POWER TRANSFORMER END-OF-LIFE MODELLING: LINKING STATISTICAL APPROACH WITH PHYSICAL AGEING PROCESS

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ABSTRACT

Replacing aged transformers requires intensive capital investment and is expensive for utilities in developed countries. A transformer end-of-life model expressed as population failure hazard curve against age is needed in order to predict the number of failure in the future and suggest the long-term capital investment. In this paper the statistical analysis on historical failure data is used to produce the failure hazard in the normal operating stage dominated by the random failure mechanism, while a physical ageing model is built based on scrapping transformer information. By linking the ageing failure mechanism with statistical approach, the population hazard curve against age is produced which can be used by operators to identify the transformer failure number a system can tolerate while maintaining a secured system operation.

INTRODUCTION

Utilities in developed countries are operating electric networks with ageing transmission and distribution assets. The majority of transformers are approaching or having exceeded their design lifetime, i.e. typically 40-50 years. A replacement program purely based on the designed lifetime requires intensive capital investment and is not an attractive proposition under the present economic climate. A good transformer end-of-life model is therefore required to optimize asset replacement whilst maintaining system reliability.

Statistical analysis of transformer failure numbers under various service ages have been carried out since the 1990s. Either normal, Weibull or exponential distribution was used to best fit the historical failure data with the purpose to predict the number of failure in the future. This approach yields valid results only if the historical failure mechanism continues into the future and therefore is suitable for a relatively young electric network. However for a mature network where the majority of asset population is ageing or aged the ageing failure mechanism might become dominant, in consequence the prediction based on statistics of historical failure data can be misleading.

Transformer ageing is profoundly perceived as thermal ageing of conductor insulating paper. Although paper ageing is predominantly controlled by thermal reaction as well as chemical reactions, dielectric strength of aged paper is reduced little but mechanical strength is severely weakened. Transformer thermal life is thus expressed as the age at which the mechanical strength of paper is reduced to below a certain threshold. The popularly used criterion is retained 20% of tensile strength of paper or degree of polymerization DP = 200 of paper.

Retiring transformers with known defects or developing faults is one of the proactive ways for utilities to manage failure risk. These retired transformers normally go through forensic examinations and this provides an opportunity to directly measure paper insulation ageing status by the degree of polymerization (DP) of paper. DP is then used to predict the thermal life of a transformer.

This paper examines the definitions of failure and failure hazard when being used in statistical analysis. As the dominant failure mechanism changes at different stages of a transformer's life, a methodology is developed to generate transformer population failure hazard curve, by using both statistical approach and paper thermal deterioration process.

FAILURE HAZARD OF INDIVIDUAL TRANSFORMER

Definitions of Transformer Failure and Failure Hazard

For an individual transformer, failure is defined as any event causing a sudden outage that requires the unit to be out of service[1], and the failure hazard curve describes the **conditional failure probability** of that unit at age *t* after it has survived (*t*-1) service years. A bathtub curve in Figure 1 shows the failure hazard against age, perceived as being universally applicable for any item. The high infant mortality at the beginning stage is caused by defective workmanship, poor processing procedure or inherent material defects. The normal operating stage shows a constantly low failure rate independent of age in which failures are caused by randomly occurring external events. The final wear-out stage corresponds to an increasing failure hazard where the unit is more likely to fail due to the increase of age under normal operating stresses.

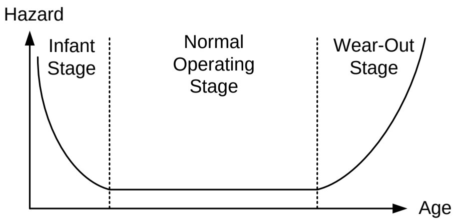


Figure 1 Bathtub Curve of Failure Hazard against Age

UK transformer operating experiences show that due to strict factory testing scheme, high failure hazard at infant stage has been avoided. At the normal operating stage failures are attributed to the random failure mechanism. Also, engineering knowledge based on transformer insulation ageing testing convinces us that a wear-out stage caused by the ageing failure mechanism should exist[1], although it has not been observed by UK utilities.

FAILURE HAZARD OF TRANSFORMER POPULATION

End-of-life Definition and Failure Hazard Calculation

When a transformer fails in service, its lifetime is the difference in years between the failure year and the installation year. On the other hand, end-of-life is a lifetime at which the asset does not meet the operation requirement anymore [2]; and therefore it is the end of transformer useful life.

The lifetimes of the failed units, and the service ages of active transformers constitute the database for statistical analysis of failure hazard of a transformer population. Population failure hazard as a function of age can be interpreted similarly to that of an individual transformer, as the instantaneous failure proneness of a group of transformers within age *t* given that they have survived (*t*-1*)* service years. The failure hazard is calculated as:

$$h(t) = \frac{failure\ number\ @\ age\ t}{exposed\ number\ @\ age\ t} \qquad (1)$$

where the exposed number is the number of transformers survived (*t*-1) service years.

Dilemma caused for Statistical Analysis by Active Retirement

Transformer retirement is a proactive action made by utilities based on individual unit's poor condition and high risk of "fail-in-service". By taking actions to retire these units, the failure risk is reduced and the system reliability increased.

The age of a retired transformer should be emphasized as the retirement age, which is deduced from the year of retirement minus its installation year. Whether the retirement age should be used in the statistical analysis is still debatable. Overall, the active management of transformer retirement artificially distorts the failure hazard function which is effectively being lowered down.

Statistical Analysis of UK Transmission Transformers

National Grid has implemented statistics analysis on their transmission transformer population [3]. The failure hazard is stably low with an average value of 0.25% up to age 36, caused by the random failure mechanism. Above age 36, there is a lack of older transformers which prevents any meaningful statistical analysis to be conducted.

The average constant hazard of 0.25% per transformer per year can not be presumed to continue into the future since the UK transmission transformer population is ageing. The hazard curve derived under random failure mechanism ought to be modified by considering ageing failure mechanism.

Thanks to the forensic examination scheme, scrapping retired transformers provides an insight into insulation deterioration. Since a quantitative relationship between the ageing condition and the transformer intrinsic dielectric strength is still under investigation, transformer thermal life, expressed as the age at which the mechanical strength of insulation paper is reduced to a pre-defined threshold, is taken as the basis to represent the transformer end-of-life.

Transformer Ageing-Related Failure Process

During normal operation years of a transformer, paper's withstand strength is high so the transformer does not fail under a through fault event, i.e. short-circuit. Only extremely rare events will cause a transformer to fail, which are called random failure events. As paper ages, its mechanical strength is reduced and the decreased withstand strength may not sustain the high radial and compressive forces caused by a through fault, therefore the transformer fails. The ageing related failure process is illustrated graphically in Figure 2[4]. The impulses in the stress curve represent the effect of through fault events and the gradually increase in the stress curve represent demand growth.

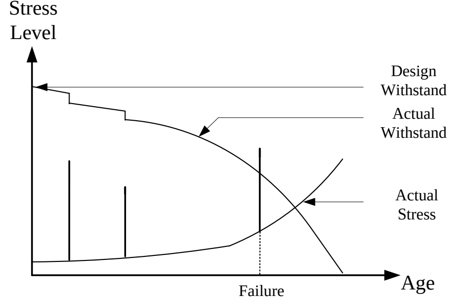


Figure 2 Transformer Ageing –related Failure Process

Transformer Thermal End-of-Life Prediction

The cellulose molecules are composed of long chains of glucose rings or monomers, and the DP value is used to describe the average number of glucose rings in the molecule[5]. The paper lowest DP value in a scrapped transformer is taken to calculate the average ageing rate *k*, as given in [6]:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = kt \qquad (2)$$

where DP_t is the DP value at age *t*, *t* is the elapsed service age, DP_0 is the initial DP when the paper is new. It is accepted that DP of 1000 indicates the new insulation paper and DP of 200 represents the exhausted paper [5, 6]. DP = 200 is set as the thermal end-of-life criterion. Assuming the average ageing rate *k* continues over the whole lifetime, transformer remaining thermal life is estimated.

61 transformers owned by National Grid have been scrapped [3]. Most of these transformer have the lowest DP higher than 200. Transformer thermal life is estimated as the sum of the service age before scrapping and the remaining life.

It should be borne in mind that thermal life differs from one transformer to another greatly, due to the differences of their loading condition, local ambient temperature and design & hotspot factor. It is also believed that not only temperature but also oxygen, acidity and moisture play important roles in thermal ageing.

Using thermal life data of scrapping transformers, the hazard function is derived according to Equation (1). Hazard increases from a fairly low value to 1 in an exponential mode $A\exp\left[B\left(t-t_0\right)\right]$, where A, B>0 and t_0 indicates the shortest thermal life. The thermal hazard curve indicates the ageing related failure risk.

Taking these scrapped units as a representative sample of the whole population, the derived thermal hazard curve is thus suggesting the hazard curve of the whole population.

Derivation of Population Failure Hazard Curve

During the normal operating stage transformer failure is determined by experiencing exceptional severe external/system events, thus the conditional probability of external/system event occurrence at age t, $h_{event}(t)$ represents the random failure mechanism. At the wear-out period transformer failure is dominated by the thermal aging of insulation paper, thus the conditional probability of insulation paper reaching DP=200 at age t, $h_{material}(t)$ represents the ageing failure mechanism. In Figure 4, (a) shows the two different failure mechanisms: random failure mechanism and thermal aging failure mechanism.

These two mechanisms are totally different and they are independent with each other. Random failure dominates at the early operating ages and can last till the ageing period, therefore transformer failure hazard is given as $h_{actual}(t) = h_{event}(t) + h_{material}(t)$, as given in Figure 4 (b) where the hazard is increased from the constant random failure hazard.

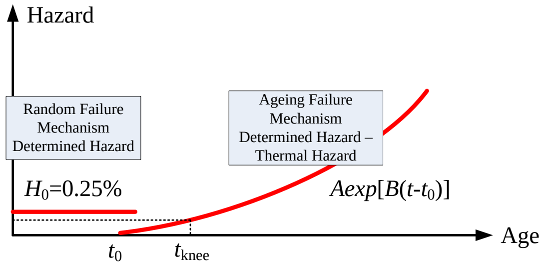
The conditional probability of external/system events $h_{event}(t)$ of a well-maintained network should be relatively constant and low thus $h_{event}(t)$ can be substituted by a constant H_0 along the transformer lifetime.

$h_{material}(t)$ represents the transformer failure risk when insulation deteriorates to a certain level, and thus can be represented by the thermal hazard curve.

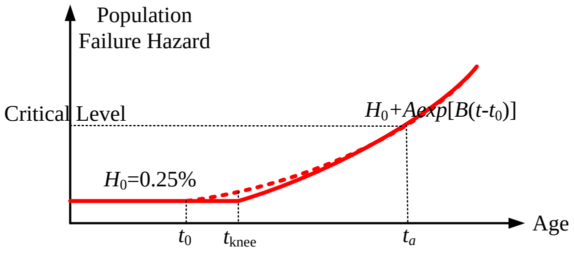
Supposing the UK transmission transformer's random failure hazard of 0.25% is representative, we can take the total conservative approach to use the point where the hazard becomes higher than 0.25% as the transition point which is also the point of t_0. t_0 is the shortest thermal life of transformer population.

By quoting the idea from [7], a knee point t_{knee} can be found in the thermal hazard curve where the increase of age can result in a certain level of increase of thermal hazard. This is an arbitrarily defined criterion which infers the critical increase rate of the number of transformers reaching DP = 200. Before the knee point t_{knee} thermal hazard is low and thus the value of population failure hazard is close to the constant external/system events conditional probability. The population failure hazard is substituted by the constant external/system events conditional probability H_0 up to age t_{knee}, and increases in the exponential model thereafter.

In asset management practice however, t_0 may not be the critical point that would be concerned. Asset managers predict the number of failure at each age in order to ensure the network reliability. The failure number, rather the failure mechanism is therefore critical for network secured operation. In other words the actual knee point age t_a in the population hazard curve infers a dangerous period start with too many failures that the system cannot afford. It could be later than age t_0.



(a) Hazard Determined by Two Failure Mechanism



(b) Population Failure Hazard Curve

Figure 4 Population Failure Hazard Curve Derivation

CONCLUSION

Transformer population failure hazard function is commonly used to predict the number of transformer failure in a future year so that the replacement scheme can be scheduled. Statistical analysis on historical data tends to be valid if the dominating failure mechanism prevails over the past and the predicting period. However, ageing failure mechanism differs from random failure mechanism and dominates aged transformer population in developed countries, therefore a transformer end-of-life model is needed in order to predict the number of failure and suggest the long-term capital investment.

The statistical analysis concerns the lifetimes of historical failures and service ages of active transformers. A constant failure hazard is derived during the normal operating stage dominated by the random failure mechanism. However ageing failure mechanism has not been observed but it is convinced that it does exist when the majority of transformer population is aged.

A physical ageing model is built based on scrapping transformer information. Lowest DP value of paper insulation from a scrapped transformer is used to determine individual unit's thermal lifetime. Thermal lifetimes of scrapped transformers are used to build up the thermal failure hazard curve representing the ageing failure mechanism.

The population hazard curve against age is produced by linking the ageing failure mechanism with statistical approach. It can be used by operators to identify the acceptable number of transformer failure that a system can tolerate while maintaining a secured operation.

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