FORECASTING RELIABILITY OF TRANSFORMER POPULATIONS

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ABSTRACT

The expected replacement wave in the current power grid faces asset managers with challenging questions. Setting up a replacement strategy and planning calls for a forecast of the long term component reliability.
For transformers the future failure probability can be predicted based on the ongoing physical degradation processes and the future loading scenarios as input. In previous work we have presented a modeling approach for individual transformers.
We here present a probabilistic approach for predicting the reliability of a transformer population from the individual transformer reliabilities.
This method has been successfully applied to a small transformer population by calculating the impact of different asset management scenarios.

INTRODUCTION

The ageing of power systems and their components are of great concern for the asset manager, especially in respect with the coming replacement wave in the electrical infrastructure [1, 2].
For supporting maintenance decisions, the asset manager can choose from several tools, e.g.:

1. linking the historical reliability data to possible maintenance or replacement strategies [3, 4];
2. extrapolating the present condition to the future [5];
3. forecasting reliability by combining the degradation process with past or present condition or performance data and using a statistical approach [6, 7].

In view of the expected replacement wave, the asset manager is in need for a prediction tool, to determine the long term effects on the statistical relevant parameters of a population of power systems components.
The present work is dedicated to the power transformer. In previous work we have presented a modeling approach for individual transformers [6]. In this paper we will describe a method for forecasting the population reliability from the individual reliabilities, partially based on [6, 8]. It also provides the basis for an asset management optimization tool for maintenance / replacement scenarios.

INDIVIDUAL TRANSFORMER RELIABILITY FORECASTING

In an earlier publication we have described a model for predicting the individual failure probabilities of a power transformer [6]. The model starts from a probabilistic approach, involves the use of the DP-value (Degree of Polymerization) as a quality parameter (an externally measurable indicator which is used to link model and reality) and involves an error propagation analysis which is used to take account of, and reduce, the inaccuracy of the predictions.
The model uses the IEC loading guide, [9], to determine the hotspot temperature. The hotspot temperature T is then related to the estimated change of the DP-value with time, using,

$$\frac{1}{DP_t} - \frac{1}{DP_{initial}} = A\exp\left(-\frac{E_a}{R \cdot T}\right)t. \qquad (1)$$

Here R is the universal gas constant, E_a is the activation energy and A is a pre-exponential. An example result of (1) is depicted in Figure 11; starting from a relatively high initial DP-value, it drops down to a value below a critical DP-threshold. Both DP-value and threshold are known with a limited accuracy, indicated with curves for the (e.g. 95 %) accuracy margin. Initial uncertainties in model parameters lead to uncertainty in the expected lifetime. By using quality parameters as defined above, the knowledge of the actual situation can be updated. This translates in narrower uncertainty margins and more accurate predictions.

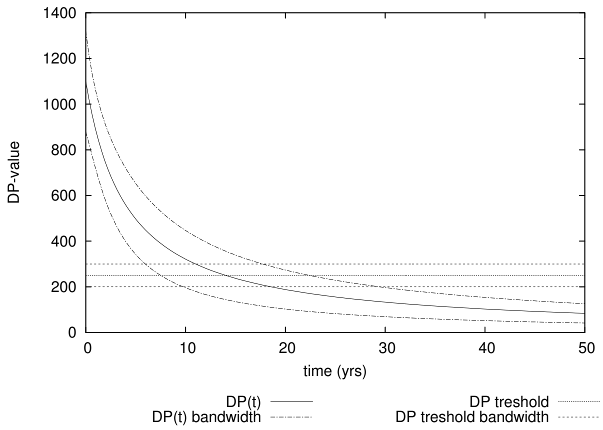

Figure 1. The DP-value and the DP-threshold with its accuracy bandwidths plotted versus time.

In [6] an error propagation analysis is performed which is used as input for the time dependent DP-value distribution function.
The individual failure probability, F_i, is obtained from

$$F_i(t) = \int_0^\infty P_{th}(x)\, p_{dp}(x,t)\, dx, \qquad (2)$$

with $p_{dp}(x,t)$ the distribution function of the DP-value at a time t and $P_{th}(x)$ the cumulative probability of a failure for a DP-value x. The individual reliability function, R_i, is defined as 1-F_i.

FROM INDIVIDUAL RELIABILITIES TO POPULATION RELIABILITY

In this paper we present a method to transfer the individual reliability results to the corresponding reliability of a given population of transformers. The principle of this method is based on [8, Ch. 3]. The method assumes that the individual reliabilities, R_i, and failure probabilities, F_i, are uncorrelated.
For a population of N transformers, the probability of having k failed transformers can be determined with,

$$P_F^{(0)}(t) = \prod_{i=1}^{N} R_i(t);$$

$$P_F^{(1)}(t) = \sum_{i_1=1}^{N} F_{i_1}(t) \prod_{i \neq \{i_1\}}^{N} R_i(t); \qquad (3)$$

$$P_F^{(k)}(t) = \sum_{i_1=1}^{N} F_{i_1}(t) \sum_{i_2>i_1}^{N} F_{i_2}(t) \ldots \sum_{i_k>i_{k-1}}^{N} F_{i_k}(t) \prod_{i \neq \{i_1,\ldots,i_k\}}^{N} R_i(t);$$

$$\sum_{k=0}^{N} P_F^{(k)}(t) = 1.$$

The probability of having less than N_F failures, $P_F(x< N_F)$ is given by

$$P_F(x < N_F \mid t) = \sum_{k=0}^{N_F-1} P_F^{(k)}(t). \qquad (4)$$

From (4) the mean-time-to-failure (*MTTF*) corresponding to up to N_F failures can be computed, as described in the appendix;

$$MTTF(N_F) = t_0 + \int_{t_0}^{\infty} P_F(x < N_F \mid t)\, dt, \qquad (5)$$

with t_0 the starting time in the simulation and t=0 the present time. Equation (5) links the time and population failure probability. The population failure probability belonging to the $MTTF(N_F)$ is given by

$$F_P\big(t = MTTF(N_F)\big) = \frac{N_F}{N}. \qquad (6)$$

The population reliability, R_P, is defined as 1-F_P.

APPLICATION TO PRACTICAL EXAMPLES

Two examples are presented in this paper. The first example describes a population with two main age groups. In the second example the consequences of different replacement scenarios are provided.

Two age groups

The first demonstration is meant to illustrate the modeling method. A population of sixteen transformers is divided in two main age groups with equal individual transformers and similar load patterns and equal environmental conditions. The only difference between the two groups is the starting time of their operational life: eight of them were installed 50 years ago and the other eight were put in operation 10 years ago.
The population failure probability of the two combined groups is calculated with (6) and is depicted in Figure 2.

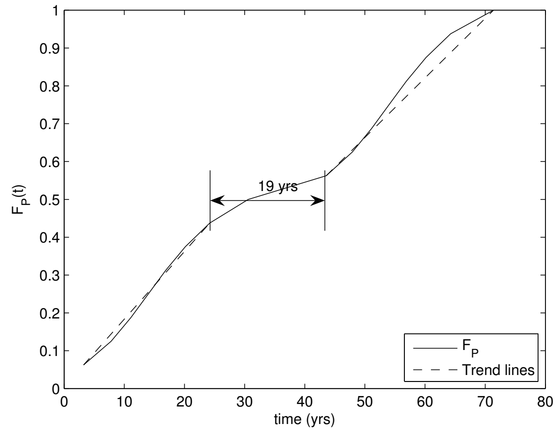

Figure 2. The failure probability for a population composed of two groups with a present age of 50 and 10 years.

Although the $MTTF_i$ of individual failure in the first group is 16 years and 40 years later for the second group, there is already a significant failure probability after 4 year, as shown in Figure 2. This is the result of the combinatorial effects of the population; another result of this effect is that the time distance separating the populations does not show an intuitively expected "quiet" period of 40 years but a more gradual transition duration of less then 20 years. The two trend lines given in Figure 2 represent the equal failure rates within each group, in agreement with the assumptions (identical transformers, load patterns and environment).

Replacement strategies

In the second and more realistic example again two age groups are chosen, 30 and 10 years old, but now each group is divided in three classes having different loading during their operational lifetime. The resulting population failure probability is plotted with dashed lines in Figure 3, and is used as a reference for comparing scenarios involving the replacement of two or three transformers within the original population.

In the first scenario one old transformer is replaced in every load group (solid line in Figure 3). In this scenario, in comparison with the original one, it is observed that the lower probabilities are shifted 1 to 2 years to the future and the higher probabilities about 5 years to the future. Almost the same effect is obtained if in every age group one high loaded transformer is replaced (dotted line in Figure 3).
The dashed-dotted line in Figure 3 represents the replacement of three old and heavy loaded transformers, providing us a 20 year postponement of worries.

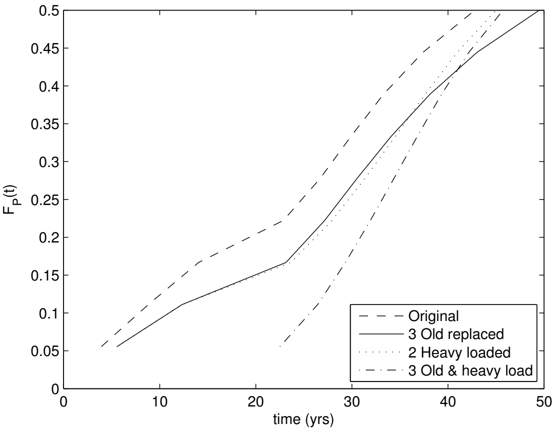

Figure 3. The population failure probability for different scenarios: original 30 and 10 year old and 3 types of loading schemes. In the original group i) one of the older transformer is replaced in every load scheme, ii) from the original group 2 heavy loaded transformers, 30 and 10 year old, are replaced and iii) the 3 oldest and most heavy loaded are replaced.

DISCUSSION AND CONCLUSION

The results of the given examples are actually quite trivial, because of the very simple population and load distributions chosen. Here the benefit of the model is that the intuitively correct approach can now be supported with a realistic simulation. In real situations, where actual load patterns are included, a more complex initial age distribution exists and updated knowledge of diagnosed transformers is available, the effect of maintenance / replacement scenarios is much harder to predict beforehand. Here the proposed probabilistic modeling will enable asset managers to optimize their policy on maintenance and replacement.
The present modeling should be developed further in order to enhance its capabilities.

- Technical improvement: The evaluation of equation (3) is very time consuming for a population consisting of a large number of transformers. The processing time can be limited by clustering transformer into groups with similar failure behavior that may be treated as a single component. The division in sub groups could be performed automatically based on the parameters defining the probability distributions.
- Degradation mechanisms: Up to now only paper degradation is included as the process limiting the transformer's expected lifetime. In future other failure mechanisms should be included. This could involve the condition of bushings and tap changers.
- Additional options: At present the model is employed to analyze the consequences of immediate actions. The asset manager also would like to evaluate the effect of future or postponed actions. In the ideal situation the asset manager may define a number of restrictions (for instance the rate at which transformers can be replaced economically or the delivery time), and the model generates the optimum strategy.

To our opinion, the probabilistic modeling based on reliability data obtained from physical degradation mechanisms of individual transformers is a main step forward to have a working tool to support maintenance and replacement strategies.

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APPENDIX

The *MTTF* is the expected value of the time t weighted with the distribution function $f(t)$ for N_F or more failures. This function is equal to the time derivative of $(1-P_F(x<N_F|t))$, where $P_F(x<N_F|t)$ is the cumulative probability that less than N_F transformers have failed.
Furthermore, we want to know the *MTTF* from a reference time t_0 with respect to the present which is taken as t=0:

$$MTTF = \int_{t_0}^{\infty} t \cdot f(t) dt; \qquad \text{(A1)}$$
$$f(t) = -\frac{dP_F(x < N_F \mid t)}{dt}.$$

With integration by parts (A1) can be transformed in,

$$MTTF = -\left[t \cdot P_F(x < N_F \mid t) \right]_{t_0}^{\infty} + \int_{t_0}^{\infty} P_F(x < N_F \mid t) dt; \qquad \text{(A2)}$$
$$MTTF = t_0 + \int_{t_0}^{\infty} P_F(x < N_F \mid t) dt.$$

Equation (A2) is only valid if t_0 is taken such that $P_F(x<N_F|t_0)$ is equal to one.