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Uncertainty Analysis in Prognostics for Optimal Maintenance

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Abstract- Reliable prognostics have become indispensable to provide predictive service solutions. In fact, by assessing the residual useful life of a product, a condition-based maintenance strategy can be adopted. Consequently, the appropriate service activity can be assigned and scheduled only if and when required. Hence cost and time related to unnecessary preventive service tasks is saved. Prognostics algorithms are usually affected by different types of uncertainties stemming, for example, by randomness and lack of knowledge in the degradation behaviour, the inherent failure mechanism and the usage of the product by the customer. Such uncertainties can have potentially large effects on the determination of the residual useful life and, consequently, on the planning and scheduling of the subsequent service activity. This paper is focused on the customer usage as a main source of uncertainty. A statistical and a fuzzy approach are presented. The application case is given by the determination of the electrical overhaul for a generator circuit breaker (GCB). Nevertheless, the suggested approaches can be generally used for any type of products.

I. Prognostics for optimal planning of predictive maintenance

A. Application scenario

The application scenario used to describe the approaches presented in this paper is the calculation of the residual useful life of a generator circuit breaker, hereinafter denoted as GCB.
A circuit breaker is a mechatronic device for interrupting the flow of current in an electrical system with a switching operation. A GCB represents a safety element in power plants, which interrupts very high fault currents (up to 250 kA) in the busbar between the generator and the main transformer. The GCB is a crucial safety element and regular inspection on its operability and overhauls for maintenance is important so that 100% availability and reliability of the product is assured. When used for applications such as pumped storage power plants, where frequent switching operations in the GCB occur, the ablation of the contacts is much higher compared with base load power plants. For pumped storage power plants, in fact, the GCB system is used to change the operation between pumping and generation mode very quickly in addition to performing its safety function.
Typical life span of a GCB is between 20 to 40 years. The electrical residual life of a GCB can be defined in terms of the amount of ablation the breaker can withstand before an overhaul is required. For every instance a circuit breaker is operated, the contacts are ablated and eventually making it no longer functional due to cumulative ablation. The amount of ablation encountered depends on the intensity of the interrupted current. Thus, each switching operation results in a reduction of residual life, with different amounts of ablation.
Typically, a breaker has three switching contacts (i.e. phases) and therefore three electrical residual useful lives (one for each phase). For the sake of clarity only one phase will be considered in this paper.

The standard procedure to assess the electrical residual useful life for a GCB is given by the following steps:

1. The condition monitoring system installed on the GCB determines the contact ablation k_j corresponding to each switching operation j (see Figure 1). The labels in the graphs are considered confidential information and are not for public disclosure.

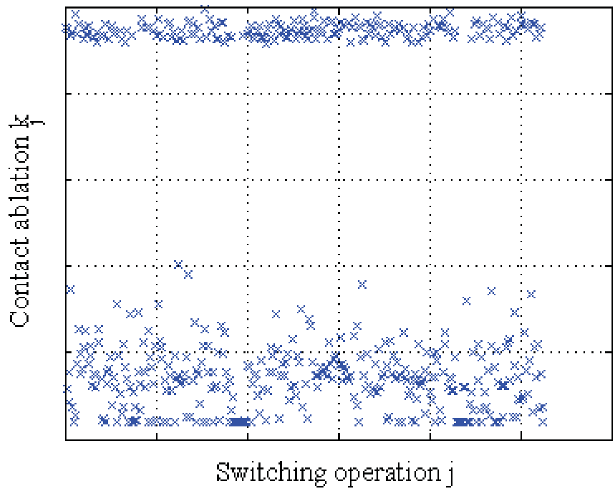

Figure 1: Contact ablation k_j corresponding to each switching operation j

2. The cumulative ablation K_i is calculated as the sum of the contact ablation k_j for each single switching operation between 1 and i, that is:

$$K_i = \sum_{j=1}^{i} k_j$$

with $i = 1, \ldots, n,$ where n is the number of the actual switching operations (i.e. the number of measured contact ablation k_j).
The cumulative ablation can be considered as a measure of the overall degradation of the GCB contacts. It is usually expressed as percentage of the maximum allowed cumulative ablation, $K_{\max}$. That is $K_{\%,i}=(K_i/K_{\max})\cdot 100$. Figure 2 shows the percentage cumulative ablation $K_{\%,i}$ as function of time for an installed GCB (blue line). The labels in the graphs are considered confidential information and are not for public disclosure.

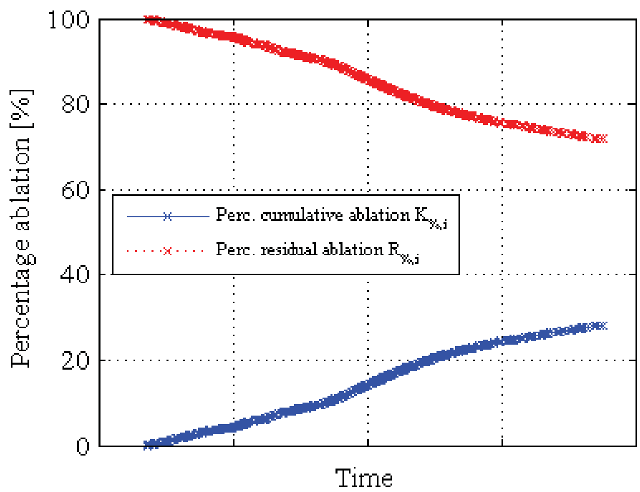

Figure 2: Percentage cumulative ablation $K_{\%,i}$ and precentage residual ablation $\boldsymbol{R_{\%,i}}$ as function of time for an installed GCB

3. The percentage residual ablation $R_{\%,i}$ is given by:

$$R_{\%,i} = 100 - K_{\%,i}$$

$R_{\%,i}$ is a measure of the amount of ablation the breaker can take before an overhaul is required (see Figure 2; red dot line).
4. The residual useful life is determined by extrapolating the values of the percentage residual ablation $R_{\%,i}$. At the point in time where the extrapolated percentage residual ablation reaches zero an electrical overhaul is scheduled. The electrical residual useful life for the GCB is then given by the time to the

next estimated electrical overhaul. The procedure for the calculation of the electrical residual useful life is illustrated in Figure 3.

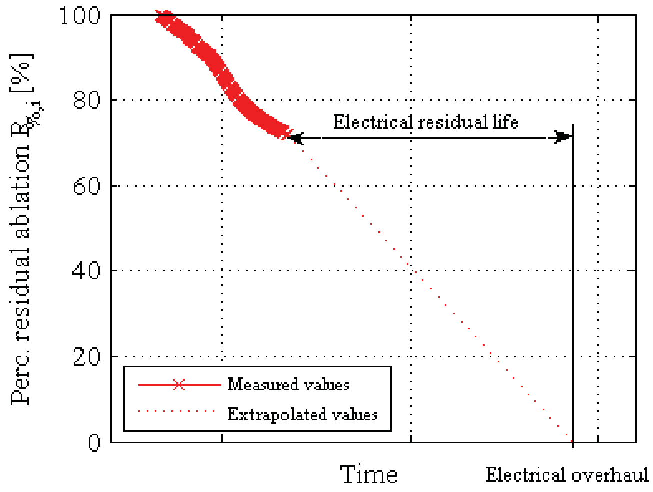

Figure 3: Determination of the electrical residual life for a GCB

As shown in Figure 3, the extrapolation of the percentage residual ablation $R_{\%,i}$ is based on a linear fitting of all (or part of) n measured values.

II. Uncertainty analysis

The prognostic algorithm presented in the previous section to determine the electrical residual life of a GCB is affected by different types of uncertainties. According to [1], two different sources of uncertainties usually affect the prediction of the residual useful life: randomness due to variability inherent in the GCB degradation behaviour (aleatory uncertainty) and imprecision due to incomplete knowledge and information on the failure mechanism of the GCB (epistemic uncertainty). Hanss, Turrin et al. [2,3] identified different sources of epistemic uncertainty that must be considered in the calculation of the residual life. This section will focus on the uncertainty related to the usage of the breaker by the customer. At the time in which the residual life is predicted, in fact, the future usage of the breaker by the customer until the electrical overhaul will occur is unknown. In the previous section, the future usage is estimated by a simple linear fit on the measured values. In other words, the future usage is approximately an average of the past usage. In this section a statistical approach and a fuzzy approach are suggested to determine the electrical residual life taking into account the uncertainty related to the future usage of the breaker.

A. Statistical approach

Starting point of the statistical approach is the assumption that the future usage will probably follow a similar pattern as how the GCB was used in the past by the customer. The past usage can be represented by the relative variation of the percentage residual ablation d_i, with:

$$d_i = \frac{R_{\%,i} - R_{\%,i+1}}{t_{i+1} - t_i}$$

where $i = 1,\ldots,n$ and n is the number of measured values. Figure 4 shows the relative variation of the percentage residual ablation d_i.

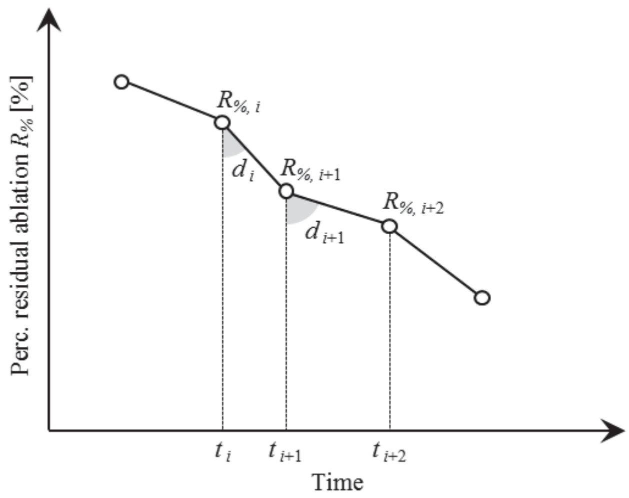

Figure 4: Calculation of the relative variation of the percentage residual ablation, d_i

In Figure 5, the past usage of the breaker is given in terms of relative frequency and empirical cumulative distribution function, respectively, for the relative variation of the percentage residual ablation d_i. These values correspond to the percentage cumulative ablation $K_{\%}$ reported in Figure 2 and statistically represent the past usage of the breaker.

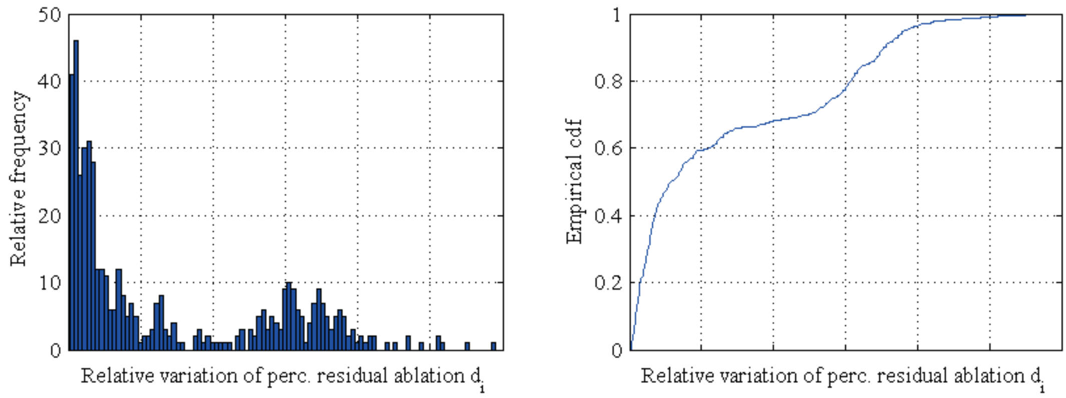

Figure 5: Relative frequency and empirical cumulative distribution function for d_i

A statistical description of the relative variation of percentage residual ablation d_i is illustrated in Figure 6 as a bimodal Weibull probability density function.

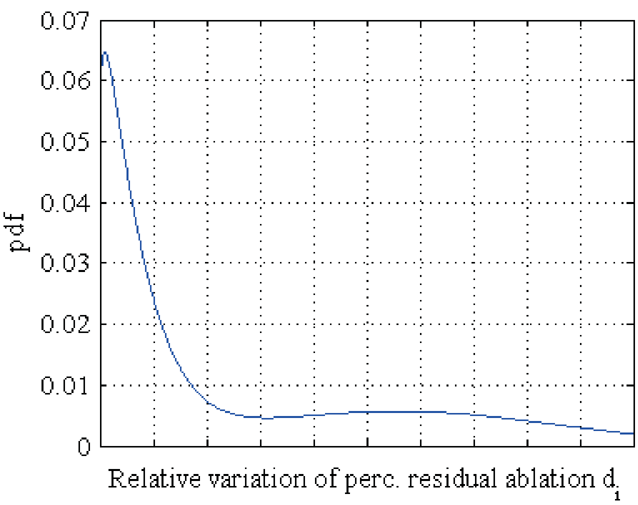

Figure 6: Bimodal Weibull probability density function of the relative variation of percentage residual ablation d_i

The probability density function plotted in Figure 6 is determined by applying a distribution fitting algorithm to the data illustrated in Figure 5. In the statistical approach presented here, the probability density function of d_i represents the slope of the extrapolation which is used to determine the electrical overhaul. By applying a Monte Carlo simulation it is possible to determine the statistical representation of the electrical overhaul in terms of its probability density function (see Figure 7). The electrical overhaul shown in Figure 7 takes into account the uncertainty related to the future usage of the breaker by the customer. Based on this result it is also possible to assess the electrical overhaul together with some confidence intervals (not reported in this paper).

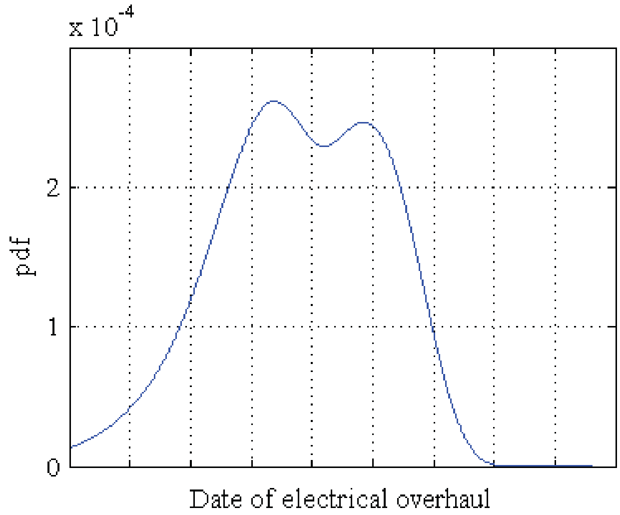

Figure 7: Statistical representation of the electrical overhaul

B. Fuzzy approach

An alternative representation of the uncertainty related to the customer usage is based on fuzzy numbers. Fuzzy numbers are efficiently used to represent and quantify epistemic uncertainty. The propagation of uncertainty is then determined by the application of fuzzy arithmetic methods, [2-3].

In Figure 8, a possible fuzzy representation of the uncertainty on the customer usage is plotted. The nominal value is given by the arithmetic mean of the relative variation of the percentage residual ablation d_i, i.e.

$$\bar{d} = \frac{\sum_{i=1}^{n} d_i}{n}$$

The left-hand worst-case deviation is given by the minimum of d_i and the right-end worst case deviation by the maximum of d_i.

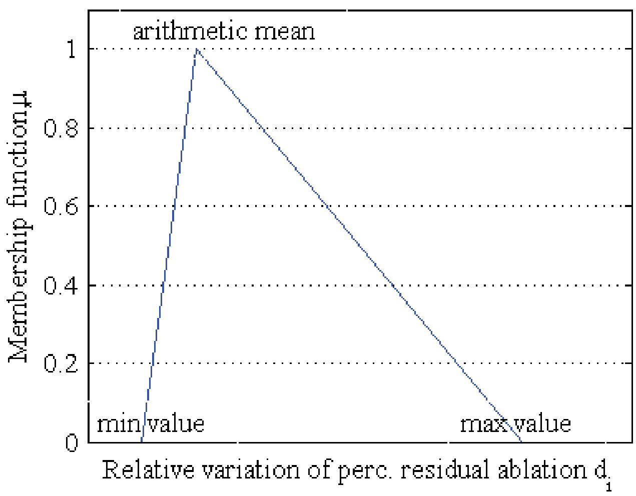

Figure 8: Fuzzy representation of the d_i

By means of fuzzy arithmetic it is possible to calculate the corresponding fuzzy representation of the electrical overhaul (see Figure 9).

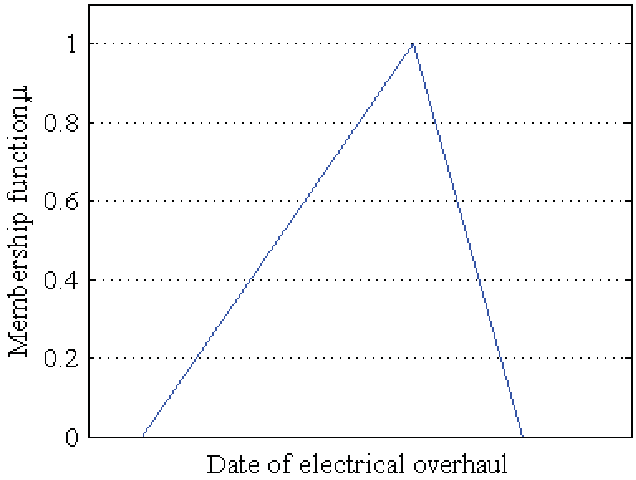

Figure 9: Fuzzy representation of the electrical overhaul

III. Conclusions

In this paper a statistical approach and a fuzzy approach to represent the uncertainty related to the customer usage in the determination of the residual life of a GCB are presented. The scope is to provide a credible assessment of the residual life which is valuable in the decision making to provide the optimal predictive maintenance activity. The work presented here is still in progress.

References

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