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Approach for an integral power transformer reliability model

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SUMMARY

In electrical power transmission and distribution networks power transformers represent a crucial group of assets both in terms of reliability and investments. In order to safeguard the required quality at acceptable costs, decisions must be based on a reliable forecast of future behaviour. The aim of the present study is to develop an integral transformer lifetime model which involves degradation mechanisms for most relevant subsystems, applicable to individual power transformers and transformer populations. In this paper, we present a predictive model for power transformer reliability which involves three essential ingredients: failure statistics, physical understanding of the degradation process, and actual knowledge of the present condition. The model is based on evaluation of existing literature and past experience on degradation mechanisms, failure modes and diagnostic techniques. The model is illustrated for integral reliability of three transformer failure modes, related to the degradation of the transformer winding insulation, of bushings and of tap-changers. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: life estimation; paper insulation; power system reliability; power transformer insulation; power transformers; remaining life estimation

1. INTRODUCTION

For making substantiated decisions it is important to know the condition of the grid and its components. Condition information is crucial to make the expected performance quantifiable, and to make risks and costs predictable and controllable. Without condition information risks and costs may either be accepted, at the possible expense of reliability or availability, or prevented at the expense of additional safety margins and costs. Specifically, condition assessment may contribute significantly to make maintenance effective, efficient and on time, allows to postpone investments in a justified way and allows controlled overloading. Nowadays many condition assessment techniques are available to measure and evaluate condition information. Three observations can be made:

- Most techniques provide information on the present condition. Although this does allow for some extrapolation, there is a lack of techniques that are able to accurately predict future behaviour and performance.
- Moreover, most techniques focus on a single quantity, process or defect type, and not on the equipment as a whole.
- There is an increasing need to distil from all possibilities available the most appropriate set of techniques that provides sufficient and accurate information for a specific purpose (the purpose being, e.g. the need for maintenance, the optimum replacement time or strategy for an individual component or a population, the ability to endure overloading, and so on).

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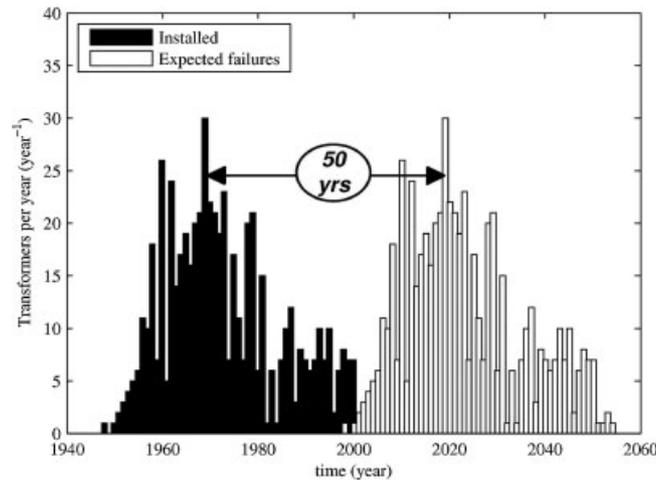†E-mail: p.a.a.f.wouters@tue.nl

Figure 1. The yearly installed power transformers and their assumed failures, e.g. after 50 years for two Dutch utilities. The total number of installed transformers for both utilities is 579.

For this reason the ultimate aim of the work here is to arrive at a model that will predict the future performance of an integral component in relation to the specific management question to be addressed: an integral lifetime model. The power transformer is a crucial component of the grid and is often mentioned in relation to quality or capacity issues. Firstly, the power transformer, next to cables and switchgear, often represents a capacity and reliability bottleneck. A second factor concerns the high costs caused by power transformer failure. A third factor involves the long delivery time of new power transformers, presently at least two years.

In the Netherlands large scale electrification took place from 1950 to 1970. This resulted in an installation wave of power transformers; for two Dutch utilities the yearly installed number of power transformers is depicted in Figure 1. If we assume that these transformers have an average lifetime of fifty years an increase of failures is expected in the 2000–2020 period. Fortunately, these trends are not observed yet. The failure of these components is, however, imminent and to counter its disastrous effects, knowledge is needed about the exact distribution of the failure wave. This challenge arises not only in the Netherlands, but in most industrialised countries [1–4].

According to the failure statistics reported by Cigré [5] the main failure mechanisms of power transformers are related to: tap-changer (41%), windings (19%), leakage (13%), bushings (12%), core (3%) and accessories (12%). Three main mechanisms which are not easily mitigated by, e.g. visual inspection (oil leakage) are selected for this paper. Paper degradation [6–8], bushing degradation [9–11] and tap-changer contact degradation [12,13], have been extensively studied in laboratories for the last two decades. These studies have provided insight in the behaviour of these degradation processes and which conditions will accelerate the process. However, the actual condition of a transformer can at present not be predicted by these models, because the models are obtained from controlled laboratory experiments. This paper presents a model where available data of various origins can be combined. After presenting the generic technical reliability model in Section 2, three failure modes are discussed in Section 3: transformer winding insulation failures, bushing failures and tap-changer failures. An integral reliability approach is discussed in Section 4 both for individual assets as for an entire transformer population.

2. TECHNICAL RELIABILITY MODEL

A technical reliability model aims to provide information on the technical condition and the way it changes over time. Such a model predicts the condition in terms of the probability that a component can perform its designated function. Basically, the state of a component evolves from a state at time t into a state at time $t + dt$. The technical reliability is extracted from the condition quantities. These condition
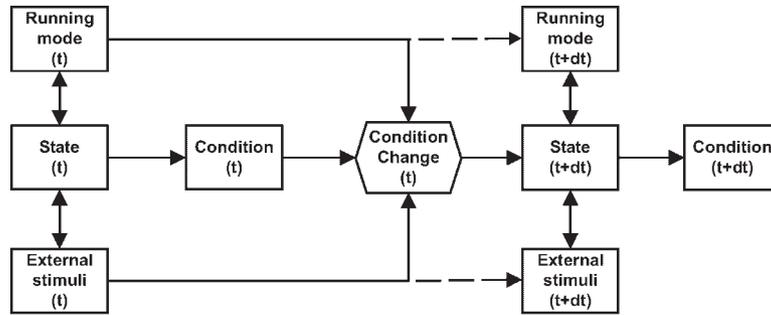
Figure 2. The process of condition change, with the actuators and the resulting state.

quantities are influenced by the condition change processes, and their outcome is the result of the previous state and the condition change process. The influence of the several actuators on the condition change process is graphically represented in Figure 2. These actuators are the running mode and the external stimuli. The running mode includes operation modes relevant to the condition change. The condition may not only deteriorate, e.g. by ageing, but may also improve owing to maintenance. It can be controlled by operational measures. External stimuli, e.g. weather, short circuits and the social environment, are influences out of direct control of the asset manager.

A schematic representation for a defect, fault and failure is depicted in Figure 3. If the condition is less than the design specifications, the component is in a defective state. A faulty state occurs, if one or more functional requirements cannot be fulfilled anymore. Having a faulty state does not immediately imply a failure. Failure still requires a trigger, and depending on the force of the trigger and the gap between specified and actual condition level the component may fail. Physical models presented in this paper actually involve the prediction of the occurrence of a faulty state. Reliability analysis based on statistical data relate usually to actual failure of the component.

Components having similar properties can be grouped to form a population of power transformers. Component reliability on a population level can address questions on optimum maintenance strategy, replacement strategy or on estimating the overall reliability of a population. To determine the reliability of a population of power transformers, two general approaches are available: statistically based forecasting and individual forecasting.

- A statistically based approach uses data available from the past to predict the short term reliability of this group of assets [14,15]. These methods predict the future based on only the past performance and fail when actual and future operational and environmental parameters deviate from the historical data.
- A more flexible way of obtaining information on a fleet of components is the degradation modelling approach, as discussed in Section 4. In this approach the reliability of each individual item is calculated, after which the reliability of the population as a whole is derived.
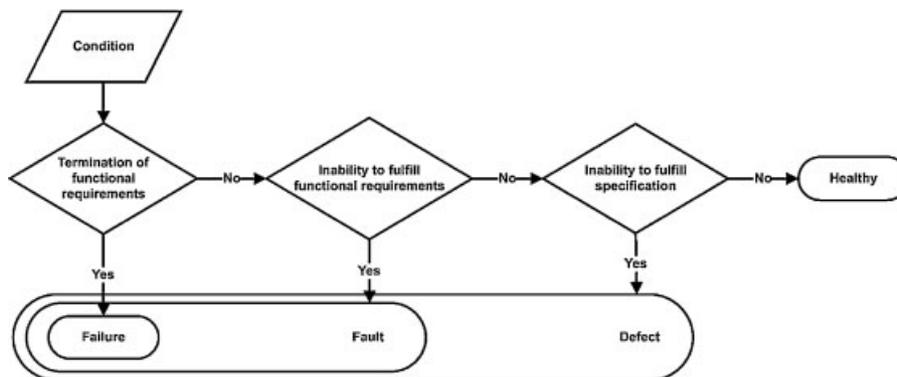

Figure 3. Interaction of condition change effects and their sequential appearance.

These methods can be combined by applying different techniques for different subcomponents of the power transformer.

3. MAIN POWER TRANSFORMER FAILURE MODES

In this section paper winding insulation, bushings and tap-changer are considered as potential causes of transformer failure and it is discussed how the condition of these subcomponents can be assessed. Quality parameters (QP, Ref. [16]) are defined as those quantities that can be assessed to retrieve the condition of a (sub)component. They either give direct information like the degree of polymerisation (DP) on the insulation paper or indirectly if, e.g. partial discharge (PD) activity is measured at bushings or contact resistance is used as a measure of the tap-changer condition. Besides these QPs that give explicit information on the assets, methods are used where from experience a lifetime is estimated and a loss of life is estimated based on the transformer loading (e.g. employed in loading guides, Refs. [17,18]). The choice for a QP is determined by the availability of measuring options and models, their accuracy and their representability. For power transformers the choice for technically and economically feasible QPs is limited.

3.1. Paper insulation

Transformer paper provides electrical insulation between windings. The quality of the electrical insulation is mainly determined by its mechanical strength. The ageing of the paper is accelerated by high temperature, high water content, and acidity. Information on the DP value is obtained by oil analysis on dissolved furans. The decline in DP value is a result of a cascaded chemical reaction resulting in the scission of the cellulose chains.

A simplified temperature dependency model of the DP-value is given by the Arrhenius relation, as is extensively discussed in among others [6,7]. This has led to the following relation:

$$\frac{1}{DP(t)} - \frac{1}{DP(0)} = \int_0^t k(\tau)d\tau \tag{1}$$

where $DP(t)$ is the DP-value at time t, $DP(0)$ is the initial DP value and $k(t)$ is the time dependent reaction rate

$$k(t) = A\exp\left(-\frac{E_a}{R_g T(t)}\right) \tag{2}$$

Here E_a is the molar activation energy, R_g the universal gas constant, A a process constant and T the absolute temperature. Values for the process parameters obtained from Ref. [7] are given in Table I. The reliability is obtained by integration over all DP-values, indicated by ν, according to

$$R_i(t) = 1 - \int P_{th}(\nu)p_{dp}(\nu, t)d\nu \tag{3}$$

Table I. Data to calculate the mean-residual-life of Kraft and thermally upgraded paper, according to Ref. [7].

Winding insulation paper	A (hour^{-1})	E_a (kJ/mol)	DP(0)
Kraft	2.0×10^8	111	1000
Thermally upgraded	0.67×10^8		

Here p_{dp} is the distribution density function of the DP-value and P_{th} the probability that the transformer will fail with a specific DP-value. To estimate the uncertainty in the reliability an error estimation technique is used, which is discussed elsewhere [19–22].

As an example the model is applied to a machine transformer with a rated power of 105 MVA, a rated primary voltage of 141 kV and secondary voltage of 10.5 kV. Although the transformer did not fail directly by a low tensile strength of the paper–oil insulation but rather by a winding short-circuit, data on the actual hot-spot DP-value became available and is used to evaluate the model. For temperature T the hotspot-value of the IEC loading guide [17] is used given by

$$\theta_h = \theta_a + \Delta\theta_{or}\left(\frac{1 + RI^2}{1 + R}\right)^x + \Delta\theta_{hr}I^y \tag{4}$$

where I is the time dependent relative load per unit. Its thermal parameters are listed in Table II (oil exponent x; winding exponent y; loss ratio R; ambient temperature θ_a; hotspot to top-oil gradient θ_{hr}; and top-of-tank oil rise $\Delta\theta_{or}$).

The transformer winding insulation material, Kraft paper, has an initial DP-value of 1200, but after drying the DP-value drops to about 1000. For the DP-threshold paper insulation has a critical condition around a DP value of 250. Data on load pattern and ambient temperature were recorded as two hourly values measured on 24 days. This data was available for a limited number of days, spread out over a period of almost 2 years. By extrapolation, shown in Figure 4, a complete pattern was estimated for dynamical modelling of the reliability. The expected DP-values are represented by a solid line in Figure 5. The dotted lines define the one σ confidence margins (see for details [21]). The calculated DP-value at the time of failure after 15 years of operation is 468 with a standard deviation of 25%. The actual measured DP-value of 454 ± 23 is indicated in the plot as well.

Table II. The thermal characteristics of the machine transformer of Section 3.1 and of a typical ONAN transformer according to Ref. [18].

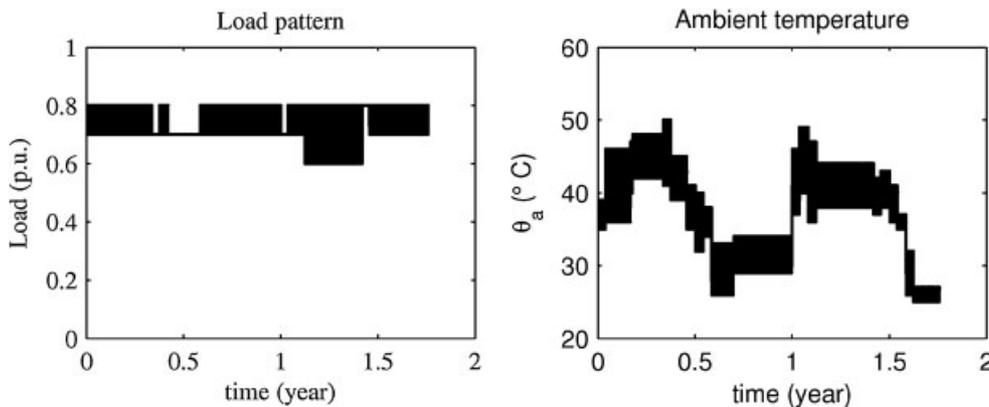| Cooling	R	$\Delta\theta_{or}$ (°C)	$\Delta\theta_{hr}$ (°C)	x	y
ONAF	5.7	48	14.3	0.9	1.6
ONAN	6.0	52	26.0	0.8	1.3

Figure 4. Load pattern and ambient temperature of the machine transformer. The width of the lines corresponds to the cyclic variation within each day.
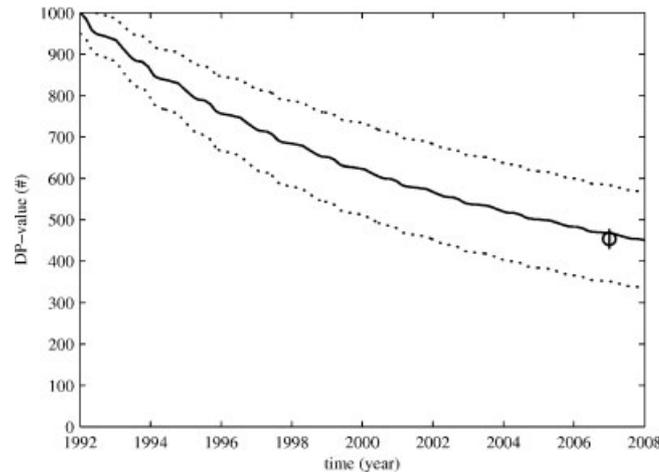
Figure 5. The machine transformer paper degradation calculated for dry Kraft paper. The circle indicates the lowest measured DP-value from a sample with its error bar; the dotted lines show the 68% error margin of the simulated result.

3.2. Bushing

The high voltage conductor is insulated from its surroundings by a bushing. Within the bushing the electrical fields are capacitively controlled to prevent breakdown. Breakdown may occur due to insulation degradation and subsequent short circuits in between the capacitive layers. Another potential hazard is over-heating by increasing bushing losses. The most common detection methods are the power factor test and the capacitance measurement [23]. Regular visual inspection and proper repair can mitigate failures from causes like oil leakage or pollution. In paper–oil bushings the quality of the oil and paper can be analysed. Early signs of possible breakdown can be provided by PD measurement.

Long term degradation of bushing insulation is related to deterioration of the insulating material of the bushing. In Refs. [9,10] it is observed that the electrical breakdown voltage and the dissipation factor of the paper insulation changes with time due to ageing. Thermal ageing gradually degrades these QPs and the loss of electrical insulation quality lowers the voltage withstand capability.

A physical model is presented, which allows for a similar probabilistic approach as applied to paper degradation in Section 3.1. To model thermal breakdown, the heat generated in the dielectric insulation and the conductor, and the maximum allowable temperature of the insulation material, must be known. The temperature inside a bushing can be modelled according to the IEEE bushing guide [24]:

$$\theta_{hb} = K_1 I^z + K_2 \Delta\theta_o \tag{5}$$

with I the per unit rated bushing current, $\Delta\theta_o$ the oil temperature rise with respect to the ambient temperature and z, K_1, K_2 bushing type dependent constants. Besides the conductor losses the dielectric bushing losses can significantly contribute (reviews accompanying [24–26]). The influence of high temperatures at nominal electric field stresses were addressed in Refs. [10,27]. Basically, the effect of the field strength is incorporated by lowering the activation energy in an Arrhenius type reaction:

$$k = A\exp\left(-\frac{E_a - c|E|}{R_g T}\right) \tag{6}$$

with $|E|$ the applied electric field strength and c a process dependent constant. The modelling techniques from Section 3.1 can be adopted to obtain failure rates caused by bushing degradation.

A statistical approach is pursued by consulting sources of statistical data on bushing failure in the Netherlands. The Dutch 'CenTram' database incorporates information of 2383 transformers of which 2009 transformers are in operation [21]. The active transformers have an average age of 31 years; this adds up to a cumulative operational life of 62 000 years. Since 1970, nine bushing failures are reported, two of which were non repairable. The failure causes are, however, not filtered by type of failure.

Table III. Weibull parameters (scale factor α and shape factor β) for statistical failure data and the corresponding MTTF for bushing and tap-changer.

Source	α	β	MTTF
CenTram database [21]	2418	1.3	2243
Switchgear bushings [15]	211	3.2	189
Tap-changer [30]	109	2.4	97

Therefore, failures caused by ageing are observed next to those caused by for instance vandalism. Also the data from switchgear bushings were analysed [15]. The results of a Weibull fit, together with the mean time to failure (MTTF) is given in Table III. The number of failures is small compared to the size of the population, limiting the accuracy of the Weibull parameters. However, the very long MTTFs found agree with the impression expressed by Dutch utilities that bushing failures have hardly any impact on the overall transformer failure rate [21].

3.3. Tap-changer

With the tap-changer the output voltage of the transformer can be regulated. Its functioning may be endangered by unsynchronised switching of the tap-selector and power-switch due to a broken axis or malfunctioning engine. An online monitoring system has been developed to detect failure of the axis [28] consisting of two sensors, which detect synchronous operation of the cylinder alone and the combination motor and cylinder. Another failure mechanism is related to polluted contacts in the tap-changer. The deterioration of the contacts can be detected by regular off-line inspection of the tap-changer. Inspection includes contact resistance measurement of the different taps of the tap-changer [29]. Because of the carbon deposits on the contacts, arcs may occur upon switching leading to floating copper or silver particles in the oil. Therefore DGA and PD methods in principle can assess the status.

A malfunctioning motor and a cylinder breach are sudden events. Only the carbon formation involves gradual ageing, which can be detected in an early stage by proper diagnostics. Models are under development for the oil/carbon film growth. These models assume that either the present degradation rate can be extrapolated to obtain mean time to failure or a empirical expression is employed to describe the growth in layer thickness (in nm) as function of contact surface temperature (in °C) and time (hours), e.g. for 'Shell Diala D' oil [13]:

$$s = 1.883 \times 10^{-7} T_{\mathrm{c}}^{3.862} t^{0.3559} \tag{7}$$

As techniques mentioned above are still under development, most reliable information is extracted from databases [30]. A statistical model based on a Weibull distribution, similar to the statistical bushing model of Section 3.2, results in an MTTF of 97 years (Table III).

4. INTEGRATION PAPER INSULATION, BUSHINGS, TAP-CHANGER RELIABILITIES

The reliability of a system depends on its subcomponents and their interactions. We will assume that the failure modes discussed in the previous section act independently. This means that the overall transformer reliability can be obtained from the product of individual subcomponent reliabilities. Further, no distinction is made between fault and failure, assuming that a faulty state more or less directly evolves into a failure. In fact, a faulty state is an unacceptable situation from an operational point of view.

4.1. Integral failure model for individual transformer

If either paper insulation or bushing or tap-changer fails the complete transformer will fail. For paper degradation the model described in Section 3.1 is used. The individual failure rates for bushing and tap-

changer are derived from statistics of these populations [15,30] as discussed in Sections 3.2 and 3.3. The integral modelling is exemplified using the following parameters:

- The paper ageing model is applied on an ONAN cooled transformer with the parameters given in [17]. The paper ageing parameters for Kraft paper are as given in Table I according to Ref. [7]. The ambient temperature of this transformer is 20 °C and the load is taken as 0.7 and 0.8 p.u.
- The Weibull parameters of the 50 kV switchgear bushing failures are taken from Section 3.2.
- The tap-changer Weibull parameters are extracted from the statistical model of Section 3.3.

The subcomponent reliabilities are depicted in Figure 6. Clearly bushings have a higher reliability than the other components and do not affect the total reliability. The tap-changer reliability in this example lies between the reliability of paper insulation with 0.7 and 0.8 p.u. load. Note, that the physical processes behind the bushing and tap-changer reliability curves should be load dependent. This information is lost by using statistical based curves.

In Figure 7 the combined reliability is calculated both for the 0.7 and 0.8 p.u. loaded transformer. Clearly, the integral reliability is always smaller than the worst case reliability of the subcomponents, due to the series topology of the subcomponents, but is close to the worst case reliability. For loads in the order of 0.8 p.u. or higher, the paper degradation mechanism dominates the total failure rate. For a load below 0.7 p.u., the overall transformer reliability is similar to the statistical tap-changer reliability. This result aligns with the practice of power transformers in the Dutch transmission grid, where the majority of transformers fail due to tap-changer related problems [5,31].

4.2. Failure model for population transformer subcomponents

To illustrate how individual reliability results can be used to obtain the reliability of a transformer population, it is applied to the paper winding model in Section 3.1. The method assumes that the individual reliabilities, R_i, are uncorrelated. Population analysis can be based on decomposition by considering the following recurrent relation for the reliability [32]:

$$R^{(i,j)}(t) = \left(1 - R_j(t)\right) \times R^{(i,j-1)}(t) + R_j(t) \times R^{(i-1,j-1)}(t) \tag{8}$$

The superscript (i, j) indicates that at least i out of j transformers are still operational. The probability that at least i out of a set of j transformers are operational is equal to the probability that the 'last' transformer j has failed and from the remaining $j - 1$ at least i transformers work, plus the probability that transformer j is in working order and a minimum of $i - 1$ of the rest are operational. The begin and
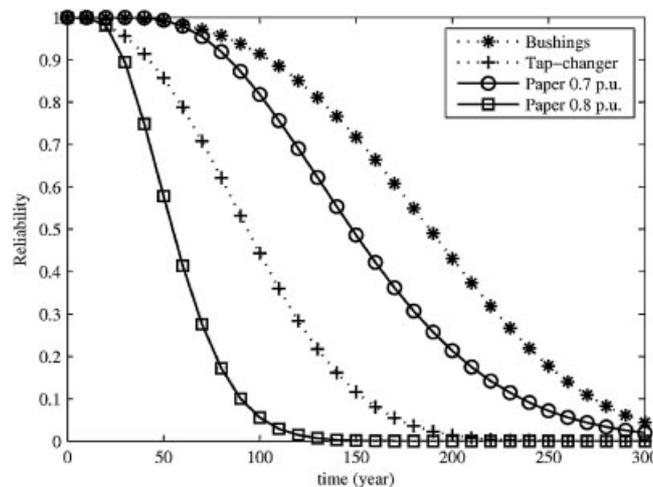

Figure 6. Individual reliabilities of the subcomponents of a power transformer. The bushing and tap-changer curves are obtained from Weibull fits; the paper ageing reliability is obtained with the model of Section 3.1.
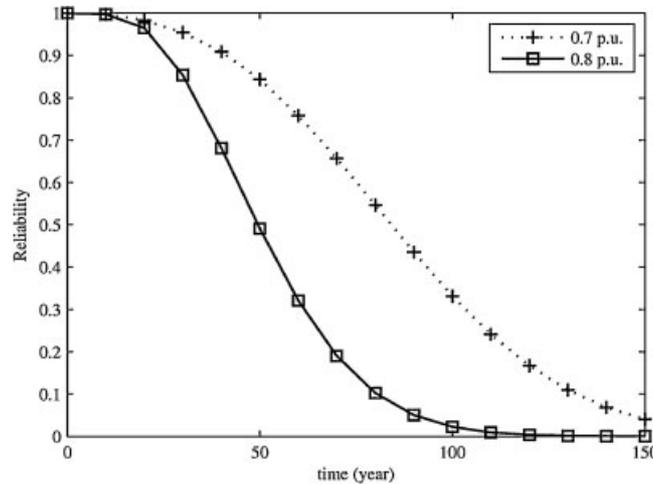
Figure 7. The integral transformer reliability based on Weibull fits for bushing and tap-changer and the paper degradation model shown in Figure 6.

end condition of Equation (8) are $R^{(0,j)} = 1$ and $R^{(j+1,j)} = 0$. A nice property of this technique is that the results for up to $j-1$, $j-2$, etc. are directly available as intermediate result of the recurrent analysis. From Equation (8) the mean-time-to-failure (MTTF) of the failure of m transformers, MTTF_m, can be written as

$$\text{MTTF}_m = \int_0^\infty R^{(N-m+1,N)}(t)\mathrm{d}t \tag{9}$$

Equation (9) links the time with the population reliability. The population reliability R_P belonging to the MTTF_m is defined as

$$R_\text{P}(t = \text{MTTF}_m) = \frac{N-m}{N} \tag{10}$$

As an example, the population reliability of a fixed load growth for the transformer fleet of two Dutch utilities, shown in Figure 1, is analysed for paper winding insulation [20,21]. The average initial load was estimated to be 0.4 p.u., and a load growth was assumed of 1.5%, 2% and 2.5%. Next, a fixed load growth of 2% was taken and 0.25, 0.4 and 0.5 p.u. was taken for the initial load. In reality the actual dynamic load with its large variations should be accounted for. Time spans with up to nominal transformer loading will increase in future, which is expected to have a comparable effect as the fixed growth values taken in the examples. The results of the simulations are shown in Figure 8a and b, respectively. Next to the observation that the lifespan gets shorter with increasing load growth, it is observed that an exponential growth tends to disguise the original population distribution. Due to the relatively low initial load, all transformers reach their rated power in a relatively short time. In Refs. [20,21] it is shown how this approach allows determining consequences of maintenance and replacement strategies.

4.3. Integral transformer population failure model

In forming a reliability for a population that consists of assets with subcomponents, there are two options. For the first option, the subcomponent reliabilities are combined to integral component reliabilities for each transformer. Next, the population reliability is extracted from these individual reliabilities. Calculating the population reliability from the individual component perspective provides the possibility to select transformers which are expected to fail soon, due to one of its subcomponents. The second option focuses on determining the population reliabilities filtered on subcomponent.
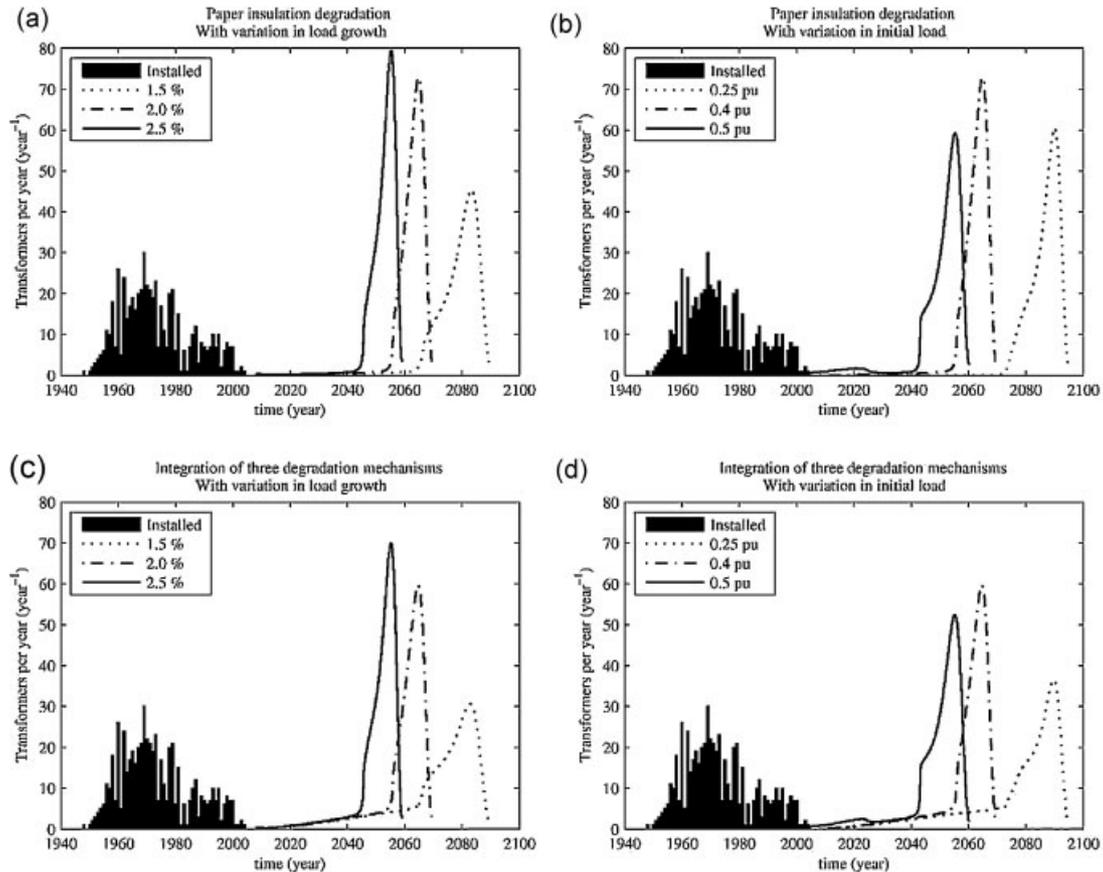
Figure 8. Transformer installation dates and the expected failure waves for a load growth of 1.5%, 2% and 2.5% (a,c) and an initial load of 0.25, 0.4 and 0.5 p.u. (b,d). In the top figures (a,b) only paper insulation degradation is taken into account; in the bottom figures tap-changer and bushing failure are included as well.

Extraction from the main failure cause may aid in determining the future focus for maintenance and revision programs. The second option can be applied by taking the paper winding failure of Section 4.2 and combine it with the statistical bushing and tap-changer distributions. This population reliability can be determined from

$$R_{\text{P,tot}} = R_{\text{P,bushing}} \times R_{\text{P,tap-changer}} \times R_{\text{P,paper}} \tag{11}$$

The result is shown in Figure 8c and d for the situations described in Section 4.2. It is observed that the early failures are related to tap-changers, but after longer time the paper insulation takes over, due to the growing load and consequently the increased paper ageing. This is in accordance to the failure statistics reported by Cigré [5] and the statistical analysis given in Ref. [30] on a fleet of several hundreds 50/10 and 50/6 kV transformers. The latter study shows at present an about 50% higher tap-changer failure rate, but the increase in failure rate for winding insulation is larger.

5. CONCLUSION

Technical reliability is defined as the probability that a component or a system performs its designated task. The concept of quality parameters was introduced to assess to a degradation process. For paper winding insulation the DP value can successfully be employed to predict and verify the paper ageing process. It demands, however, knowledge of its past, present and future operational parameters to make

an educated guess of the probability of future failure. For other subcomponents, like bushings and tap-changers, appropriate quality parameters are harder to find for which proven models exist. Failure statistics can be used instead. The statistical data of the bushings and tap-changers on the other hand are based on the population failure data censored on the failure cause. For instance, the bushing reliability provides insight on the quality of this subcomponent without considering its unique stress history. The statistical information does not differentiate between the probability of failure of a heavily polluted bushing and its clean counterpart.

The integral model presented is able to combine different sources of information on different subcomponents. Also it can be applied to estimate the reliability of a single asset as well as a large fleet of similar assets. Reliability forecast is always hampered by uncertainties in the degradation process parameters and in the operational conditions. For physical ageing processes, as the paper winding degradation, an uncertainty analysis is included [19–21]. Besides knowledge on the uncertainty itself, this analysis informs on the most critical factors determining this uncertainty. By diagnosing, e.g. DP measurement on a transformer, the actual information on transformer paper condition can be updated, narrowing down the uncertainty and even allowing for updating the degradation parameters of the model to improve future predictions.

6. LIST OF SYMBOLS AND ABBREVIATONS

6.1. Symbols

A	pre-exponential factor of Arrhenius rate
c	constant for electric field effect on activation energy in bushings
$DP(t)$, $DP(0)$	degree of polymerisation at time t and its initial value
$|E|$	applied electric field strength
E_a	activation energy of Arrhenius reaction rate
I	per unit current
K_1, K_2	hotspot temperature constants in IEEE bushing guide
$MTTF_m$	mean time to failure of up to m transformers
N	total number of assets in population
$p_{dp}(v,t)$	probability density function for DP value v at time t
$P_{th}(v)$	cumulative threshold distribution for DP value v
R	loss ratio in IEC loading guide hotspot temperature
R_g	molar gas constant: 8.314 J/K
$R_i(t)$	reliability for (sub)component i at time t
$R^{(i,j)}(t)$	probability that at least i out of j transformers are operational at time t
T	absolute temperature in reaction rate
T_c	temperature contact surface tap-changer in °C
$k(\tau)$	time dependent reaction rate
s	oil/carbon layer thickness in nm
x, y, z	constants accounting for current dependencies of hotspot temperatures
θ_h, θ_a	hotspot winding temperature and ambient temperature
$\Delta\theta_{hr}$, $\Delta\theta_{or}$	hotspot to top-oil gradient, top-of-tank oil temperature rise
θ_{hb}, $\Delta\theta_o$	bushing hotspot temperature and oil temperature rise with respect to ambient

6.2. Abbreviations

CenTram	CENtre for Transformer Reliability, Availability and Maintenance
Cigré	Conseil International des Grands Réseaux Électriques
DP	degree of polymerisation
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
MTTF	mean time to failure
ONAF	oil-natural-air-forced transformer cooling

ONAN   oil-natural-air-natural transformer cooling
PD   partial discharge
QP   quality parameter

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