PREDICTION OF POWER TRANSFORMER INSULATION LENGTH OF LIFE USING THERMAL MODEL AND PARETO DISTRIBUTION

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ABSTRACT: *Estimation of the power and distribution transformers remaining lifetime is the major distress due to the owners of these instruments, especially in situations where the transformer is under continuous or periodic overload. One of the important factors in preserving the useful life of electrical transformers in the transmission, sub transmission and distribution ranges is due to insulation issues of the equipment. In this field, there are many factors that can have an impact on the lifetime of the transformer insulation. In the operation of a transformer, the transformer insulation system can experience electrical, thermal, mechanical and environmental stresses. So each of mentioned factors can increase the aging and finally deterioration of the transformer insulation system. Therefore, to assess the remaining lifetime of the transformer insulation system, due to stress, the appropriate model should be used. In this paper using a Pareto distribution as an appropriate model to estimate the insulation lifetime of the power transformers is proposed.*

Keywords: *Power Transformer, Insulation, Thermal Model*

1. INTRODUCTION

In the power networks, power transformer is one of the most important and expensive equipment. When the transformer exits from the network due to a Fault, It may cause irreparable damages. Today, estimation of the power system lifetime, especially the estimation lifetime of the transformers in the power system is considered as an effective factor that can improve and enhance equipment reliability and increase the lifetime of the equipment and also the entire system. Insulation failure in transformers can happen during transformers operation in power system or transformer testing in HV laboratory [1], [2,3]. In the 1920s, Muntysngr was the first in examining the issue of insulation life [4]. He put forward insulation mechanical properties (the tensile strength) as a criterion in decreasing insulation lifetime. He stated in his article that increase of temperature, reduces insulation lifetime. But article [5], rejected the increase of temperature as the only reducing factor due to lifetime. In [6] the degree of polymerization and tensile strength of the sheet in the vicinity of the oil at a temperature of 160 ° C investigated and its thermal behavior is studied.

In [7] the effect of the transformer hot spot temperature that reaches to 160 ° C on the mechanical properties of tested paper insulation, so that within measuring the paper mechanical strength and paper deterioration products such as gases based on CO, furfural concentrations, showed that passing time, cause severe degradation of the mechanical strength of the paper. In addition, the deterioration and loss of mechanical strength of paper, carbon monoxide and carbon dioxide and furfural concentration has increased and mathematical changes over time were determined. In [8] changes in physical and chemical properties of cellulose pulp used in power transformers at existence of thermal stresses are investigated. Somehow with doing paper tests and with presence of the insulating oil (such as degree of polymerization and the amount of oil furfural) and under different temperatures, a mathematical model for the lifetime of paper insulation as a function of temperature and it is same as Arynus equation. In [9] change in tensile strength and degree of polymerization of paper and the amount of furfural of oil at high heat stress period, have been tested. As can be seen in all things mentioned in the previous section using only natural and ideal degree of polymerization behavior considered in estimating lifetime of the insulation paper that ideal behavior in different operating conditions, such as transformer overload and short-circuit is not correct. Thus, the authors were forced to use the Pareto distribution model due to modeling of uncertainty in ideal behavior of the degree of polymerization and determine remaining life of a transformer. In this paper authors avoid engaging issues of design and maintenance of transformers and they investigate factors affecting the insulation life of exploitation, such as loading and environmental conditions such as temperature. Finally the simulation of different stages in insulation lifetime determination has been done in MATLAB software and the simulation results are shown.

2. SITUATION ANALYSIS OF SOLID INSULATION

Paper insulation coils and terminals and press board is known as an insulating paper. Solid insulation should have high electrical and mechanical strength. New transformers have this important property. But commonly used and old transformer may be due to erosion, such as analysis, development of cavities and cracks lose this property.

Much of the insulators used in transformers, which are cellulose-based material and they are positioned on the coils and between the reels. The thickness of these papers is between 30 to 120 microns and they are used as coils insulator and loops on copper conductor with up to 15 layers. Of course in areas with very high electrical and mechanical stresses, the press board made from compressed paper are produced in several layers, are used. The cellulosic material due to their multipartite structure is subject to severe erosion of the victims that they are irreversible. Paper insulation that complicate directly onto the copper windings are subject to severe heat stress. Also, this type of insulation due to transformer severe eddy current or external short circuit and also stresses due to expansion and contraction cycles (thermodynamic effect), subjected to mechanical stress. Besides, since in the oil transformer cellulose insulation system is immersed in transformer oil and metal catalysts such as copper, iron, moisture, oxygen, air and acid types of oil oxidation reactions are exist. So cellulose insulation affected by these factors. Therefore, these factors besides causing deterioration of cellulose insulation result reducing electrical and mechanical resistance.

So far, various articles investigated the effect of heat stress and water and oxygen on the rate of insulation system aging in oil / paper transformer. In [7] the degree of polymerization and tensile strength of the sheet in the vicinity of the oil and at 160 ° C investigated and its thermal behavior is studied. In [8] the effect of the transformer hot spot temperature that is up to about 160 ° C, on tested insulation mechanical characteristic as measuring so paper mechanical strength and paper products, such as the decline in carbon emissions and furfural concentrations, indicating that with passing time, cause severe degradation of the mechanical strength of the paper. Meanwhile the deterioration and loss of mechanical strength, carbon monoxide and carbon dioxide and furfural concentration have increased and their changes over time in the following mathematical relationship are expressed in next section.

3. LIFETIME ESTIMATION BASED ON THERMAL STRESSES

Thermal stresses that are due to increasing the temperature, or due to improper cooling system or losses under overload conditions, are one of the factors that effect on insulation aging process of electrical machines especially power transformers. To estimate the lifetime of the transformer insulation and the effect of heat Aynyus conjunction can be used that has proven true in practice. But also electrical stresses such as over voltages and impulses of lightning and switching can decrease the insulation lifetime. Thus Rynyvs thermal model must be modified. In [8] a combined thermal-electrical model is proposed. But the lack of a clear method for determining the constants of the model resulted some problems. In [9] also proposed a model based on the inverse power law that its parameters are a function of temperature. Recently, using of intelligent and expert systems techniques in the determination of transformer insulation aging and lifetime has been suggested [10]. It went on to explain a combined thermal-electrical stress model - which focuses on the Rynyvs relationship and is based on parameters that are resulted from electrical and thermal tests [11], [12].

The remaining life of the insulation system under thermal stress according to the equation Rynyvs relation is:

$$t_F = B.\exp(\frac{E}{kT}) \qquad (1)$$

That in this equation, t_F is the remaining life, B is the one constant has been obtained from the experiments, E is the activation energy (ev), k is Boltzmann's constant and T is the temperature in absolute terms. By taking the logarithm of both sides of the above equation [13]:

$$\ln(t_F) = \ln B + \frac{B}{kT} \qquad (2)$$

Thus efficient linear relationship between the logarithm of the lifetime of the machine and the inverse absolute temperature will be established. Once this relationship is established when the insulation system only under heat stress and no stress or other reactions exist. Also by using Rhnyvs relationship accelerates the aging process of the insulation system at temperatures above the nominal operating temperature of the machine can be determined.

4. LIFETIME COMPOSITIONAL MODEL CONSISTS OF THERMAL AND ELECTRICAL STRESSES

Studies have shown that electrical stresses decrease the activation energy (E) and Thus with exertion of electrical stresses, insulation system declines at lower temperatures. In other words at the nominal temperature of the transformer, electrical stress speeds up the aging process. Inverse power law defines the relationship between insulation lifetime and the applied voltage:

$$t_F = t_{F0} V^{-N} \qquad (3)$$

In this relationship, t_F and t_{F0} are insulation lifetime in nominal voltage and overvoltage, N is a constant coefficient and v is the applied voltage in PU. The above equation can be exponential relationship (A is the reaction constant):

$$t_F = A\exp(-nV) \qquad (4)$$

The relationship between the intensity of the electric field (σ) and voltage (V) is as follows (ξ: Electrical Permittivity):

$$V = \sigma.\xi \qquad (5)$$

Hybrid model combining the above relationships that results the lifetime with both thermal and electrical stresses is expressed as follows:

$$t_F = B.\exp(\frac{E-\beta.\xi}{kT}) \qquad (6)$$

5. ESTIMATION OF LIFETIME USING THE PARTEO DISTRIBUTION

As described in the previous sections, the remaining life of a transformer due to the aging of the insulation is evaluated. In modeling first the survival insulation curve of a transformer ideally is checked. But since a transformer insulation in its lifetime for various reasons such as overvoltage , temperature changes and other reasons does not always ideal behavior so using the Parteo distribution can help to model this uncertainty [13]. In this modeling, the Parteo distribution with the factors that are important in aging of transformer insulation can make a certainty margin around the insulation aging curve. After the construction of the transformer Health history, prediction based on the history and determination of the remaining lifetime and the time of paper insulation elimination can be done.

5.1. Insulation Aging Equations and Aging Rate Factor

DP or the degree of polymerization is the number of cellulose polymer chains. Furfural content of oil is higher than other hydrocarbons. Therefore due to oil test to determine the paper DP, relative concentrations of furfural are used. Furfural test is more common and easier than DP test. While the sampling of the oil is possible in operation situation the correlation curve between furfural in oils (F) and DP are represented by four different methods that these relationships are expressed as follow [14]:

5.1.1. Burton method

Relationship expressed by this method are as follows:

$$DP = \frac{2.5 - \log[F]}{0.005} \qquad (7)$$

5.1.2. Vuarchex method

Relationship expressed by this method are as follows:

$$DP = \frac{2.6 - \log[F]}{0.0049} \qquad (8)$$

5.1.3. Chendong method

Relationship expressed by this method are as follows:

$$DP = \frac{1.51 - \log[F]}{0.0035} \qquad (9)$$

5.1.4. Depablo method

Relationship expressed by this method are as follows:

$$DP = \frac{1850}{F + 2.3} \qquad (10)$$

5.2. Determination of Hot Spot Temperature

The transformers load curve are repeat every 24 hours. Depending on the type of load connected to the transformer, the load curve is associated with a fluctuation. For analysis, often times at fixed intervals (half or one hour) are classified. Due to losses in the transformer, load variations can change amount of θ_{hs}. Different methods have been used for the calculation including the following relation [15].

$$\theta_{hs} = \theta_a + \Delta\theta_{To} + \Delta\theta_2 \qquad (11)$$

In this equation, θ_α is environment temperature and $\Delta\theta_2$ is maximum temperature difference, also $\Delta\theta_{To}$ is increasing the temperature of transformer oil volume in the upper part which is related to changes in load.

5.3. Ideal Behavior of the Polarization Degree Curve

In order to predict the remaining life of the transformer needed to model the ideal behavior of transformer insulation that this behavior is expressed by the following equations [16].

$$\frac{dDP(t)}{dt} = -k(t)\left[DP(t)\right]^2$$

$$DP(t) = \frac{DP(t_0)}{1 + DP(t_0)\int_{t0}^{t} k(\tau)d\tau} \qquad (12)$$

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

Ea is the activation energy of the above relationships, Rg is the gas constant, A is the reaction constant and T is the temperature of the transformer hot spot which in the 5-1-3-1 was calculated. Ideal behavior of the polarization degree curve is shown in Figure 1.

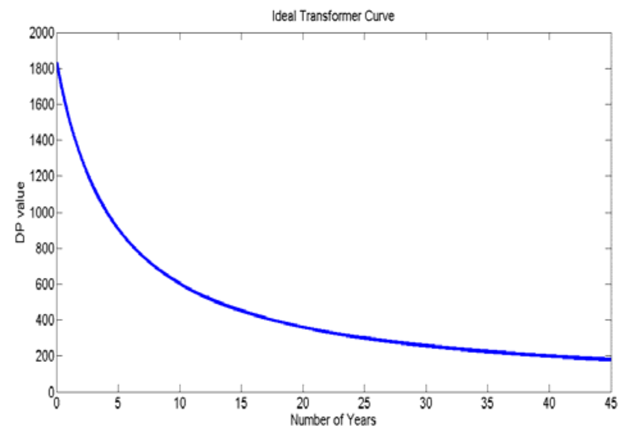

Figure. 1. The ideal behavior polarization degree curve with passing the time

5.4. Parteo Distribution

Pareto distribution is one of the most important statistical distributions which named from the italian economist vilfredo parteo. Pareto distribution as a model for many economic- social phenomena. The distribution used for studying organism's lifetime and also reliability is one of the topics which Parteo can help effectively. As shown in Figure 2, the Pareto cumulative distribution function for different values of k and Xm = 1 is shown in this diagram. the horizontal axis is the parameter Xm display. When the limit of infinite k is tended to infinity, the probability distribution function tend to $\delta(x - x_m)$ that δ is delta function.

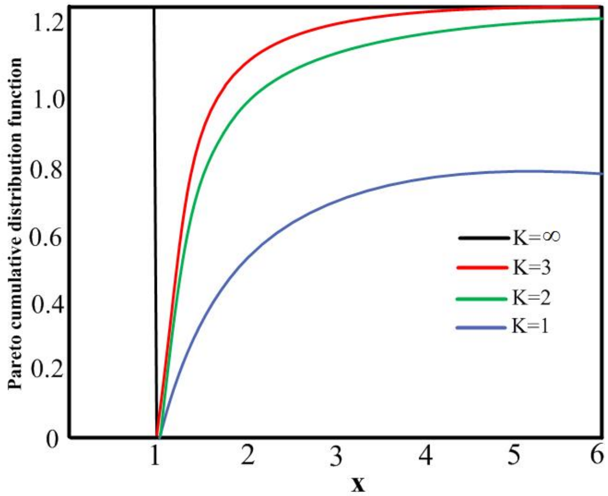

Figure. 2. Parteo cumulative

Pareto distribution is an exponential probability distribution can describe many social, scientific, geophysical phenomena etc. it is sometimes also referred to as the Bradford distribution. As shown in figure 3 can be seen on the basis of reference [16] Since the transformer insulation aging behavior is consistent with the Pareto probability distribution function. thus can model uncertainty of insulation aging. Pareto distribution function is expressed in the following modeling parameters:

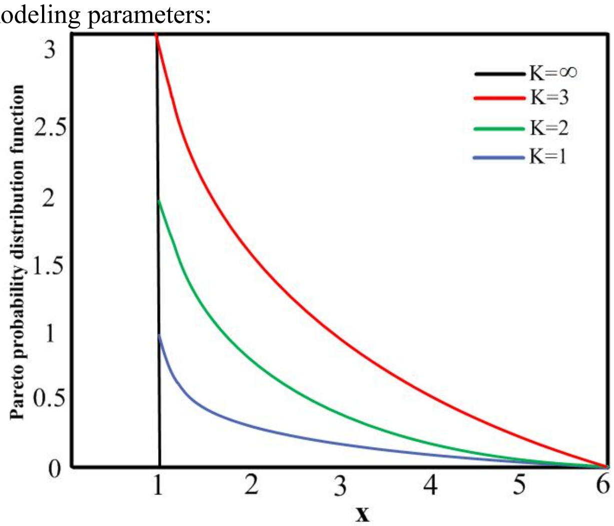

Figure. 3. Parteo probability distribution function

Parteo probability distribution function parameters are:

1-The actual location : $x_m > 0$

2- The actual figure : $K > 0$

3- Scope :x ϵ $[x_{m,+\infty}]$

4- Probability density function : $\dfrac{k\, x_m^k}{x^{k+1}}$

5-Cumulative distribution function (CDF) : $1-\left(\dfrac{x_m}{x}\right)^k$

6- average : $for \quad k>1 \quad \dfrac{k\, x_m}{k-1}$

7- Median : $x_m \sqrt[k]{2}$

8- Extension : X_m

9- Variance : $\dfrac{x_m^2 k}{(k-1)^2 (k-2)}$

10- Stress : $\dfrac{6(k^3+k^2-6k-2)}{k(k-3)(k-4)}$

In order to model History of Health of the transformer and the uncertainty of ideal behavior of transformer parteo distribution can be used with a marginal certainty around the DP curve following the figure 4.This distribution can be defined by an algorithm.

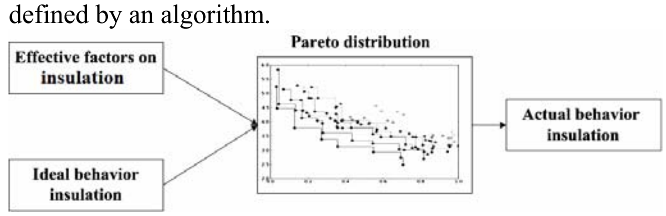

Figure. 4. Parteo distribution behavioral curve

After simulating the actual behavior of DP using the Parteo distribution can estimate remaining life of the transformer paper insulation based on health history and use of Monte Carlo algorithm. Figure (5) shows actual behavior of DP curve for a typical sample transformer.

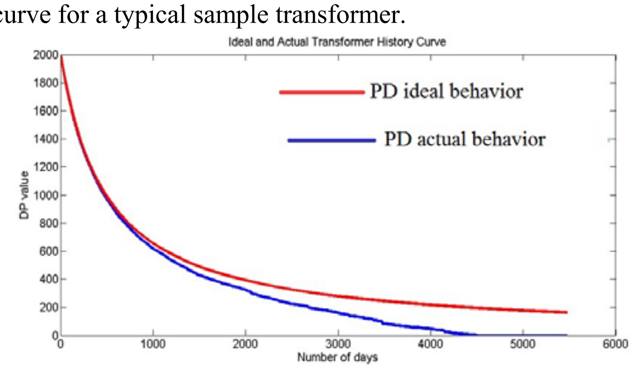

Figure. 5. Actual DP behavior curve of sample transformer

Finally the remaining life of the transformer insulation aging with considering the extremity follow the figure 6 is determined.

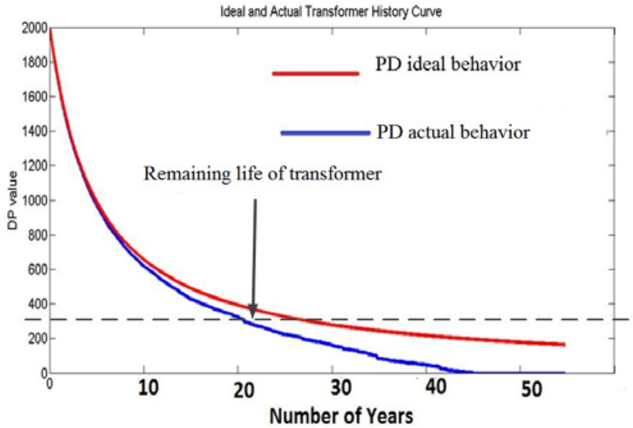

Figure. 6. Estimation of transformer remaining life based on insulation aging

6. CONCLUSION

The estimation of the power system lifetime especially about transformers, is considered as an important factor that can improve and enhancing lifetime and reliability of the equipment and the whole Power system. Since a transformer insulation aging is an important parameter in determining lifetime, in this paper, using the Pareto distribution and thermal stress that can model uncertainty based on the transformer health history due to estimation the remaining lifetime of the transformer insulation transformer was employed with regard to aging. Simulation results indicated the proposed method functionality.

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