ESTIMATION OF THE DEGRADATION POWER TRANSFORMERS INSULATION USING THE CHARGE CURVES

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***Abstract* – The paper herein aims to propose a mathematical pattern to estimating the degradation of power transformers insulation. If we consider for the transformer charge factor a normal statistical distribution law, we can establish the degradation distribution function and we can also fix the medium value of this degradation.**

Keywords: *degradation of power transformers insulation.*

1. INTRODUCTION

The transformers are very important elements of the electrical networks of transport and distribution and their good function it is esential for electrical fittings safety. Any interruption of the electrical power bring about many damages both to producers and to consumers of electrical power. In this situation it is very important to know witch is the proper moment for pull out the transformer for replacement or revision. This problem remain also for the transformers witch need to be repair or for the situation of transportation at other station. For this events the Question is how can we evaluate the remain lifetime of the transformers? It is better to repair or to annul them? The manufacturer must know the long term behavier of the transformers and their elements for construction improving through a good selection of suitable materials and insulations types.

The evaluation of the lifetime of transformers is vey important because of association between lifetime and ageing phenomenon. The electrical equipment damaged in many ways depending of constructions and usage type. Some of them contain mobile pieces, some no, but all of them are expose of strains (electrical, mechanical, thermal and environmental). Although the transformers dos'nt have mobile pieces still are forced to important mechanical strains during the short circuits time. ageing The ageing and ageing rate are described in standards (CEI 354, ANSI 5792, Norma IEEE 756 etc), whitch describes the effects of undertaking especially when it is outrun the nominal value from the write down platse equipment In accordance with this standards, thermal strains represent the most important factor for ageing and lifetime influence. [4], .[4], [6], [9], [11], [17].

We can establish the degradation of power transformers insulation.

The paper herein aims to propose a mathematical pattern to estimating the degradation of power transformers insulation.

2. INSULATION DEGRADATION

We can define the insulation degradation [6] with the following relation:

$$\nu = A\int_0^T \exp\left[\chi\,\theta(t)\right]\mathrm{d}t \tag{1}$$

where ν is the insulation degradation, χ is the proportional ratio, which is 0,11552 (according to „the six degree" rule), A is a constant which depend of insulation type and $\theta(t)$ is the insulation overtemperature. The nominal degradation is:

$$\nu_n = A\int_0^T \exp\left[\chi\,\theta_n\right]\mathrm{d}t \tag{2}$$

where θn is the nominal insulation overtemperatu-re. For relative insulation degradation we obtain the following expression:

$$\nu_r = \frac{\nu}{\nu_n} = \frac{A\int_0^T \exp\left[\chi\,\theta(t)\right]\mathrm{d}t}{A\int_0^T \exp\left[\chi\,\theta_n\right]\mathrm{d}t} = \frac{1}{T}\int_0^T \exp\left\{\chi\left[\theta(t)-\theta_n\right]\right\}\mathrm{d}t \tag{3}$$

The aleatory modification of load factor generate the aleatory modification of winding temperature, which also produce the accidental modification of insulation degradation and this mean that it is a statistical measure.

3. WINDING INSULATION OVER TEMPERATURE AND LOAD FACTOR

Most of distribution transformers operate in variable load-conditions, characterized by load curves variable in time for the active power $P(t)$, the intensity of the electrical current $I(t)$, the active electrical energy $W(t)$, and respectively over-temperature curves of winding insulation $\theta(t)$, variable as well.
The equivalent over-temperature is a parameter which describes almost completely the thermal stress. The equivalent over-temperature it is that temperature which is assume to be constant, if the winding insulation is solicited and will be produced the same effect of insulation degradation like the effect produced by the real temperature[14], [16].
As the actual system of monitoring the functioning parameters of the transformer consist in recording the load curves values and the temperature ones, the authors propose the establishment the correlation between over-temperature and load factor of transformer.
The thermal model assimilates the transformer with a homogeneous body having as heat sources the losses P, which is given by the differential equation:

$$C\frac{\mathrm{d}\theta_i}{\mathrm{d}t}+\Lambda\,\theta_i = P \tag{4}$$

In this relation the following notations are used:
C – caloric power of winding [J/K]; Λ – coefficient of heat transfer through conduction, convection and radiation [W/K]; θ_i – over-temperature of the winding, respectively, its insulation system.
Having in view the fact that the power transformer functions at various values of electrical current intensity, the load factor is defined as:

$$\beta = \frac{I}{I_n} \tag{5}$$

where I is the current intensity in various conditions, and I_n is the current intensity in rate functioning conditions. The power losses P could be expressed in function of the load factor as:

$$P \approx P_k = \frac{P_{kn}}{I_n^2}\cdot I^2 = \left(\frac{I}{I_n}\right)^2 P_{kn} = \beta^2\, P_{kn} \tag{6}$$

where P_k represents the copper losses in certain operation conditions, and P_{kn} represent the copper losses in rate ones. The relation (6) is valid only if the iron losses are neglected, as well as the winding resistance variation with temperature.
Having in view relation (6), relation (4) becomes:

$$\frac{\mathrm{d}\theta}{\mathrm{d}t}+\frac{\Lambda}{C}\theta = \frac{P_{kn}}{C}\beta^2 \tag{7}$$

The solution of differential equation (7) is:

$$\theta = \frac{P_{kn}}{\Lambda}\beta^2 + C_1\exp\left(-\frac{\Lambda}{C}t\right) \tag{8}$$

where, the integration constant C_1 can be determined from the initial condition (for $t = 0$ it will result $\theta = \theta_0$):

$$C_1 = \theta_0 - \frac{P_{kn}}{\Lambda}\beta^2 \tag{9}$$

With the relations (11) and (10) the expression for winding over-temperature will become:

$$\theta = \frac{P_{kn}}{\Lambda}\beta^2 + \left(\theta_0 - \frac{P_{kn}}{\Lambda}\beta^2\right)\exp\left(-\frac{\Lambda}{C}t\right) \tag{10}$$

As, for short time, $C \ll \Lambda t$, we can consider the expression $\exp\left(-\frac{\Lambda}{C}t\right) \approx 0$ and in the relation (10) the second term can be neglected. In this case, the equation solution (1) becomes:

$$\theta = \frac{P_{kn}}{\Lambda}\beta^2 \tag{11}$$

The over-temperature depends on the square of the load factor of the current intensity and on the constructive parameters of the transformer. But, these quantities should be treated as random variable, and the statistical approach is necessary.

4. THERMAL STRESSES AS STATISTICAL PROCESS

An estimation of the thermal stress degree of the transformer can be done with the equivalent over-temperature. The equivalent over-temperature of the winding insulation, corresponding to a certain functioning period and load-conditions, represents that over-temperature value, considered as constant, which produces the same degradation effect on the insulation as the exploitation over-temperature. Its calculus can be done having in view the statistical approach.
The thermal stresses of the power transformer can be considered as a statistic process, where the current intensity $I(t_i)$, the load factor $\beta\,(t_i)$ and the over temperature θ_i, as random quantities, are characterized by specific statistical distributions.
We can add, that in the case of rate functioning conditions ($\beta = 1$) the value of random over

temperature θ_i coincides with the value of nominal winding over temperature θ_n ,which, for winding force cooling is 70ºC [2].
Therefore, the relation (12) can be described as:

$$\theta_i = \theta_n \beta_i^{\,2} \qquad (12)$$

In the following considerations, the random quantities θ_i and β_i will be noted θ and β.
In the hypothesis of a normal repartition for the current intensity [10] and, respectively, for the load factor, the expression of the repartition density of the load factor is:

$$f(\beta) = \frac{1}{\sqrt{2\pi}\,\sigma_\beta} \exp\left[-\frac{\left(\beta - \overline{\beta}\right)^2}{2\sigma_\beta^2} \right] \qquad (13)$$

where $\sqrt{\sigma_\beta^2}$ represents the standard deviation of the load factor and $\overline{\beta}$ is the mean value of the load factor.
The over-temperature repartition density can be established based on the density repartition of the load factor. Considering the equation (14), the load factor β can be expressed in function of the temperature θ:

$$\beta_1 = \frac{1}{\sqrt{\theta_n}}\sqrt{\theta} \quad ; \quad \beta_2 = -\frac{1}{\sqrt{\theta_n}}\sqrt{\theta} \qquad (14)$$

and its variation with temperature will be:

$$\frac{d\beta_1}{d\theta} = \frac{1}{2\sqrt{\theta_n}\sqrt{\theta}}\; ; \; \frac{d\beta_2}{d\theta} = -\frac{1}{2\sqrt{\theta_n}\sqrt{\theta}} \qquad (15)$$

For the over-temperature repartition density we obtain the following expression:

$$g(\theta) = A \exp(-\alpha\theta) \frac{1}{\sqrt{\theta}} \operatorname{ch}\left(\gamma\sqrt{\theta}\right) \qquad (16)$$

where:

$$A = \frac{1}{\sqrt{2\pi}\sqrt{\theta_n}\,\sigma_\beta} \exp\left(-\frac{\overline{\beta}^2}{2\sigma_\beta^2} \right) ;$$
$$\alpha = \frac{1}{2\theta_n \sigma_\beta^2} \quad ; \quad \gamma = \frac{\overline{\beta}}{\sqrt{\theta_n}\sigma_\beta^2} \qquad (17)$$

It is demonstrated [12] that for over-temperature repartition density, the relative insulation degradation (the relation (3)), which it is depending from temperature, we obtain for relative insulation degradation the following expression:

$$\overline{\nu_r} = \int_0^\infty \exp\left[\chi(\theta - \theta_n)\right] g(\theta)\, d\theta \qquad (18)$$

or, if we take into account the relation (16), we obtain:

$$\overline{\nu_r} = \int_0^\infty A \exp\left[\chi\left(\theta - \theta_n\right)\right] \times$$
$$\times \exp(-\alpha\theta) \frac{1}{\sqrt{\theta}} \operatorname{ch}\left(\gamma\sqrt{\theta}\right) d\theta \qquad (19)$$

If we integrated, we obtained for medium insulation degradation we obtain the following expression:

$$\overline{\nu_r} = \frac{1}{\sqrt{1 - 2\theta_n \sigma_\beta^2 \chi}} \times$$
$$\times \exp\left[\chi\theta_n \left(\frac{\overline{\beta}^2}{1 - 2\theta_n \sigma_\beta^2 \chi} - 1 \right) \right] \qquad (20)$$

5. DETERMINATION OF DEGRADATION INSULATION FOR A 250 MVA POWER TRANSFORMERS AND THE VOLTAGE 400/110/20 KV

The daily working condisions of this transformer (for 1999-2006) are characterized by the daily active electrical power (Wi).
To establish the degradation of the winding insulation it was take into account the regiter of the active counter for TRAFO 2, for which it was notice the daily active electrical comsuption power (Wi), on an 8 years period.
Knowing the daily active electrical comsuption power, it was determinated the current intensity for the 110 kV winding insulation:

$$I_2 = \frac{\frac{W_i}{24} 10^6}{\sqrt{3}\, U_2 \cos\varphi}, \qquad (21)$$

where $\cos\varphi$ =0,92 is the value for power factor, the transformer it is equiped with a adjustable power factor.
The nominal current intensity value for 110 kV winding is:

$$I_{2n} = \frac{S}{\sqrt{3}\, U_2 \cos\varphi} = \frac{250 \cdot 10^6}{\sqrt{3}\, 110 \cdot 10^3 \cdot 0{,}92} = 1427{,}95 \text{ A} \qquad (22)$$

If we make the ratio between the secundar current intensity value and the nominal current intensity value we obtain the load factor β (expression 5).
To establish the mean value for wearing insulation of the transformer it is necessary to determine the mean value of the load factor ($\overline{\beta}$)and the standard deviation of the (σ_β).
On the base of official date that we had, there was obtained the load factor distribution law of the transformer.
It was remove the abnormal data and the other 2297remain value was divided by rank.
In Figure 1 there is shown the dependence betwen the frequency of the load factor and the rank values.

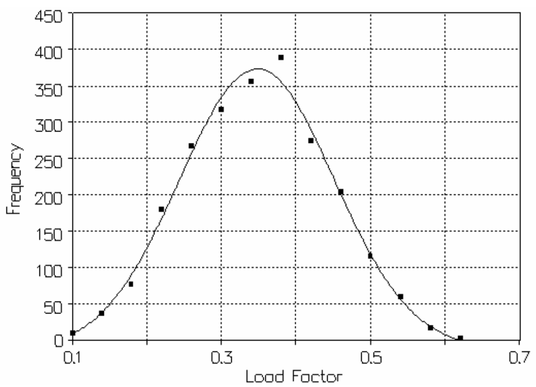

Fig. 1. The dependence betwen the frequency of the load factor and the rank values

The Fig. 1 suggest for the the load factor a normal distribution.
The proceeding to test the empirical distribution at a theoretical distribution it is named conformity test.
To verify the conformity between the presume distribution an normal distribution it was used the Kolmogorov – Smirnov test.
The l Kolmogorov – Smirnov test shown that exist a good conformity between the load factor repartition of transformer 2 and the normal repartision.
It is mean that we can use the (20) relation for rellative degradation insulation evaluation for T1, T2 and T3 transformers.
The results are presented in Table 1.

Table 1

	$\overline{\beta}$	σ_β	$\overline{\nu_r}$
TRAFO 1	0,55658	0,17122	0,04971
TRAFO 2	0,62736	0,14755	0,05178
TRAFO 3	0,59632	0,19485	0,05055

6. CONCLUSIONS

1. Table 1. show that rellative degradation insulation have big values, and one of the reason is the big values for the dispersion of load σ_β.

2. From (19) relation result that the expresion under root sign tinde către zero the degradation tende to către infinite. In this way result the criticall value for dispersion (0,06182), respectively for medium insulation degradation (0,24865).

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ANNEX

The integral calculus (19):

$$\overline{\nu_r} = \int_0^\infty A \exp\left[\chi(\theta-\theta_n)\right]\times \exp(-\alpha\theta)\frac{1}{\sqrt{\theta}}\mathrm{ch}\left(\gamma\sqrt{\theta}\right)\mathrm{d}\theta \tag{A1}$$

Which also can be write:

$$\overline{\nu_r} = A\exp(-\chi\theta_n)\int_0^\infty \exp\left[-(\alpha-\chi)\theta\right]\frac{1}{\sqrt{\theta}}\mathrm{ch}\left(\gamma\sqrt{\theta}\right)\mathrm{d}\theta \tag{A2}$$

It is use the change variable: $\sqrt{\theta}=t$ and result : $\theta=t^2$, $\mathrm{d}\theta=2t\,\mathrm{d}t$.

The expression (A.2) become:

$$\overline{\nu_r} = 2A\exp(-\chi\theta_n)\int_0^\infty \exp\left[-(\alpha-\chi)t^2\right]\mathrm{ch}(\gamma t)\mathrm{d}t \tag{A3}$$

By change variable: $\sqrt{\alpha-\chi}\,t=x$, the expression (A.3) become:

$$\overline{\nu_r} = \frac{2A}{\sqrt{\alpha-\chi}}\exp(-\chi\theta_n)\int_0^\infty \exp(-x^2)\,\mathrm{ch}\left(\frac{\gamma}{\sqrt{\alpha-\chi}}x\right)\mathrm{d}x \tag{A4}$$

It was notice:

$$I(\gamma)=\int_0^\infty \exp(-x^2)\,\mathrm{ch}\left(\frac{\gamma}{\sqrt{\alpha-\chi}}x\right)\mathrm{d}x. \tag{A.5}$$

It was derived (A.5) integral by γ parameter.

$$\frac{\mathrm{d}I(\gamma)}{\mathrm{d}\gamma}=\frac{1}{\sqrt{\alpha-\chi}}\int_0^\infty \exp(-x^2)x\,\mathrm{sh}\left(\frac{\gamma}{\sqrt{\alpha-\chi}}x\right)\mathrm{d}x \tag{A.6}$$

The (A.6)expression it was in part integrated by :

$$\frac{\mathrm{d}I(\gamma)}{\mathrm{d}\gamma}=\frac{-1}{2\sqrt{\alpha-\chi}}\int_0^\infty \left[\exp(-x^2)\right]'\times \mathrm{sh}\left(\frac{\gamma}{\sqrt{\alpha-\chi}}x\right)\mathrm{d}x \tag{A.7}$$

and result:

$$\frac{\mathrm{d}I(\gamma)}{\mathrm{d}\gamma}= \frac{1}{-2\sqrt{\alpha-\chi}}\left[\exp(-x^2)\right]\mathrm{sh}\left(\frac{\gamma}{\sqrt{\alpha-\chi}}x\right)\Bigg|_0^\infty - \frac{1}{-2(\alpha-\chi)}\left\{\int_0^\infty\left[\exp(-x^2)\right]\mathrm{ch}\left(\frac{\gamma}{\sqrt{\alpha-\chi}}x\right)\mathrm{d}x\right\} =\frac{1}{2(\alpha-\chi)}I(\gamma)$$

(A.7

And result:

$$\frac{\mathrm{d}I(\gamma)}{\mathrm{d}\gamma}=$$

$$=\frac{1}{-2\sqrt{\alpha-\chi}}\left[\exp\left(-x^2\right)\right]\mathrm{sh}\left(\frac{\gamma}{\sqrt{\alpha-\chi}}x\right)\Bigg|_0^{\infty}-$$

$$-\frac{1}{-2(\alpha-\chi)}\left\{\int_0^{\infty}\left[\exp\left(-x^2\right)\right]\mathrm{ch}\left(\frac{\gamma}{\sqrt{\alpha-\chi}}x\right)\mathrm{d}x\right\}=$$

$$=\frac{1}{2(\alpha-\chi)}I(\gamma)$$

(A.8

In A.8 relation it was take into account that:

$$\left[\exp\left(-x^2\right)\right]\mathrm{sh}\left(\frac{\gamma}{\sqrt{\alpha-\chi}}x\right)\Bigg|_0^{\infty}=0. \qquad \text{(A.9)}$$

And also it was take into account the (A.5) relation for $I(\gamma)$.

From (A.8) rlation result the folowing diferential ecuation:

$$\frac{\mathrm{d}I(\gamma)}{\mathrm{d}\gamma}=\frac{1}{2(\alpha-\chi)}I(\gamma) \qquad \text{(A.10)}$$

After it was separated the variables and the ecuation A.10 was integrated result:

$$I(\gamma)=C\exp\left[\frac{\gamma^2}{4(\alpha-\chi)}\right], \qquad \text{(A.11)}$$

Where C is a constant. For $\gamma=0$, we obtain:

$$I(0)=C \qquad \text{(A.12)}$$

From A.5 relation result:

$$I(0)=\int_0^{\infty}\exp\left(-x^2\right)\,\mathrm{d}x=\frac{\sqrt{\pi}}{2}. \qquad \text{(A.13)}$$

From A .47 and A.48 result the expression of constant C. If we substitute the constant C in expression A.45 result for $I(\gamma)$.integrale is:

$$I(\gamma)=\frac{\sqrt{\pi}}{2}\exp\left[\frac{\gamma^2}{4(\alpha-\chi)}\right] \qquad \text{(A.14)}$$

If we substitute in A.14 relation the α, γ and A constantes from relations (17) result the folowing expresion for the medium insulation degradation:

$$\overline{\nu}_r=\frac{1}{\sqrt{1-2\theta_n\sigma_\beta^2\chi}}\exp\left[\chi\theta_n\left(\frac{\overline{\beta}^2}{1-2\theta_n\sigma_\beta^2\chi}-1\right)\right] \qquad \text{(A.15)}$$