CLASSIFICATION OF DISTRIBUTION SUBSTATIONS BY OPERATIONAL AND ENVIRONMENTAL STRESSES LEADING TO FAILURE OF EQUIPMENT

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ABSTRACT

This paper introduces measurements from smart grid as additional information for condition based maintenance of distribution substations. An investigation of ageing phenomena and the most frequent failures in distribution substations is used to determine the information content of common sensors and to select additional sensors. Based on a field study where 38 substations have been equipped with temperature and humidity sensors as additional sensors, a cluster method is developed and utilised, classifying substations due to its ageing stresses as pre-processing for condition assessment.

INTRODUCTION

Increasing penetration of information and communication technologies in distribution networks leads to the availability of large amounts of data from online measurements. Besides the necessity for grid operation, continuous information about the equipment’s history and measures of environmental stresses might give additional value to condition based maintenance. Furthermore, new and possibly susceptible primary and secondary equipment and accelerated ageing due to rising utilization might lead to decreasing reliability.

The use of grounding measurements, infrared thermography and partial discharge measurements as diagnostic measurements for distribution substations is in the introduction phase [1]. Still the integration of operational and environmental stresses that lead to ageing of equipment is not taken into account for condition assessment. Distribution substations will play a key role in smart grids because of the distinguished closeness to future needs for measurements and availability of space.

The aim of this paper is to integrate measurements from smart grid sensors into the condition assessment process of distribution substations. An investigation of minor failures and known stressors is used to determine the information content of measurement data. Furthermore, this analysis supports a selection of additional sensors. Also new secondary equipment which is based on electronic devices is considered. Condition assessment deals with the comparison of maintenance needs. Although ageing models for equipment are missing, the awareness of the stressors exists. Cluster methods will be used to classify distribution substations based on stresses they are exposed to. The classification aims to rank the equipment in distribution substations for urgency of maintenance.

SENSORS FOR THE CONDITION ASSESSMENT IN SMART GRIDS

An analysis of common failures in distribution substations and known stressors of equipment are used to investigate the information content of measurement data and to select additional sensors for condition assessment.

Statistical Analysis of Minor and Major Failures

A statistical analysis of 1825 inspection protocols of distribution substations of a German distribution system operator is given by figure 1. The protocols comprise of 38 checkpoints that record if components are in good condition or damaged. The ten most common failures are shown.

Figure 1: Hazard rate of the ten most common minor failures in distribution substations

Pollution and damaged labelling are most common. Surfaces pollution in combination with humidity can lead to surface discharges if they form a conductive layer. The risk of discharges is significantly reduced if the relative humidity is below 60 % [2]. A measurement of the humidity level inside substations could determine stations that are immune to discharges due to pollution.

An analysis of switch-disconnectors (SWDs) that failed during operation or overhaul in a four years period in the network of a German distribution system operator is shown in figure 2. The total failure rate is divided into transformer-SWDs and cable-SWDs that failed.
Transformer-SWDs fail 16 times more frequently than cable-SWDs. The higher failure rate is attributed to less frequent operations. Transformer-SWDs are opened only to disconnect the transformer during maintenance. A separation into indoor-non-enclosed, enclosed-air-insulated and SF6-insulated switchgears shows that the open air installation fails two times more often than the enclosed ones and eight times more often than SF6-insulated switches. The higher failure rate of non-enclosed switches can be caused by the influence of environmental stressors such as temperature and humidity, while hermetically sealed SF6-insulated switches show the lowest failure rate.

**Ageing Models and Stressors of Equipment**

In general, ageing of electrical equipment is contributed to the presence of thermal, electrical, chemical, mechanical and environmental stressors [3]. For some equipment ageing models are known on the basis of lifetime test under single or multiple stresses. But if the model is pending, basic stressors can be assessed based on experience and tests of similar equipment.

Transformer’s top-oil-temperature (TOT) and loading can be utilised to calculate the loss of life of the insulating materials. Oil leakages are driven by mechanical cycling fatigue due to varying oil volume during heating and cooling of the oil [3]. Corrosion of the tank can be attributed to the humidity level of the substation. It is known that surface corrosion will start at a relative humidity level of 60 % [4]. Measurements of the TOT, loading and humidity in air could give additional value to decide about replacement, for comparison of mechanical stresses and to determine the susceptibility to corrosion.

The end-of-life of SF6-switchgears is determined by blocked mechanism due to corrosion, swelling of synthetic parts, leakage currents, dielectric breakdowns due to partial discharges and loss of SF6. Temperature, humidity and the dielectric stress are the drivers of ageing [5]. Especially SWDs mostly fail due to loss of lubricant and corrosion which is driven by temperature and humidity [6]. Temperature and humidity sensors are most promising for condition assessment.

Measurement, control and communication equipment plays a key role for smart grids. Because these components are new to distribution substations, experience in the field of ageing is missing. Table 1 shows stressors of electronic components in other applications than secondary equipment in substations.

<table>
<thead>
<tr>
<th>failure mechanism</th>
<th>relevant loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>fatigue</td>
<td>Mean and dwell temperature gradient, humidity, voltage and temperature cycles</td>
</tr>
<tr>
<td>corrosion</td>
<td>mechanical stress, voltage cycles, temperature</td>
</tr>
<tr>
<td>electromigration</td>
<td>temperature, current density</td>
</tr>
<tr>
<td>conductive filament</td>
<td>mechanical stress, voltage gradient</td>
</tr>
<tr>
<td>stress driven fusion</td>
<td>mechanical stress, temperature</td>
</tr>
<tr>
<td>time dependent</td>
<td>voltage, temperature</td>
</tr>
<tr>
<td>electrical breakdown</td>
<td></td>
</tr>
</tbody>
</table>

Because of the application in distribution substations, some of the ageing stressors are negligible. Considering the environmental and operational loads, the temperature, humidity and moisture are important. Fast changes in temperature and humidity are not expected. Mechanical stresses, shock loads and varying pressure gradients are irrelevant due to the stationary application. Furthermore, it is assumed that the current density and voltage of the secondary devices are equal for every component of the same product line and independent of external influences.

IEC Standard 61709 [8] provides a formula for temperature dependent ageing rates $\pi_T$ of electronic devices. This formula is based on an Arrhenius model that was standardised to prevent temperature dependent activation energies. The standard also provides values for constants and activation energies $E_{A1}$ and $E_{A2}$ for different types of electronic devices.

$$\pi_T = \frac{A e^{E_{A1}/T} - (1 - A) e^{E_{A2}/T}}{A e^{E_{A1}/T_{ref}} - (1 - A) e^{E_{A2}/T_{ref}}}$$

$$z = \frac{1}{K_0 \left( \frac{1}{313 K} - \frac{1}{T_{op}} \right)} ; z_{ref} = \frac{1}{K_0 \left( \frac{1}{313 K} - \frac{1}{T_{ref}} \right)}$$

Where $K_0$ is the Boltzmann constant, $A$ is a constant, $T_{op}$ is the operating and $T_{ref}$ is the reference temperature for an ageing rate of one. Monitoring of the temperature and humidity level could identify susceptible secondary equipment and support the decision for replacement.

Overcurrents and voltages due to lightning impulses or short circuits can be hazardous to equipment. Current and voltage measurements can be used to identify extraordinary stressed equipment. Additionally, these measurements are applicable to register switching operations of SWD and tap changers.

**Selection of Sensors for Condition Assessment**

Future smart grids will be able to control the power quality and load flow during operation. It is assumed that
they will provide current and voltage measurements in substations. Based on the analysis of ageing of equipment in distribution substations, temperature and humidity sensors are selected to be additionally installed for condition assessment. Furthermore, the transformer’s TOT could be measured to get valuable information about the lifetime for decisions about replacement.

Secondary equipment in smart grids frequently provides additional analogue channels for sensors. Furthermore, the basic functionality of measuring, storing and transmitting data from sensors is provided by existing technologies. If the used equipment provides the option to connect additional sensors or to , an upgrade to more sensors will be cost efficient. In this case the additional costs will be raised mainly by the sensors and the conditioning equipment itself.

To determine environmental stresses of temperature and humidity, a general point for measurement should be chosen that is little influenced by self-heating of equipment. Therefore, the housing of the medium voltage switchgear is selected to install additional temperature and humidity sensors to monitor the substation.

**INTEGRATION OF MEASUREMENTS INTO CONDITION ASSESSMENT PROCEDURES**

Condition based maintenance aims at performing maintenance on equipment only if the condition implies urgency. Therefore, a synthetic condition value for every asset is determined to rank equipment.

**Integration of Measurements into Common Condition Assessment Procedures**

Common condition assessment procedures evaluate the condition of the substation \( C_{\text{substation}} \) based on statistical analyses, master data or inspection. The given information is aggregated by a weighted sum of individual evaluations \( C_i \) of the \( n \) components, as follows:

\[
C_{\text{substation}} = \frac{\sum_{i=1}^{n} C_i \cdot w_i}{\sum_{i=1}^{n} w_i}
\]

Usually the weights \( w \) are assigned by experienced personnel to account for the individual importance of components compared to each other. High condition values imply urgency for maintenance.

The aim is to integrate measurements into condition assessment procedures. Therefore, it is necessary to analyse possible improvements of the condition assessment. The investigation of information contents reveals that ageing models are available for some components. For many ageing phenomena, models are unknown but the stressors are clear. Known ageing models implicate that equipment which is exposed to more intense stresses will fail to operate earlier if the durability against ageing is similar. Therefore, a comparison of stresses can be used to rank equipment due to susceptibility to ageing.

Ageing models can be directly integrated into assessment procedures by calculation of the remaining lifetime. For known stressors, a classification of similarly stressed substations can be used to cluster stations and rank the groups according to the intensity of stresses. An important assumption for the condition assessment is that components in a network suffer from similar ageing processes. This assumption is supported by the small number of manufacturers. More than 80 % of the transformers of one exemplary German network operator are produced by five manufacturers.

**Clustering Methodology for Stresses**

Cluster algorithms aim to group similar objects based on attributes. A cluster analysis necessitates five steps, see figure 3. In this context a hierarchical agglomerative cluster method is used. At the beginning every object represents one cluster. Then they are iteratively merged until one cluster contains all objects. The dissimilarity of objects is determined by a distance measure.

First the object’s data is pre-processed to provide concentrated information. Then the proximity matrix is calculated that contains the distance between each pair of objects. After calculating the distances, the two nearest objects are merged to a new cluster. The proximity matrix then needs to be recalculated to account for the new cluster. The merging of clusters is continued until one cluster remains. At the end, a criterion is used to determine the optimal number of clusters.

Histograms with relative frequencies of occurrence are used for the classification of environmental stresses based on absolute values such as temperature or humidity. The histogram contains the complete information about the stress as absolute values. Relative frequencies offer the possibility to compare measures of different durations.
Generally, the Euclidean distance is used to measure the distance of objects [9]. For the comparison of histograms, this method is unsuitable for two reasons. Two adjacent data points cannot be considered as independent because a similar frequency of two neighbouring values also leads to similar histograms even if they are slightly diverse. Also ageing processes, such as the Arhenius model, tend to accelerate nonlinear with rising stress levels. Therefore, a distance measure is developed that considers these aspects, given by the following formula.

\[
D_{\text{inh}}(k) = \sum_{k=\infty}^{\infty} \frac{\sum_{n=2}^{n} \theta(n) \cdot |M(k) - m(k + n)| \cdot A(M(k)) \cdot \sum_{n=2}^{n} \theta(n)}{\sum_{n=2}^{n} \theta(n)}
\]

The distance \(D\) between two histograms \(M\) and \(m\) is calculated by summation of the difference between two relative frequencies for each \(k\) values. The relative frequency of \(M(k)\) is also compared to two neighbouring values of \(m\) multiplied by a weighting factor \(g\) to consider the closeness and normalized by division by the sum of all weights. Each \(k\) distance is then weighted by the relative ageing rate of the stress factor \(M(k)\) to consider the nonlinear acceleration of the ageing process. The weighting factors \(g\) are chosen to be linearly rising from zero at the third neighbour to one at the same point. The factor \(A\) represents the ageing rate at the given absolute stress value. This factor guarantees that stress levels which lead to more intense ageing are more important for the building of clusters. If no ageing model is known, the factor can be set to one to achieve identical importance.

The average linkage method is used to merge clusters and to recalculate the proximity matrix. The distance is calculated as the mean difference of each pair of objects in two clusters. This guarantees that the inhomogeneity of the elements in one cluster is kept small [9].

The inhomogeneity of the clusters is calculated by summation of the original distances between the merged objects. A one-object-cluster has an inhomogeneity of zero while the inhomogeneity of a two-object-cluster equals the object’s distance. The sum of inhomogeneity of all clusters rises continuously with every merge of clusters. As criterion to determine the optimal number of clusters, the elbow criterion is used that identifies a step of the inhomogeneity as the stop criterion [9].

FIELD STUDY AND FIRST RESULTS

A field study is initiated to investigate typical stresses of equipment in substations. Temperature, humidity, current, TOT and the voltage are measured in 38 substations during operation. To determine design specific differences, different kinds of substations are chosen, containing compact substations, concrete stations, and substations inside building on ground and underground level. The temperature and humidity sensors are placed on the medium voltage switchgears housing one meter above ground. The cluster methodology is used to classify 38 substations according to their absolute temperature and humidity level in the time span from June to November 2014. The measurements are sampled every 10 minutes with an accuracy of +/- 0.4 K with a NTC and +/- 1.5% relative humidity with a capacitive humidity sensor. Currently TOT and current measurements are available only from 12 substations, so that the cluster methodology is not applicable.

Figure 4 shows the histograms of the mean temperature values after clustering the 38 substations. A number of 3 clusters is determined to be the optimal number of clusters. As ageing acceleration factor, the ageing model for secondary equipment from [8] was used (\(A = 0.3, E_{A1} = 0.7, E_2 = 0.9, T_0 = 50 \, ^\circ C\)). The mean temperature value of the environment during the time span is 14.6 \, ^\circ C. The results can be used exemplary to rank secondary equipment according to risk of failures.

![Figure 4: Result of the cluster analysis of absolute temperature (vertical line: mean value)](image)

The cluster 1, 2 and 3 contain 2, 8, and 28. Cluster 1 shows a narrow bandwidth of temperature values. The substations in this cluster are underground substations that are little influenced by the ambient temperature. These substations have the highest temperatures with a mean value of 27.9 \, ^\circ C. Cluster 2 consists of one compact, underground and overground concrete stations. The temperature level is in the middle of the temperature of cluster 1 and 3. These substations are exposed to a mean temperature of 23.8 \, ^\circ C. Different designs of substations are represented by cluster 3. The mean temperature value is 5 \, ^\circ C higher than the ambient temperature. Due to the temperature distribution, these clusters can be rank from 1 to 3. Secondary equipment in cluster 1 is expected to fail first while the ones in cluster 3 are stressed the least. A wider distribution of the histogram implies greater cycle depths which is also a driver of ageing mechanism. The stations in cluster 1 have the highest absolute temperature values but the least cycle depths. Cluster 2
and 3 are nearly equally stressed by temperature cycles.

Figure 5 shows the cluster analysis of 38 substations regarding the relative humidity inside. A number of 4 clusters is determined as the optimal number by the elbow criterion. According to the numeration, the clusters contain 2, 25, 8 and 3 substations respectively.

Cluster 1 has humidity values that are below 60 % continuously. It is unlikely that these substations suffer from corrosion of metal parts or surface discharges. The cluster consists of 2 underground substations that have high temperature values (temperature cluster 1) which lead to a low relative humidity. Cluster 2 is the largest cluster with humidity values between 35 % and 71 %. The mean value is below 60 %. It is assumed that these substations are moderately stressed by corrosion and surface discharges. Clusters 3 and 4 have the highest humidity values. Both clusters have mean values higher than 60 %. Cluster 4 has a wider bandwidth of values. The mean relative humidity of cluster 3 is the highest. It is assumed that clusters 3 and 4 should be maintained more often to prevent corrosion, greasing and surface discharges. Cluster 1 is presumably safe from corrosion and the stations need cleaning seldom.

CONCLUSION

The analysis of common failures and ageing of equipment shows that temperature and humidity measurements inside substations might give additional value for the condition assessment of equipment. Especially concerning new secondary equipment, these are expected as the main stressors. A cluster methodology was developed and applied to field measurements of temperature and humidity. The results show that substations have different levels of these stresses and that the substations can be ranked according to the expectation of failures. Concerning the relative humidity, a cluster was identified that is unlikely harmed by corrosion or surface discharges due to the low humidity.

The field study was initiated in 2014 and will be continued until 2017. It is expected that a comparison of yearly inspections and diagnostic measurements promises a more detailed analysis of the development of failures and the correlation to measurement data. Additionally, voltage, current and transformers TOT measurements will provide measurements of operational stresses in future.

Because heat in substations is produced by electric losses and relative humidity decreases by rising temperature it is assumed that the temperature and humidity level might correlate with loading of the substation. Therefore, an analysis of the correlation might substitute the additional sensors. The influence of the sensor position for temperature and humidity measurements will be further investigated by comparative measurements.

REFERENCES