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An approach on lifetime estimation of distribution transformers based on degree of polymerization

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ABSTRACT

Lifetime of oil-immersed transformers is highly dependent on condition of paper insulation. This contribution is aimed to quantify the deterioration and ageing process of the paper insulation of distribution transformers based on degree of polymerization (DP). The proposed approach involves real operating conditions of a transformer such as variable ambient temperature, load factor, and moisture content of the paper insulation through calculation of hot-spot temperature to estimate remaining lifetime of the transformers. The results indicate that a DP profile obtained based on actual conditions is completely different to that usually discussed in other researches under completely constant conditions. Consequently, the proposed dynamic DP model could predict lifetime of the transformers more precisely based on real-time measurable quantities. In addition to the remnant lifetime estimation, the proposed dynamic DP profile is utilized to suggest the optimum time for implementing reductions in moisture content of the paper insulation through three scenarios regarding the practical limitations. Finally, reliability of the transformer is evaluated based on statistical data.

1. Introduction

Power transformers are among the most expensive and important components in power systems. Therefore, condition assessment of these worthy components has been the main subject of many researches. Solid and oil insulation of transformers are the two dominant factors limiting transformers lifetime. Quality and condition of the oil insulation can be monitored either online or offline due to possibility of a rather convenient access to the oil. However, this access for the paper insulation is not as straightforward as it is for the oil. In this regard, two methods based on thermal modeling and cellulose degradation kinetics have been developed for indirect assessment of the paper insulation [1]. Moreover, it has been discovered that condition of the transformer can be evaluated through its insulation ageing byproducts such as methanol [2,3] and 2-furfural [4] as well as mechanical [5] and chemical [6] indicators.

Looking for a precise non-invasive method for assessment of oil-immersed transformers is always welcome. Therefore, this contribution aims to estimate lifetime of the paper insulation of oil-immersed transformers based on the cellulose degradation kinetics because of its comprehensiveness in considering various parameters that contribute to the paper deterioration. Note that lifetime of the paper insulation can be considered as the life span of the transformers. The paper insulation used in the transformers is either Kraft or thermally upgraded Kraft (TUK) paper that is mainly composed of cellulose [7–9]. The average number of glucose rings in a cellulose molecule is called degree of polymerization (DP) [8]. Earlier studies [8] indicated that water, oxygen, and heat are the three factors that contribute to the paper degradation, and thus result in a decline in the DP value. Further experiments revealed the significant effect of low molecular weight acids in hydrolysis process [10,11].

Initial DP value for a new transformer lies within the range 1000–1250 [7]. An end-of-life criterion for transformers is usually defined when DP reaches 200 [7]. This DP value is associated with 70% reduction in the initial tensile strength of the paper [7]. Nevertheless, higher DP values can be considered for the end-of-life criterion to increase reliability of the transformer.

Emsley and Stevens [12] utilized the following relation to determine DP value after a specific time:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = Ae^{-\frac{E_a}{RT}}t \quad (1)$$

where t is the time in hrs, DP_t and DP_0 are DP at time t, and initial DP, respectively, A is a constant in hrs^{-1}, E_a is activation energy in J mol^{-1}, R is the gas constant (8.314 J mol^{-1} K^{-1}), and T is the temperature (hot-spot) in K. To date, several researches [11–15] have attempted to

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evaluate the effects of the aforementioned detrimental factors on the paper insulation. Those researches have been conducted under completely constant conditions in view of hot-spot temperature (HST), moisture, and oxygen content. Obviously, these parameters are not constant over time due to variations in the environmental and operating conditions of the transformers in the real world. Therefore, applying the life expectancy curves presented in [11–14], which are based on constant conditions, will not provide an acceptable estimation of the transformer lifetime. The life expectancy curves in [11–14] show the lifetime of the paper insulation within a range from 0.1 to 1000 years. However, a typical transformer has a lifetime up to a few decades. Hence, a new approach is required for lifetime estimation based on (1). It has been demonstrated in [16] that considering the effect of cumulative moisture content results in a more realistic DP profile than the profile obtained under completely constant conditions. However, the joint effect of increasing moisture content and time varying HST has not been studied in [16–18].

It has been comprehended that the index of the DP is a well-known and applicable criterion for non-invasive assessment of the transformers. However, ignoring the dynamic behavior of the paper degradation parameters leads to an over/under lifetime estimation. This paper clearly indicates how the results could be far from each other while practical concerns are omitted. The novel contribution of this paper is considering the real operating circumstances of a transformer including ambient temperature, load factor, and moisture content of the paper in the lifetime estimation based on DP values, which have not been included in the previously proposed lifetime estimation models [19,20]. In addition, instead of considering a constant value for the load factor like in [19], a dynamic load factor pattern is applied in this study. Moreover, it is demonstrated in this contribution that the DP profile of an actual transformer is completely different form the profiles obtained under accelerated ageing tests in [9–11,21].

The outcome of this paper provides a new insight into the behavior of DP profile in the light of real condition for real-time estimation of the transformers lifetime. In addition, the proposed dynamic model is utilized for the lifetime estimation purposes of transformers and assessing the optimum time to implement a reduction in the moisture content of the transformer. The method can ultimately be incorporated into a condition-based maintenance program to help power system operators in increasing life span of the in-service transformers in the power grid [22,23]. Note that power distribution grid as a large scale system has been analyzed in terms of maintenance planning [24,25] and failure rate [26–28]. However, this paper focuses on life management of distribution transformers as key components of a distribution grid.

In the following, the quantification of deterioration process as well as the effective parameters on this process and how they are involved in the model have been presented. The next section deals with a case study with real data from Helsinki. Having presented the dynamic model, it is used to suggest the optimum time of the moisture reduction to extend the lifetime of distribution transformers. Finally, a formula is represented to calculate reliability of the transformers based on statistical data derived from prominent surveys.

2. Ageing model of oil-immersed transformer's paper insulation

In this paper, deterioration of the paper insulation is evaluated using (1). However, a recursive form of the above-mentioned relation, similar to what has been proposed in [16], is applied to enhance the accuracy of the calculations, which is as follows:

$$\frac{1}{DP_{(n)}} - \frac{1}{DP_{(n-1)}} = A_{(n-1)}\, e^{-\frac{E_{a(n-1)}}{RT_{(n-1)}}} \times (t_{(n)} - t_{(n-1)}) \tag{2}$$

where the index n represents the iteration stage. The first and final DP values for the corresponding iterations are considered equal to 1000 and 200, respectively [7]. Since the parameters of (2) are updated in hourly steps, the period of each iteration is one hour. The cumulative time of iterations yields the lifetime of the transformer. It should be noted that the DP calculations are conducted for the part of the paper insulation that is located in vicinity of the transformer hot-spot, where the lowest value of DP is expected due to the highest rate of degradation. Monitoring of this citron has been recognized as an old-fashioned method to evaluate the ageing process of the papers used in the transformers. However, the approach in previous investigations was established based on a constant condition in an experimental environment. This static viewpoint is not precise for the lifetime prediction of the transformers in reality. As it is shown in Fig. 1, the significant parameters in deterioration procedure of the transformers are moisture, oxygen level of oil/paper as well as loading and ambient temperature. While the moisture and oxygen level have been involved via E_a and A, the loading and ambient temperature have been involved through hot-spot in the model. In response to this, the following subsections are dedicated to the method applied for obtaining the parameters of (2) to clarify how the practical concern could be involved in the model. The correlation between real conditions such as variations in load, moisture, ambient temperature, and HST, E_a and A enables us to provide a dynamic ageing model for precise condition assessment of papers used in oil immersed transformers.

Fig. 1. The main players in the ageing procedure of oil-immersed transformers.

2.1. Hot-spot temperature

Ambient temperature and load factor are variable during lifetime of distribution transformers. These are the two dominant factors that cause variations in the HST and it could highly affect the ageing process. Therefore, a dynamic thermal model is required to calculate it at each iteration of (2). The method presented in the IEC standard [29] is implemented for calculating the HST. In the IEC method, the differential equations for calculating the HST have been converted into difference equations to make the calculations as convenient as possible. This simplification comprises a constraint that is satisfied when the time step of calculations is not greater than one-half of the lowest time constant available in the model [29]. Since the lowest time constant of the IEC method is 2 min, the time step for HST calculations is considered equal to 1 min.

Input parameters of the difference equations are the ambient temperature, load factor, rated power, and cooling type of the transformer. Predetermined values of the constants applied in the model are available in [29]. The difference equations are as follows [29]:

$$D\theta_o = \frac{Dt}{k_{11}\tau_o}\left(\left(\frac{1+K^2R}{1+R}\right)^x \times (\Delta\theta_{or}) - (\theta_o - \theta_a)\right) \tag{3}$$

$$\theta_{o(n)} = \theta_{o(n-1)} + D\theta_{o(n)} \tag{4}$$

$$D\Delta\theta_{h1} = \frac{Dt}{k_{22}\tau_w}(k_{21} \times \Delta\theta_{hr}K^y - \Delta\theta_{h1}) \tag{5}$$

$$D\Delta\theta_{h2} = \frac{Dt}{(1/k_{22})\tau_o}((k_{21}-1) \times \Delta\theta_{hr}K^y - \Delta\theta_{h2}) \tag{6}$$

$$\Delta\theta_{h(n)} = \Delta\theta_{h1(n)} - \Delta\theta_{h2(n)} \tag{7}$$

$$\theta_{h(n)} = \theta_{o(n)} + \Delta\theta_{h(n)} \quad (8)$$

where,

D Difference operator.
θ_o Top-oil temperature, °C.
t Time, min.
k_{11}, k_{22}, k_{21} Thermal model constants.
τ_o Average oil time constant, min.
K Load factor.
R Ratio of load losses to no-load losses.
x Oil exponent.
$\Delta\theta_{or}$ Top-oil temperature rise in steady state, K.
θ_a Ambient temperature, °C.
$\Delta\theta_h$, $\Delta\theta_{hr}$ Hot-spot to top-oil gradient at the considered load and at the rated current, respectively, K.
τ_w Winding time constant, min.
y Winding exponent.
θ_h Hot-spot temperature (T in (2)), °C.

Value of the constants $x, y, k_{11}, k_{21}, k_{22}$, and τ_w are determined based on the cooling type of the transformer. A detailed discussion about ambient temperature and load factor data is provided in Section 3.

2.2. Value of a parameter and activation energy (E_a)

The moisture and oxygen could highly affect transformer ageing process. Value of A depends on the environmental conditions of the paper insulation such as moisture and oxygen content. The method for obtaining A-value involves defining reaction rate K, as follows [12]:

$$K = Ae^{-\frac{E_a}{RT}} \quad (9)$$

Afterwards, plot of ln(K) against $1/T$ yields a line with a slope of -E_a/R and an intercept equal to ln(A). Various environmental conditions result in lines with different slopes and intercepts. Several experiments have been accomplished to attain the empirical data for values of E_a and A [11–14]. In this paper, the A-values presented in [13,14], which are a combination of various experimental results for three oxygen levels (low oxygen level, below 6000 ppm, medium oxygen level, 7000–14,000 ppm, and high oxygen level, 16,500–25,000 ppm) are used.

Table 1 shows six polynomial functions that have been developed in [16] based on the data in [13,14] for both Kraft and TUK papers to obtain value of 'A' at each iteration of (2) as follows:

$$A = x_1m^3 + x_2m^2 + x_3m + x_4 \quad (10)$$

where m in the paper moisture content in percent, and value of x_1, x_2, x_3, and x_4 parameters are listed in Table 1 for different oxygen levels and paper types. It is worthwhile to mention that the activation energy E_a, is 111 kJ mol^{-1} for the A-values calculated by (10) regardless of the oxygen level.

As it can be seen from Table 1, the water content along with the oxygen level have to be available to determine the corresponding A-value. A procedure for attaining moisture content of the paper is to install a capacitive probe inside the transformer oil tank. This probe provides moisture content relative to saturation level of the oil insulation [30]. Applying this value to the equilibrium curves in [30] yields the moisture content of the paper insulation. Although an equilibrium between the water content in the oil and in the paper is hardly reached, continuous monitoring of the moisture along with the temperature at limited areas having slow oil flows makes this procedure applicable in practice [30,31]. To cope with these difficulties and due to the fact that such a huge amount of data on moisture content of the paper insulation is not available for lifetime of a transformer, an alternative approach is adopted.

Table 1
Coefficients required to obtain value of the A parameter.

Type of paper	Oxygen level	x_1	x_2	x_3	x_4
Kraft	Low	1.0E+5	1.7E+8	1.0E+8	5.3E+7
Kraft	Medium	2.3E+6	-3.6E+6	1.2E+9	-2.9E+7
Kraft	High	5.2E+6	-2.9E+7	1.7E+9	1.3E+8
TUK	Low	9.3E+7	-2.2E+8	3.2E+8	-6.2E+7
TUK	Medium	4.0E+6	2.2E+8	1.5E+8	5.6E+7
TUK	High	-4.7E+6	2.8E+8	8.6E+8	-7.9E+7

A survey has shown that the water contamination rate of cellulosic materials for open-breathing transformers is up to 0.2% per year, while this rate is about 0.03–0.06% for sealed transformers [31]. Accordingly, in this study, it is assumed that the moisture content of the paper increases linearly across lifetime of the transformer considering the above-mentioned values for the annual moisture growth rate. In fact, if a transformer is equipped with a capacitive probe for moisture measurement, several days are required to achieve a value for the moisture content of the paper. The reason is that about one week is required for moisture content in the oil and in the paper insulation to reach an equilibrium [32]. In this regard, using an average value for the moisture content of the paper is unavoidable. With respect to availability of the paper water content at each hour of the transformer lifetime, the associated value of A parameter can be determined by (10) and Table 1.

3. Case study

Distribution transformers are among the assets in a power system that experience a significant level of variation in the operating conditions. In this regard, this section is aimed to evaluate the paper insulation lifetime of the distribution transformers. Note that the same method can be adopted for lifetime estimation of power transformers, since the ageing factors are the same for oil-immersed transformers with paper insulation.

A hypothetical transformer with a nominal rating of less than 2500 KVA according to the IEC 60076-7 is considered to implement the ageing model and evaluate its lifetime. The case considered for the lifetime estimation is a distribution transformer installed in Helsinki supplying commercial load. Different types of actual measured loads in Helsinki are available and the hypothetical transformer is assumed to supply these loads.

In the following, operating conditions of the transformer is discussed. Moreover, the data required for calculating the DP value based on (2) is represented.

3.1. Ambient temperature

The pattern of actual ambient temperature for Helsinki is depicted in Fig. 2. This pattern provides the ambient temperature for 8760 h of a year. Nevertheless, the ambient temperature for lifetime of a transformer is required for the lifetime estimation. In response to this requirement, the same pattern is considered for the rest of the transformer lifetime.

3.2. Load factor

The first step to create the load factor pattern consists of gathering the amount of various types of power consumptions such as heating, cooling, and lightning. These measured data were available for Helsinki in hourly steps for one year. In the second step, the amount of all types of power consumptions are added up for each hour. The third step is to determine the largest load datum through the year. Afterwards, the value of this load is multiplied by a factor such that the resultant value equals one-half of the nominal rating of the transformer. The remaining load data are then multiplied by the same factor. In the final step, all the load data are divided by the nominal power of the transformer to

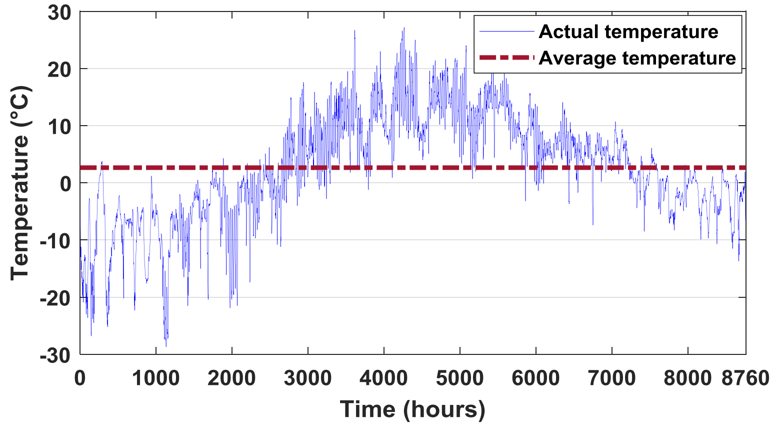

Fig. 2. Hourly ambient temperature of Helsinki in year 2008.

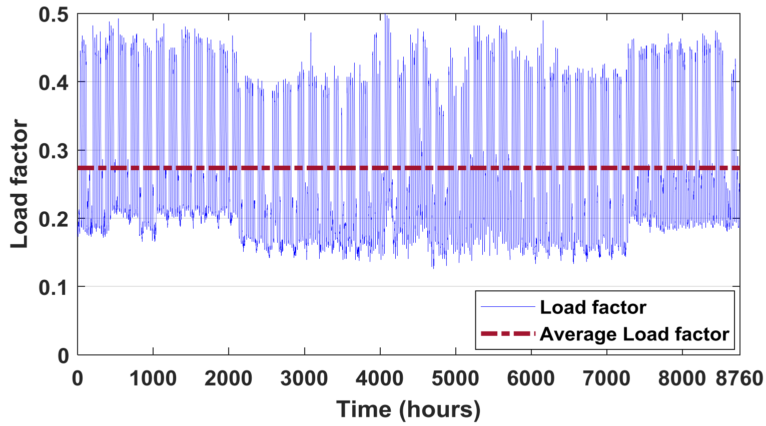

Fig. 3. Hourly commercial load factor for Helsinki.

provide the load factors. The load factor pattern is illustrated in Fig. 3 in hourly steps for the first year of the transformer lifetime.

The load factor does not remain constant over the lifetime of a transformer. In response to this, an annual load increase of 2.5% is considered for the transformer. Considering Fig. 3 as the basis load factor pattern for the first year, load factor for the subsequent years is obtained by multiplying the load factor of the corresponding previous year by a factor of 1.025. Note that another research [33] considered a value of 2.6% for the load growth rate of a transformer installed in Finland.

Two cases are defined to set a limit for the increase in the load factor of the transformer. For the first case, it is assumed that the load factor increases annually till it reaches 75% of the rating of the transformer. For the subsequent years, it is assumed that the transformer supplies the same load. Therefore, the annual load factor pattern is remained the same for the rest of the transformer life. This case is defined with respect to a common rule that a transformer has to supply the total load of two identical transformers up to 150% of its nominal capacity if one of the transformers fails. The second case is similar to the first case, but the load factor is assumed to be increased annually till it reaches 100% of the transformer rating. The load factor pattern of the transformers increases annually by a specific percentage, i.e., 2.5%, until it reaches the above-mentioned limits for the two cases. The annual load increase is not applied afterwards, and the last annual load factor pattern is reproduced for the subsequent years that the transformer may remain in service.

The constants $x, y, k_{11}, k_{21}, k_{22}$, and τ_w that are required to calculate the hot-spot temperature are determined based on the nominal rating of the transformer regardless of the instantaneous load factor. These constants have the same respective values for distribution transformers with a nominal rating of less than or equal to 2500kVA [30].

3.3. Preliminary assumptions

Initial DP value (DP_0), initial moisture content of the paper insulation, and the annual moisture growth rate of the paper insulation are the three substantial parameters required for the lifetime estimation based on (2). The value of these parameters may differ from one transformer to another.

If transformer manufacturers provide DP_0 and the initial moisture content of the paper they use in their products, a higher precision of the estimation would be expected. In this study, however, the common values for these two parameters are applied, which are 1000 for DP_0 and 0.5% for the initial moisture content [7,31]. Note that initial moisture content of the paper insulation for a new transformer is less than 0.5–1% [31].

The oxygen level of the oil insulation of the transformer is considered to be maintained at a low level, i.e., below 6000 ppm. In practice, the oxygen level can be measured using dissolved gas analysis, and the ageing model can be modified accordingly. A value of 0.2% is considered for the annual growth rate of the moisture content based on the survey results represented in Section 2B. In case of periodic measurements on the moisture content, this value could be modified.

3.4. Results of implementing the ageing model

Block diagram of the DP calculation method is depicted in Fig. 4. DP_0 and the initial moisture content are 1000 and 0.5%, respectively

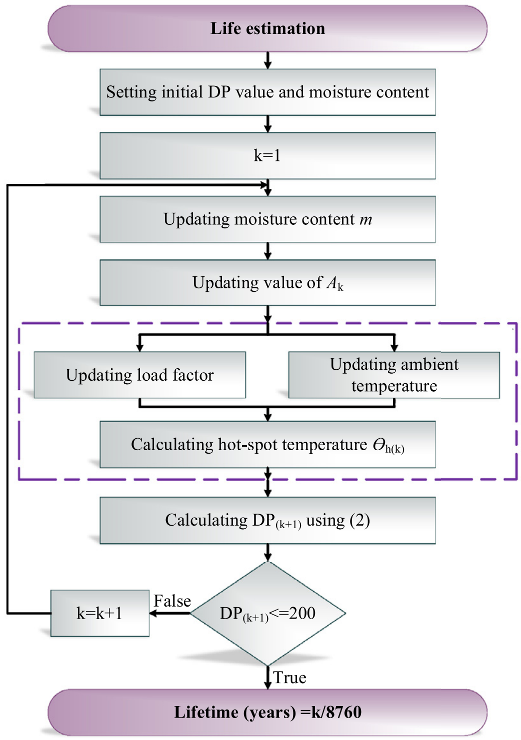

Fig. 4. Life estimation algorithm of transformer.

for the case studies discussed in this contribution. The moisture content *m*, is then updated considering the annual increase rate and vale of *A* is obtained according to the coefficients presented in Table 1. The next step is comprised of updating the ambient temperature and load factor to calculate the hot-spot temperature using (3)–(8). Given all the parameters of (2), the DP value is finally calculated and compared with the predetermined limit of 200. In each iteration, the DP value decreases and this process continues until DP becomes equal to or less than 200. The total number of the iterations *n*, represents the estimated lifetime of the transformer in hours. Moreover, the DP values obtained at the end of each iteration can be plotted to yield DP profile of the transformer.

The DP profiles for the two cases are illustrated in Fig. 5. As it can be seen, lifetime of cases I and II are 80.4 and 42.5 years, respectively. These two lifetimes are obtained by determining the points that the DP profiles reach 200. It is worthwhile to mention that average lifetime of transformers is about 30 years, and some may remain in service up to 60 years without experiencing a failure [7]. The estimated lifetimes are in agreement with usual lifetime of a distribution transformer, which is in the order of a few decades. However, 80.4 years of lifetime for case 1 implies an overestimation. The reason is that the in-service transformers do not necessary operate under the loading conditions defined in this contribution. To cite an instance, the transformer may be loaded over 75% of its nominal rating for long term operation due to the annual load increase or for short term emergency loadings. This leads to a significant reduction in the lifetime, since DP is exponentially related to the hot-spot temperature. A comparison between DP profiles of cases 1 and 2 where the load limits are 75% and 100%, respectively, demonstrates that an increased load can affect the lifetime significantly. This implies the importance of considering the variations in both the ambient temperature and load factor, which have not been considered in the life expectancy curves [11–14] and in [19]. Note that the life expectancy curves and experimentally obtained DP profiles only model the ageing process under specific constant conditions, and they do not incorporate the actual dynamic ageing process of the paper insulation.

Apart from the attained life spans, the trend of these DP profiles is completely different from what has been obtained under a constant HST and a given moisture content conditions. In other words, part of the DP profile with the highest negative slope in Fig. 5 lies within the terminal of the profile, while this significant decrease occurs at early stages for the DP profiles obtained under constant conditions in [9–11,21]. Moreover, the DP profiles depicted in Fig. 5 include ripples that represent variations in the HST due to the variable load factor and ambient temperature.

In order to clarify the impacts of static ageing model on overestimation of the lifetime, two simulations are conducted with respect to a constant HST to investigate how the variations in the ambient temperature and load factor affect the lifetime of the two cases. According to Fig. 4, HST is calculated at each iteration of the life estimation process. Note that the HST is calculated for each hour of the transformer lifetime. The constant HST considered for each case is the average of the calculated HSTs over the estimated life of the transformer. To give an illustration, according to Fig. 5 in which the lifetime of case I has been estimated to be 80.4 years, the average of hourly HSTs calculated during these years is considered for the constant HST of case I. The average HST for the first and second cases is 29.6 °C and 33.4 °C, respectively. The DP profiles with respect to the average values of HSTs for the two cases are illustrated in Fig. 6. Note that the 0.2% annual moisture growth rate is included in these simulations. A comparison between Figs. 5 and 6 clarifies that the estimated lifetime under a constant HST is considerably longer than the lifetime obtained under a variable HST. The reason is related to the existence of an exponential relationship between the HST and DP in (2).

According to Figs. 5 and 6, considering the variations in the ambient temperature and load factor results in a more realistic estimation of the lifetime in comparison with the lifetimes obtained under the constant conditions. Therefore, ignoring dynamic behavior of the load profile and considering a constant value for the ambient temperature lead to an imprecise estimation for the transformer lifetime. As shown in Fig. 1, the proposed dynamic ageing model enables us to involve significant

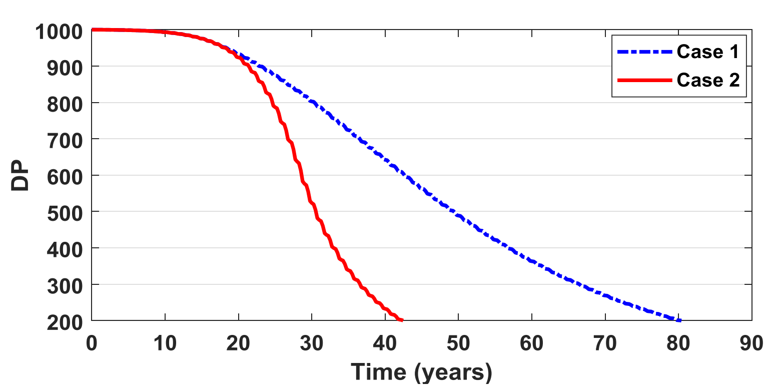

Fig. 5. DP profiles for case I (load limit equals 75%) and case II (load limit equals 100%).

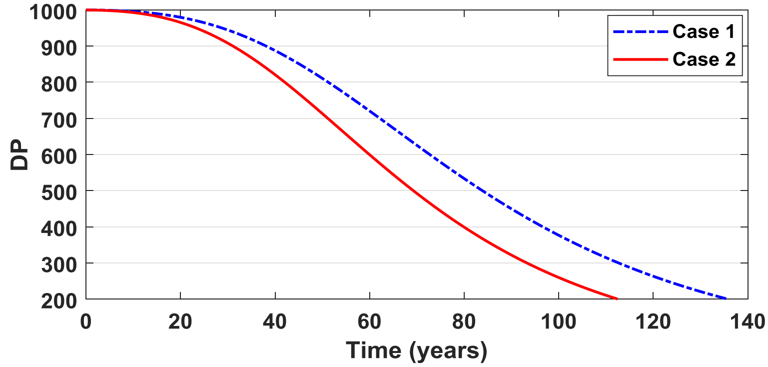

Fig. 6. DP profiles for cases I and II with respect to a constant HST.

parameters on ageing process such as loading, ambient temperature, moisture, and oxygen level of the transformers for an acceptable estimation of the transformer lifetime. Noteworthy is that this information is available for online condition assessment of components, and consequently, it is feasible to use the proposed model for real time assessment of the transformers.

4. Determination of optimum time for paper moisture reduction

Having presented the dynamic ageing model of oil immersed transformers, this section is devoted to determine the optimum time of moisture reduction in distribution transformers using the proposed model. Moisture could severely decrease the lifetime of the transformers, especially those that work 60–70% of the rated power. Therefore, extraction of the moisture could highly extend the lifetime. The optimum time for extracting moisture content of the paper insulation can be assessed due to availability of an accurate and reliable DP profile for a transformer. A detailed discussion on the methods of moisture reduction can be found in [34]. In this section, however, it is aimed to determine the optimum time for decreasing moisture content of the paper to achieve the maximum increase in the transformer lifetime. Three scenarios are established to investigate how the time of implementing moisture reduction affects the extension in the transformer lifetime. It should be emphasized that the investigations conducted in this section are pertained to a low oxygen level.

4.1. Scenario I: moisture reduction under no limitation

The first scenario is to reduce the moisture content of the paper insulation to the initial value, i.e., 0.5%, which is assumed to be feasible at any time during lifetime of the transformer. In fact, this scenario considers the most applicable value for implementing the moisture reduction, which is expected to result in the maximum possible increase in the transformer lifetime by just a single reduction in the moisture content.

Lifetime of a transformer with respect to a reduction in the moisture content can be defined based on (2) as follows:

$$L(t_{\mathrm{m}}) = \sum_{n=1}^{k(t_{\mathrm{m}})} (t_{(n)} - t_{(n-1)}) \tag{11}$$

where L is lifetime of the transformer, t_{m} is the time of implementing the moisture reduction, and k is the number of iterations of (2), which is written as a function of t_{m}. Therefore, the optimization problem can be written as:

$$\min_{t_m}\{-L(t_m)\}$$
$$s.\ t.\quad \{1 \le t_m \le T,\quad mr = t_m \times 0.2\} \tag{12}$$

where T is the estimated lifetime of the transformer without implementing a moisture reduction, and mr is the amount of reduction in moisture content of the paper in percent. Note that the 0.2 coefficient in the equation defined for mr refers to the considered value for the annual moisture growth rate. A constraint is defined for the three scenarios discussed in this paper, which ensures that the remaining moisture content in the paper insulation after implementing the moisture reduction is greater or equal to the initial moisture content of the paper, i.e., 0.5%.

A genetic algorithm is used to determine the optimum time for implementing the moisture reduction concerned with this scenario. The reader may refer to [35] for the details of the genetic algorithm applied in this study.

The results of implementing this scenario for case II are listed in Table 2. In this table, a nonlinear relationship between the amount of reductions in the moisture content and the associated increase in the lifetimes is remarkable. The optimum time related to scenario I that is obtained by the genetic algorithm is reported in Table 3 for the two cases. It is worth mentioning that the lifetimes presented in Table 3 are the longest achievable lifetimes due to a single moisture reduction.

4.2. Scenario II: considering a specific value for moisture reduction

The values obtained for implementing a moisture reduction based on scenario I are rather high values that lead to three major problems. First, extracting a large amount of water from the paper insulation may cause the transformer windings to loosen [10]. Second, the moisture content has to be reduced when it reaches the permissible level defined in the IEEE standard [36]. Third, the routine procedures for moisture reduction are not capable of extracting the most part of additional moisture content available in the paper. In response to these difficulties, the second scenario is defined such that the moisture content of the paper is to be decreased by a specific value. Therefore, the optimization problem with respect to the 0.2% annual moisture growth can be written as:

Table 2
Extension in the Lifetimes for Case II Due to Implementing the Moisture Reduction Associated with Scenario I.

Time of moisture reduction (years)	Amount of reduction in the moisture content (%)	Extension in the lifetime (years)
5	1.0	3.1
10	2.0	7.1
15	3.0	11.2
20	4.0	16.0
25	5.0	20.0
30	6.0	22.3
35	7.0	22.2
40	8.0	17.1

Table 3
Maximum achievable increase in the lifetimes due to implementing the moisture reduction associated with Scenario I.

Case number	Time of moisture reduction (years)	Amount of reduction in the moisture content (%)	Extension in the lifetime (years)
I	65	13.0	45.1
II	33	6.6	23.0

Table 4
Extension in the lifetimes for case i due to implementing the moisture reduction associated with Scenario II.

Time of moisture reduction (years)	Extension in the lifetime (years)		
	0.6% moisture reduction	1.2% moisture reduction	2% moisture reduction
10	2.8	5.5	9.4
20	2.4	5.2	9.2
30	2.2	5.1	8.4
40	2.1	4.2	7.4
50	1.4	3.3	6.2
60	1.1	2.3	4.3
70	0.3	1.2	2.2

$$\min_{t_m}\{-L(t_m)\}$$
$$s.\ t.\ \left\{\frac{mr}{0.2} \le t_m \le T,\quad 0 < mr \le T \times 0.2\right\} \tag{13}$$

In this scenario, a given value for *mr* has to be chosen according to the defined range. As it can be seen, the constraints have been defined in such a way that the remaining moisture content after the extraction will not be less than the initial moisture content, i.e., 0.5%.

Three values, i.e., 0.6%, 1.2%, and 2%, are considered for the amount of reduction in the moisture content to implement the second scenario. The results of implementing this scenario for case I and II are listed in Tables 4 and 5, respectively. It can be concluded from these tables that postponing the moisture reduction until 20 years from the first date of operation of the transformer has a negligible effect on extension of the lifetime. The reason is that the DP profiles in Fig. 5 are decreased slightly during the first 20 years of the transformers' lifetime. Hence, the effect of a delay in implementing the moisture reduction is dominated by the DP profile of the transformer. Doubling the amount of reduction in the moisture content does not necessarily result in an increase in the extended lifetime by two times. A comparison between Tables 4 and 5 reveals that the extension in the lifetime due to a given decrease in the moisture content is longer for transformers with a longer life span. This conclusion is in agreement with the data presented in Table 3.

The extended DP profiles for case II along with the normal profile in which the moisture content has not been reduced are illustrated in Fig. 7. In this figure, the first and the second scenarios are concerned with a moisture reduction by 6.6% and 2%, respectively.

Table 5
Extension in the lifetimes for Case II due to implementing the moisture reduction associated with Scenario II.

Time of moisture reduction (years)	Extension in the lifetime (years)		
	0.6% moisture reduction	1.2% moisture reduction	2% moisture reduction
10	2.0	4.0	7.1
15	1.9	4.0	7.0
20	1.9	4.0	7.0
25	1.6	3.6	6.5
30	1.1	3.0	5.1
35	0.9	2.0	3.3
40	0	0.2	1.0

In general, the optimum time related to the second scenario was discovered to be when the increase in the moisture content of the paper insulation due to the annual growth rate becomes equal to the moisture reduction capability. To cite an instance, assume an annual moisture growth rate of 0.2% for the paper insulation, and consider the available technique for performing the moisture reduction is capable of a 0.6% reduction in the moisture content of the paper. Therefore, the optimum time for performing a 0.6% reduction in the moisture content will be in 3 years, when the added moisture content due to the annual growth rate, i.e., 3 × 0.2%, and the capability of performing the reduction in the moisture content are the same.

4.3. Scenario III: repetitive moisture reductions

The common approach used in practice for the moisture reduction includes multiple repetitions. Therefore, this subsection is dedicated to investigate the effects of a multiple moisture reduction. In fact, this scenario is a repetitive form of the second scenario. Various conditions can be introduced for the multiple moisture reductions from the perspective of time, number, and amount of reductions in the moisture content. The effects of these three parameters are discussed in this subsection.

In this scenario, number of the moisture reductions is increased, while the amount of each reduction is remained the same. It is worthwhile to mention that the time of implementing each moisture reduction is at the optimum time specified in the previous subsection. Amounts of extension in the lifetimes are listed in Table 6 for the two cases. As it can be seen, a same approach of moisture reduction results in a distinct extension in the lifetime of transformers operating under different conditions. Moreover, extension in the lifetime due to each increase in the repetition number of a specific moisture reduction is different for case II. On the other hand, this extension is approximately the same for case I regardless of the repetition numbers.

Taking samples from the paper insulation of the transformer after accomplishing the moisture reduction causes improvements in quantifying the ageing process and in calibrating the ageing model. In this way, the model could be used individually for each transformer to estimate its remaining lifetime under various maintenance scenarios.

5. Reliability assessment of distribution transformers

The life estimation model of distribution transformers presented in this paper enables planning for maintenance or replacement of the unit. The planning is performed by evaluating reliability of the transformer. The benefit of this study is to provide power utility companies with the condition of their transformers in a long-run as well as the corresponding reliability measures. In this section, a formula is presented to calculate reliability of the transformers based on statistical data.

First step towards calculating reliability of a transformer is to determine its failure rate. Results of three independent surveys have been gathered, and an exponential function has been fitted to them in [37] as follows:

$$F(t) = 0.001.\ e^{0.0994t} + 0.0169 \tag{14}$$

where t is the time of operation in years and F indicates the failure rate of the transformer. Transformers usually experience a higher failure rate in the first two years of operation, and therefore, the failure rate for the lifetime of the transformer can be written as [37]

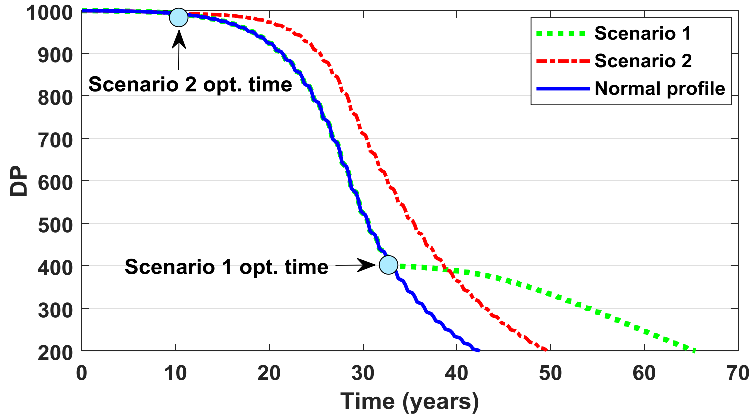

Fig. 7. DP profiles for case II under normal and modified conditions; 6.6% and 2% reduction in the moisture content for the first and second scenarios, respectively.

Table 6
Increase in the lifetime by implementing Scenario III for the moisture reduction; investigating effect of repetition rate.

Amount of each reduction in the moisture content (%)	Number of moisture reductions	Extension in the lifetime (years)	
		Case I	Case II
0.4	2	3.8	2.4
0.4	3	5.7	4.1
0.4	4	7.6	5.4
0.4	5	9.5	7.1
0.4	6	11.5	9.0
1.2	2	11.4	9.0
1.2	3	17.4	14.2
1.2	4	23.3	20.0
1.2	5	29.3	26.0

$$F_{base}(t) = \begin{cases} F(t) \times (1.5 - 0.25t) & 0 \le t \le 2 \\ F(t) & t > 2 \end{cases} \quad (15)$$

According to a survey on 1724 transformers in [38], a conservative factor of 0.65 has been considered for the effect of a major overhaul in [37]. Hence, the fault rate for a transformer in case of a major overhaul in year T_{oh} is obtained by

$$F_{OH}(t) = \begin{cases} F_{base}(t) & 0 \le t < T_{oh} + 1 \\ F_{base}(t) \times 0.65 & t \ge T_{oh} + 1 \end{cases} \quad (16)$$

Given the failure rate, reliability of the transformer is calculated using an exponential probability distribution function [37]

$$R(t) = e^{-F(t)} \quad (17)$$

This reliability analysis together with the DP profile obtained for a specific transformer yields a comprehensive assessment of its current and future condition. This assessment allows the power utility companies to predict the condition of their transformers. Moreover, the time-based maintenance plans for the transformers are supported by a quantitative analysis, which leads to a more accurate planning.

6. Conclusion

The classic ageing model of oil-immersed transformers using DP profile includes a static viewpoint on the operating conditions of the transformers. In this contribution, it has been indicated that the DP profiles attained with respect to the variations in the ambient temperature, load factor, and moisture content are different in trend from the linear profiles attained under constant conditions. The DP estimation model proposed in this paper provides a distinct DP profile for each transformer, which can be used to estimate remnant lifetime of the transformer by setting a lower limit for end-of-life DP value. Although the case studies in this paper are concerned with distribution transformers, the life estimation model can be applied to oil immersed transformers.

The moisture content plays a critical role in lifetime reduction of oil immersed transformers. In addition to the lifetime estimation, the optimum time to perform a reduction in the moisture content of the paper insulation can be determined using the obtained DP profile. The optimum time to reduce the moisture content by a given value was found to be when the additional moisture content due to the annual growth rate equals the capability of the moisture reduction process. Postponing the moisture reduction has low to significant effect on the prolonged lifetime of the transformer depending on its operating conditions and the delay in implementing the moisture reduction.

CRediT authorship contribution statement

Mohamadreza Ariannik: Methodology, Software, Validation, Investigation, Writing - original draft, Visualization. **Ali A. Razi-Kazemi:** Supervision, Writing - review & editing, Conceptualization, Resources. **Matti Lehtonen:** Supervision, Conceptualization, Resources.

Declaration of Competing Interest

None.

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