating mechanism. Regarding the different GIS components several methods are applicable. Generally they concentrate on evaluation of current, voltage, path and time. Limit values proceeded by manufacturers or norms already exist. Additional analysis of time-based signals is done and compared to reference functions. IT-based interpretation tools support the evaluation.
Combining these approaches allows evaluation of the condition and related risk assessment [2].

AGGREGATION SCHEME

For evaluating the GIS´s condition knowledge about the usable methods is important. Previous paragraphs illustrated the applicability of measurements referring to this. Processing incoming measurement data requires that information.

General Principle

The system-approach consists of several layers. In the context of aggregation different methods are used. Figure 3 shows the related layers and the corresponding aggregation scheme.

Layer	Notation	Aggregation
1	Bay	
2	Function	Weighting
3	Main component	Weighting
4	Subassembly	Weighting
5	Parameter	Weighting
6	Valuation method	**Theory of Evidence**
7	Incoming data	Valuation

Figure 3: Layers and aggregation of the system-approach

Bottommost area evaluates the incoming data. As a function of extent of wear a standardised factor is assigned like conventional valuation schemes do. That score represents the incoming data for the next level: the valuation method. At this area elements of the theory of evidence are used. The theory uses degrees of belief based on probability numbers. For utilization in the context of the described system-approach several assumptions were made. The result can only be an occasion and its complementary: abnormality and no abnormality. Consequently probability numbers can express degrees of belief in an uncomplicated way. [6; 7; 8, 9] The following paragraphs will only concentrate on the probability numbers. Three of them are necessary for each valuation method. Its sum totals up to one. The masses express different states: extent of wear, condition reserve and uncertainty. Generally they express the extent of approval. Its origin is the evaluation of the lower layer. It is the input for the correlation to masses. Each mass has a specific trend concerning the input data. The trend is given by previous investigations. Figure 4 illustrates the procedure for assigning masses. Only the trend of one mass is shown in that model. The x-axis of the graph represents the incoming data. « 1 » means no wear, « 4 » means maximum wear was detected. At each point of the incoming data the total sum of all masses is one.
At the end of that procedure each valuation method consists of three numbers. Valuation methods matched into the layer parameter are combined by using theory of evidence. Those methods can be based on measurements (hard facts) or visual inspections (soft facts). Therefore Dempster´s rule is used. [6]

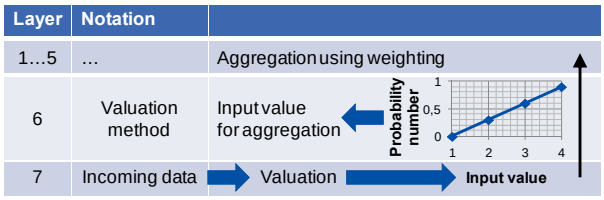

Figure 4: Assigning probability numbers

The result of that combination is three masses for each parameter. They represent the trend of condition in combination with the corresponding uncertainty. If there are some evidences regarding the condition the uncertainty is reduced. The more hints for the condition are present the higher the validity. The less hints are available the higher the uncertainty. It can achieve a value up to one if there is no hint regarding the condition.
The next layers use weighting factors for combining intermediate results. These factors are determined by analysing statistics and importance of GIS components.
At the end of the aggregation scheme reliable data for the condition of functions, bays and substations results regarding the specific validity are achieved.

Probability Numbers

As shown in the previous paragraph probability numbers are necessary for determining uncertainty. This paper discusses working principles of them and possible trends, which represent the values of probability numbers depending on incoming data.
Several trends are conceivable. Figure 5 shows possible trends in the context of condition assessment. It is diverted into basic trends (No. 1-3) considering one mass and pooled trends (No. 4-7) considering all three masses.
In general varieties 4 to 6 are used for the introduced system-approach. Variety 4 describes a scenario with constant validity regardless of incoming data. The valuation method has the same uncertainty in both directions: no wear and maximum wear. An example might be a visual control of a component. Variety 5 is an example of metrology which cannot detect all possible defects within the appropriate layer of the system-approach – for example acoustic partial discharge detection. Uncertainty decreases if a defect is identified. In the case of an imperfection uncertainty is low because the metrology gives a detailed hint and for that instance it is very reliable. If its result shows no wear the evidence is as much reliable as relevant defects can be detected. Because the number of detectable imperfections is smaller than the number of relevant ones uncertainty is high. Variety 6 describes for example a valuation method based on soft facts. Some of them cannot express a hint for no wear. But on the other hand they can contribute to the condition assessment if they detect a wear. An abstract example could be visual control for leakage of the enclosure. On the one hand visual control is not

reliable for detecting no wear. On the other hand if a leakage can be detected by visual control it is very critical and reliable.
Next to the trend of numbers its value is important to express the condition of the valuation method and the overall layer. The value describes the extent of wear in combination with the validity of the method. For measurements corresponding values are assigned by analysing laboratory tests mentioned in the previous paragraphs. If no wear is detected the ability to identify relevant imperfections is determining.

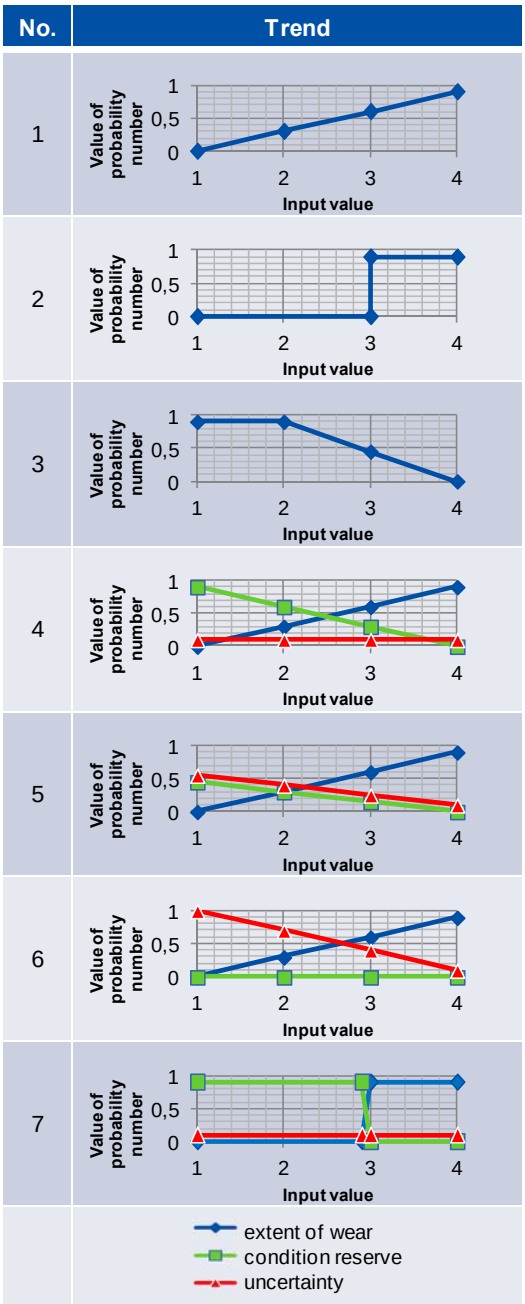

Figure 5: Typical trends of probability numbers

In the case of the acoustic partial discharge detection the mass amounts to 0.6. The uncertainty comes to 0.4 (40%). In the case of identified critical imperfection the appropriate mass amounts to 0.9. The uncertainty comes to 0.1 (10%). In that case the method is very reliable. The uncertainty left describes measuring inaccuracy. The maximum values can be held on a constant range or they can be dynamic. The dynamic procedure is more relevant in the context of measurements if its validity is not constant at all. Reasons might be the usage of sensors with different sensitivities. As shown for the UHF partial discharge detection sensitivity might decrease up to an amount of 45%. This fact has to be observed in context of assigning masses.
Generally there are more possible varieties of handling masses, but this paragraph describes specific, selected possibilities and gives recommendation in the context of realistic condition assessment.

Handling of Imperfect Data

The present paper deals with a system-approach for realistic condition assessment. In this context all available data concerning the substation condition have to be used. This paragraph regards incomplete and temporarily delayed incoming data.
The handling of incomplete data is done by adjusting the uncertainty. Hence, uncertainty of missing data is assigned to the value 1. In conclusion there is no hint known concerning the valuation method generating a decrease of the result´s validity. However, the working principle is not influenced.
Because of internal processes incoming data might have been gathered at different points of time. This fact is considered by the valuation layer. In contrast to other schemes no aging process is assumed. The validity will be aligned to the higher age of incoming data. In detail, hints for an imperfection will be considered at respective valuation methods. They have the same value like current surveys. Self-recovery effects are not considered. Indication for no wear gets a decreased confidence level. In conclusion the uncertainty increases because the mass for no wear decreases. This effect is transferred to the final result by the design of the system-approach.
Generally both, incomplete and aged data generate higher uncertainty. Incomplete data reduces both masses. Aged data reduces only the mass for no wear.

Output Data

As described before, the system-approach generates three values for each layer up to the whole substation. These masses are used to generate a condition index. That index can be found within the area of uncertainty.

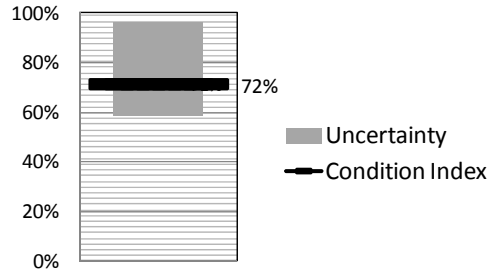

Figure 6: Result of system-approach

Its position depends on the risk affinity of the asset owner and has to be determined once. It should be held at a constant level to achieve comparable results of condition.

If the asset owner is rather risk-averse, the condition index is decreased and hence an asset decision has to be made more early than in a risk-affine scenario.
Figure 6 exemplifies the result of a risk-averse asset owner. Consequently the index can be found at the lower end of the uncertainty. The depiction is reduced to the most important facts according realistic condition assessment: condition index and respective uncertainty. Other illustrations are possible depending on the asset owner's intention.
Additionally defected parameters are separately revealed. This is done because of the general working principle. Some parameters might have just small effect on the overall condition index.

FIELD TESTS

The system-approach was applied to assets of Westnetz GmbH. The presented results concentrate only on selected substations.

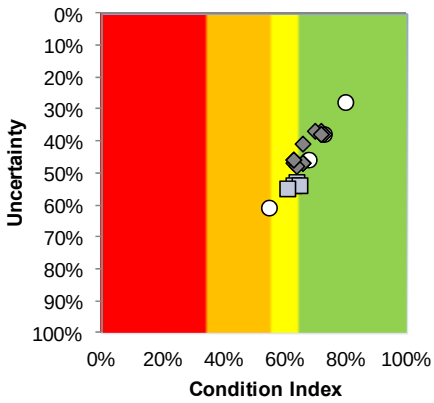

Figure 7: Condition of bays as a function of uncertainty

Figure 7 gives a summary of the condition of the chosen bays as a function of uncertainty. The asset owner's risk affinity is taken into account by the condition index as explained in previous paragraphs. Such an illustration gives an overview of the condition of investigated bays. In the centre of interest is the relation between themselves. Provider can also recognize how reliable a result is. Guidance can be deduced, which does not exclusively mean maintenance tasks. Further investigation might also be acceptable tasks.
For getting impulses of action an additional perception is necessary. Therefore the identified wear referred to each bay should be presented.
Field tests showed the need of both illustrations. The system-approach was able to generate realistic condition assessment. Referring to the age of data and applied methods the uncertainty was determined.
Generally, there was primarily small wear detected. Bays and substations having several abnormalities were separated by the illustrations. Major defects were depicted, too.

CONCLUSIONS

The present paper introduces a system-approach for realistic condition assessment of high-voltage gas-insulated substations. The principle of operation is demonstrated including the adapted aggregation scheme and systematic integration of measurements.
In contrast to other schemes it combines visual inspections and metrological investigations concerning relevant parameter sets and finally bay functions. The systematic approach achieves comparable results of different variants of substations. Regardless of the type of substation the same procedure is performed with respect to specific features.
Additionally to the calculated condition index the uncertainty is displayed which takes the specific applicable valuation methods into account. Consequently asset owners, like grid operators or grid service providers, get results for bay and substation condition concerning the validity of the assessment, too.
Field testing illustrated several impressing advantages of the developed approach: Minor and major failures were detected and suitable depicted by the result. Assertions concerning validity of the condition assessment are given, too.
Without any doubt a comprehensive system-approach for realistic condition assessment of GIS has been developed and proven in practical application as a solid base for optimal asset management.

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