Methods for Predicting Remaining Service Life of Power Transformers and Their Components

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***Abstract* – This paper presents the overview of methods for prediction of remaining service life of power transformers and the analysis of possibility to apply these methods to transformers in power system in Latvia. Particular attention is paid to the methodology for the analysis of transformer components since due to statistical data of faults this issue is topical for transformers in Latvia. Calculations, performed for 4 power transformers, are presented as a case study.**

***Keywords* – Maintenance, power transformer, prognosis, reliability.**

I. Introduction

Lifetime data analysis of power transformer is important for a cost efficient and risk minimized maintenance process. Common maintenance strategies of electrical equipment can be subdivided into two basic approaches:

- Unplanned maintenance that relies on no-failure operation of electrical equipment throughout its rated service life;
- Planned maintenance that requires performing diagnostic tests to gather data for assessment of technical condition.

Since power transformers are major equipment of substations, and their reliability affects the reliability of power system maintenance electric energy availability of the supplied area their maintenance is planned, often using several techniques in combination [1].

Condition based maintenance (CBM) uses diagnostics to monitor and to evaluate condition of power transformer continuously or intermittently during operation. As its name implies, CBM is triggered by actual electrical equipment condition rather than a predetermined interval of time as in time based maintenance (TBM).

A critical part of developing and implementing effective diagnostic and prognostic technologies such as risk centered maintenance (RCM) and prognostic and health management (PHM) is based on the ability to detect faults in early enough stages to have time for doing something useful with the information.

Prediction of a fault and remaining service life (the operating time between fault detection and an unacceptable level of degradation) is the most important information for maintenance engineering group to avoid system outages.

Remaining service life of the transformer is determined through at least one of the factors mentioned below:

- Degree of polymerization of paper insulation decreases to 200 - 250;
- Irreversible faults in construction;
- Use of transformer with inadequate technical and economic characteristics [2].

The related literature describes various different methods that allow estimating remaining service life of the transformer. However it has to be noted that development of such prediction for power transformer requires direct cooperation with diagnostics, which provides information on faults.

Therefore, the main objective of this paper is to analyze methods for determining remaining lifetime, considering the aspect whether information provided by diagnostic tests used for power transformers in Latvia is sufficient.

II. An Overview and Practical Application of Approaches of Remaining Service Life Prediction

A. Direct Evaluation of Degree of Polymerization of Paper Insulation

Remaining resource of the transformer can be evaluated basing on the changes in the degree of polymerization (DP) of paper insulation, since DP correlates with mechanical strength and other physical properties.

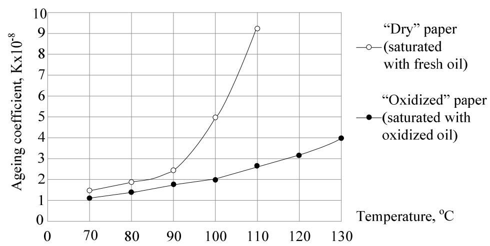

Fig. 1. Coefficient *K* as a function of temperature and oxidation of paper insulation.

The remaining resource L_{rem} of the transformer can be determined by formula (1):

$$L_{rem} = \frac{1}{K} \cdot \left(\frac{1}{DP_k} - \frac{1}{DP_t}\right) \qquad (1)$$

where K is empirical coefficient of ageing that depends on temperature and condition of paper insulation (Fig. 1); DP_t - value of DP of the transformer that has worked for t hours; DP_k - value of DP at the end of the transformer's life time [2].

This method was applied to estimate the remaining lifetime of the transformer TCG 200000/330 that has been put into operation in 1966. Measured value of DP_t is 908 for this transformer. Yet the value of coefficient K has to be read off the chart from. Reading is performed at normal operational temperature (80°C), but at different conditions of paper insulation. If the condition of insulation is stated as "dry" $K = 1.5 \cdot 10^{-8}$, and $K = 2 \cdot 10^{-8}$ for "oxidized" paper insulation. Consequently the values of L_{rem} are not equal:

$$L_{rem1} = \frac{(\frac{1}{200} - \frac{1}{908})}{1.5 \cdot 10^{-8}} = 259669h \approx 30 years, \quad (2)$$

$$L_{rem2} = \frac{(\frac{1}{200} - \frac{1}{908})}{2 \cdot 10^{-8}} = 194751h \approx 22 years. \quad (3)$$

Another significant deficiency of evaluating the remaining resource through degree of polymerization is necessity to open transformer tank in order to measure DP in the hottest areas of solid insulation.

B. Indirect Evaluation of Degree of Polymerization of Paper Insulation Based on Furfural Analysis

Furan compounds appear in oil during degradation process of solid insulation, and can be measured by taking oil sample (does not require opening a transformer). Various methods have been developed to express by a formula the relation between furans and DP. Four of them are analyzed in this paper:

- Chendong method,
- Stebbins method,
- De Pablo method,
- Pahlavanpour method.

The Chendong method proposes formula (4) that was developed for transformers without thermally–upgraded paper

$$DP = \frac{\log_{10}\left[2 - FAL_{ppm}\right] - 1.51}{-0.0035}. \quad (4)$$

But modified equation (5), called Stebbins method, was designated for thermally upgraded paper [3]:

$$DP = \frac{\log_{10}\left(2 - FAL_{ppb} \cdot 0.88\right) - 4.51}{-0.0035}. \quad (5)$$

The De Pablo method proposes empirical equation (6):

$$DP = \frac{7100}{8.8 + \left[2 - FAL_{ppm}\right]}. \quad (6)$$

Formula (7) of the Pahlavanpour method is based on an assumption that 20% of winding paper and their inner paper layer degrade twice as fast as rest of the paper [4]

$$DP = \frac{800}{\left(0.186 \cdot \left[2 - FAL_{ppm}\right]\right) + 1}. \quad (7)$$

After determining the DP value it is possible to determine the remaining lifetime of the transformer by formula (8):

$$\%Life\,Used = \frac{\left[\log_{10}(DP) - 2.903\right]}{-0.006021}. \quad (8)$$

The performance time of the transformer can be estimated by following formula (9) [5]:

$$Elapsed\ life\ (in\ years) = 20.5 \cdot \ln\left[\frac{1100}{DP}\right]. \quad (9)$$

All four methods were applied on transformer T1 (OLF 25000/110, in operation since 2000) and transformer T2 (TCG 200000/330, in operation since 1966) with following furan values:

- T1: *2-FAL*$_{ppm}$ = 0.30;
- T2: *2-FAL*$_{ppm}$ = 0.16.

TABLE I

THE RESULTS OF PRACTICAL IMPLEMENTATION

	by Chendong		by Stebbins		by De Pablo		by Pahlavanpour	
	T1	T2	T1	T2	T1	T2	T1	T2
DP	581	659	597	675	780	792	758	777
(8)	23	14	21	12	2	1	4	2
(9)	13	11	13	10	7	7	8	7

Value of *%LifeUsed* that is calculated by formula (8) approximately corresponds to actual service life for the transformer T1. However, after analyzing the results of the transformer T2, such conclusion can not be drawn. Acquired results indicate that the transformer T2 is in good technical condition and has not used up its resource. Yet in practice the transformer T2 is planned to be replaced since diagnostic tests show inadmissible level of vibrations and partial discharges.

C. Hot Spot Temperature

Arrhenius method is based on the concept that temperature is the only ageing parameter. According to this model, transformer ageing is dictated by the ageing of the most thermally stressed location i.e. hot spot. This model is given by formula (10):

$$LoL = 100 \cdot \Delta t \cdot 10^{-\left[A + \frac{B}{\Theta + 273}\right]}, \quad (10)$$

where *LoL* - loss of life, %; *A* and *B* - constants which based on testing and reaction conditions; Θ - hot spot temperature, °C; and *Δt* - transformer operating time (in hours), with hot spot temperature of Θ [6].

The disadvantage of this method lies on the fact that such relevant ageing factors as humidity and oxidation are not considered; furthermore precise measuring of hot spot temperature is difficult.

D. Analysis of Maintenance Data of a Transformer

Insulation is significant component in power transformer, since the insulation practically determines remaining service life. However, if the identified fault affects another relevant component, then the prediction of remaining service life also must reflect this diagnosis.

Fig. 2 shows distribution of the faults depending on location that is obtained by applying Nordel classification method of faults [7] to statistical data on faults of power transformers in Latvian transmission network. The diagram allows to conclude that highest percentage of faults is related to tap changer (53.6%), followed by bushings (14%) and cooling system, including integrated automatics for cooling (8%).

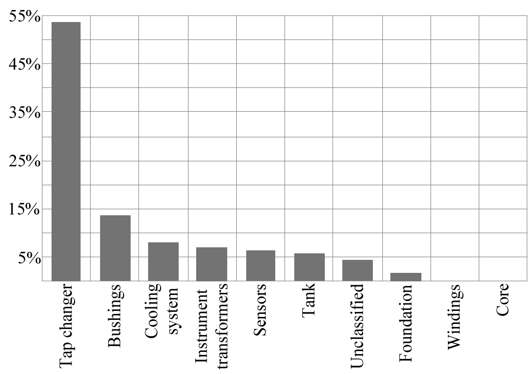

Fig. 2. Classification of faults (by Nordel method).

The Weibull distribution accurately describes the distribution of data on service life of electrical equipment and is particularly effective in prediction. It can provide reasonably accurate analyse and prediction of failures with few data points, and therefore facilitates cost-effective and efficient component testing. Application of Weibull distribution has proven to be successful also for power transformers [8].

The three-parameter Weibull cumulative distribution function, $F(t)$, that predicts the cumulative probability of failure up to a specific time, t, is mathematically expressed by (11). The probability density function, $f(t)$ which is a derivative of the cumulative distribution function, is expressed by formula (12):

$$F(t) = 1 - e^{-(\frac{t-t_0}{\eta})^{\beta}} , \qquad (11)$$

$$f(t) = \frac{\beta}{\eta} \cdot (\frac{t-t_0}{\eta})^{\beta-1} \cdot e^{(\frac{t-t_0}{\eta})^{\beta}} , \qquad (12)$$

where η – scale factor or characteristic life; β – shape parameter or slope of Weibull plot; and t_0 – location parameter or guarenteed life ($t_0 = 0$ in a two-parameter Weibull) [9].

One way how to estimate parameters is a graphical method (probability plotting). Probability plotting provides a visual goodness–of–fit test. Before a probability plot can be constructed, an estimate for the cumulative distribution function $F(t)$ is needed. The most common estimate is the median rank. The median rank is a non-parametric estimate of the cumulative distribution function based on ordered failures. The expression for rank is (13)

$$Median\ rank(t_i) = \frac{i - 0.3}{n + 0.4} , \qquad (13)$$

where i is the failure order and n is the total number of data points, both edited and unedited.

Statistical data of two transformers from substations of power transmission grid in Latvia were analyzed using the Weibull calculations method.

The transformer T3 and the transformer T4 is in operation since 1977 and 1971 accordingly. Since 2002 the majority of the faults have been registered for the tap changer for these transformers. Therefore two-parameter Weibull distribution was used in order to determine service life of the tap changer. Probability plotting in Fig. 3 was constructed by using median rank method, the results of analysis are provided in Table II.

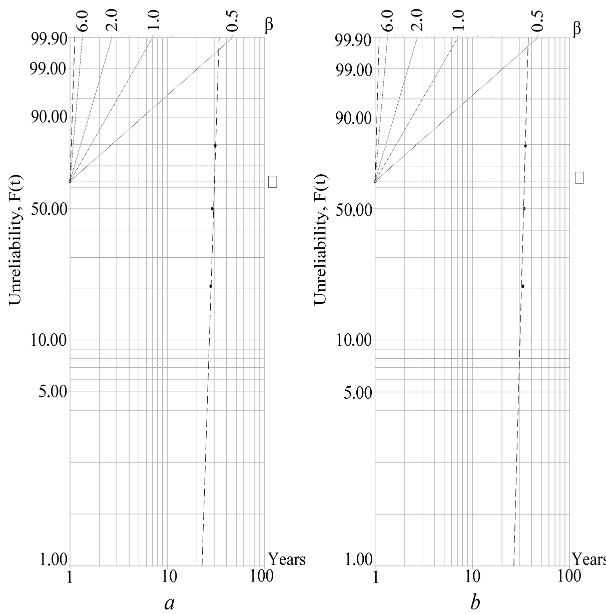

Fig. 3 Weibull cumulative distribution functions for the tap changers of a) transformer T3 and b) transformer T4.

TABLE II

RESULTS OF WEIBULL METHOD FOR THE TAP CHANGER

	Transformer T3	Transformer T4
β	6.5	6.5
η	31	34
Mean service life	30	33

The method allows evaluating the technical condition of the component and its mean service life. The obtained results show that risk of failure is high due to technical condition of tap changer for both transformers.

III. RESULTS AND CONCLUSIONS

Methods of remaining service life prediction of power transformers are not always suitable for practical use due to measuring difficulties of specific parameter or due to lack of necessary information (as shown in Table III).

TABLE III

MAIN DISADVANTAGES OF METHODS OF REMAINING LIFE PREDICTION

A Direct evaluation of DP	- Requires opening transformer tank for determining value of DP; - Involves the use of the empirical coefficient; - Fails to analyze a single component of a transformer.
B Indirect evaluation of DP	- Discrepancy in formulas relating furans and DP; - Fails to analyze a single component of a transformer.
C Hot spot temperature	- Relevant ageing factors are not considered; - Involves the use of the empirical coefficients; - Measuring is difficult; - Fails to analyze a single component of a transformer.
D Analysis of maintenance data	- Requires statistical data from the beginning of the transformer operation that can not be obtained later on, if not recorded in time.

The research based on statistical data about faults of power transformers allows concluding that for power transformers in Latvia the technical condition of the individual components determines overall remaining service life at a large extent. Tap changer, cooling system, and bushings are components with the highest contribution of faults and in coming years such faults can be expected repeatedly.

The research of scientific papers and practical case studies of transformers T1, T2, T3, and T4 allows concluding that the Weibull analysis method is the most suitable in such situation. The necessary maintenance data of the transformer can be obtained by using CBM strategy; also this method does not require additional and complex diagnostic tests.

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Julija Badune, Sandra Vitolina, Vjaceslav Maskalonok. Lieljaudas transformatora un tā konstrukcijas elementu darbmūža prognozēšanas metodes.
Transformatora defektu un atlikušā darbmūža prognozēšana ir būtiska informācija transformatoru ekspluatācijas procesā, kas palīdz izvairīties no atslēgumiem. Šajā rakstā ir apskatītas četras atšķirīgas prognozēšanas metodes, kuras ļauj novērtēt transformatora atlikušo darbmūžu. Tomēr jāatzīmē, ka prognozēšanas metožu pielietošana un to precizitāte ir tieši saistīta ar transformatora diagnostiku, kura sniedz informāciju par transformatora defektiem.
Šā darba galvenais mērķis ir atlikušā darbmūža prognozēšanas metožu analīze, pielietojot pieejamo informāciju no Latvijas elektropārvades tīkla transformatoru diagnostikas rezultātiem. Šis pētījums ļauj secināt, ka Latvijas transformatoru atlikušais darbmūžs lielā mērā ir atkarīgs no tā sastāvdaļu tehniskā stāvokļa. SRI, dzesēšanas sistēma un ievadi ir tie transformatora konstrukcijas elementi, kuriem raksturīgs augsts defektu īpatsvars un paredzams, ka tuvākajos gados defektu skaits tikai pieaugs. Tādēļ Veibula sadalījuma izmantošana, kas ļauj analizēt vienu konkrētu elementu, ne tikai visu transformatoru kopumā, ir īpaši piemērota Latvijas situācijai.

Юлия Бадуне, Сандра Витолыня, Вячеслав Маскаленок. Методы прогнозирования остаточного срока службы трансформатора и его компонентов.
Прогнозирование неисправностей и остаточного срока службы трансформатора является одной из важной информацией для инженерной группы для обслуживания, чтобы избежать простоев системы. В статье рассмотрены четыре различных метода прогнозирования, которые позволяют оценить остаточный срок службы трансформатора. Однако следует отметить, что развитие прогнозирования требует прямого сотрудничества с диагностикой трансформатора, которая предоставляет информацию о неисправностях.
Основной целью данной работы является анализ методов определения остаточного ресурса, учитывая доступную информацию, которая получена по результатам диагностики трансформаторов Латвии. Такое исследование позволяет сделать вывод, что для латвийских трансформаторов остаточный срок службы в значительной степени зависит от технического состояния отдельных компонентов. РПН, система охлаждения и втулки это компоненты с высоким количеством неисправностей и в ближайшие годы неисправностей следует ожидать больше. Поэтому использование распределения Вейбулла особо подходит для латвийской ситуации.