Evaluation and Comparing the Loss of Life for Outdoor and MV/LV Prefabricated Oil Immersed Power Transformer Based on Nonlinear Thermal Models

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Abstract

Power transformers are the most critical and expensive equipment in the field of transmission and distribution of electric energy. Any major fault in these units can cause not only catastrophic damage to various equipments but also cause interruption of electricity supply. These direct or indirect effects often lead to large economic losses. The most important parameter in transformers life expectancy is the insulation hot-spot temperature value which accelerates the rate of aging of the insulation. This Study proposes a life expectancy model for oil immersed power transformer using the hot-spot temperature based on transformer nonlinear hot-spot and top-oil temperature rise models. Since the thermal transfer is different for indoor and outdoor transformers considering their operating conditions, their thermal and loss of life models are different and are analyzed and compared in this study.

Key words: loss of life, oil immersed transformers, thermal aging, indoor, outdoor

1. Introduction

The insulation aging of transformers is an important parameter affecting their life expectancy. Insulation aging depends deeply on the insulation temperature, the humidity level, and the oxygen included in it [1]. The humidity level and the oxygen included in oil can be taken under control in the new designed oil immersed transformers. Therefore, the most important parameter that should be cared is the operating temperature of transformer. For this purpose, the study and deriving the thermal model of a transformer is getting more importance. The thermal model of a transformer is also important when it is aimed to manage the load profile of a power transformer [3, 5] and to program its loading.

The insulation aging phenomenon has been well documented as a thermal deterioration process in the literature. The application of loading on a transformer, i.e., the load current in the transformer coils, results in heating and, consequently, reduction in the age of the transformer.

Loading capability of power transformers is limited mainly by winding temperature [1]. One of important test that is applied on a transformer is the temperature rise test which is carried out under rated power and ambient temperature conditions. The average temperature of the winding should be less than the corresponding values given the International Standards such as IEC or IEEE. However the temperature of the winding is not uniform and the real limiting factor is actually the hottest section of the winding commonly called winding hot spot. This hot spot area is located somewhere toward the top of the transformer, and not accessible for direct measurement with usual methods.

Recommendations in IEEE C57.94 guide are based on life expectancy of transformer insulation as affected by hot-spot temperature and time [5, 12].

The Permissible loading of transformers for normal life expectancy depends on different parameters such as; the design of the particular transformer, hot-spot temperature rise at rated load, temperature of the cooling medium, duration of the overloads, the load factor, and the altitude above sea level. Transformers are designed considering the ambient and the winding average temperature obtained from measuring the winding resistance. For proper design of transformer the hottest-spot temperature should be used as the limitation rather than the average winding temperature rise.

2. Insulation paper degradation

The power transformer is a component operating in high voltage, high current, and consequently high power condition. Each aspect imposes its specific challenge on the transformer design. High voltage poses a need for dedicated insulation measures to prevent flashovers, especially during temporary over-voltages due to switching or lighting strokes. High currents are associated with high magnetic fields, which corresponds to strong electromagnetic forces, during high load and short-circuit situations. Though transformers are extremely efficient devices, the heat generated by the power losses must be disposed of the insulating medium in power transformers. Hence, the insulation must be capable of dealing with electric stresses, large electromechanical forces, and high temperatures [8, 14].

Paper-oil insulation is widely used in power transformers. Oil has an intrinsic high insulating strength and at the same time serves as cooling medium by either passive or active flow. The paper prevents electric bridging by contaminants left behind and serves as a mechanical barrier between the windings and winding layers. The paper is a critical factor in paper-oil insulation. Oil is easier to replace and its quality can be monitored. The paper insulating properties may be affected by displacement or by ageing. The insulating papers consist of cellulose chains with their average length expressed in the degree of polymerization (DP). The chemical formula of one cellulose unit, the monomer, is $(C6H10O5)n$ [8].

The chemical structure of two connected cellulose rings, i.e. one cellobiose unit, is depicted in Figure 1. A practical value for the DP of unaged paper is 1000–1200. The paper tensile strength is a measure for the sensitivity to paper rupture. The tensile strength is directly related to the degree of polymerization of the insulating paper. If the mechanical strength of paper is reduced to 50% of the initial strength, its strength is considered to be in a faulty state [6]. This corresponds with a DP-value in the range of 200–300 [4, 14].

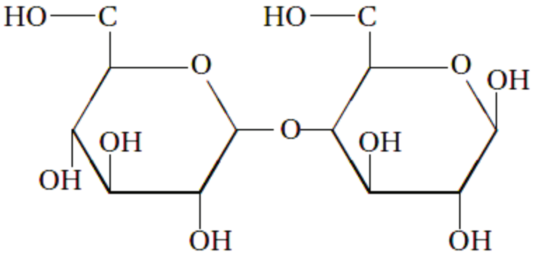


Fig. 1. The chemical structure of one cellobiose consisting of two cellulose molecules.

The Cellulose materials immersed in oil are a kind of insulation materials in transformers which has sited on windings, between turns and core and, the parts with different potential. Thermal stress caused by copper, core and, dielectric losses and ambient temperature is one of the applied stresses on the insulation which affects the oil-paper insulation system. The thermal stress will change oil-paper insulation system characteristics and decreases the expected life by degradation. Most of researches have been done on ageing of oil-paper insulation in transformers under different stresses.

3. Thermal modeling

Power losses are converted into heat in a transformer. These losses are composed of no-load losses and load losses. The no-load losses are comprised of eddy-current and hysteresis losses of the core. The load losses are comprised of resistive losses (windings losses, joint points losses and connectors losses), winding eddy losses and the stray losses.

The heat generated in a transformer transfers (from heat source to oil, from oil to surface and from surface to external environment) by three different heat transfer mechanism as i-convection ii-conduction and iii-radiation.

The thermal model is based on the energy balances for the windings, oil, core and tank, cooling equipment and cooling environment.

3.1 Outdoor situation

The thermal equivalent circuit of an ONAN/OFAF (oil natural air natural, oil forced air forced) power transformer includes nonlinear heat resistance, heat capacitor and heat current source. The top-oil Extended thermal circuit and model of a power transformer is presented in [2] .

The equivalent thermal model given in [2] can be simplified as Fig. 2.

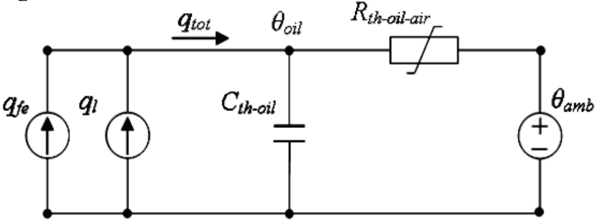


Fig. 2. The simplified equivalent top-oil thermal model.

The thermal resistance $R_{th-oil-air}$ is given by Eqn. 1 [6, 9].

$$R_{th-oil-air} = \frac{\Delta\theta_{tor}}{q_{tot}} = \frac{1}{h \cdot A} \tag{10}$$

Fig. 3 shows the variation of these properties against temperature in per unit. It is shown that the variation of viscosity with temperature is much higher than the variation of other transformer oil physical parameters with temperature (ρ_{oil}, c_{oil}, k_{oil}, β_{oil}). In this figure the values of parameters at 45° C are taken as based quantities[2].

By Substituting of variation of transformer oil properties against temperature in Eqn. 1 gives Eqn. 2 [2, 9].

$$h = C_1 \times (\frac{\Delta\theta_{oil}}{\mu(\theta)})^n \tag{2}$$

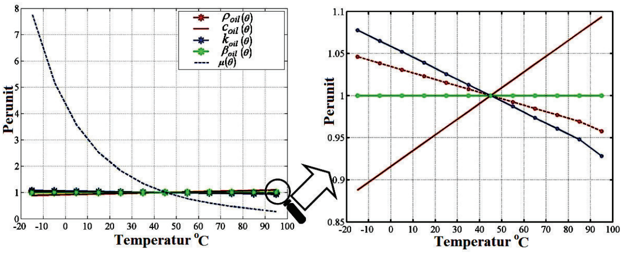


Fig. 3. Variation of physical properties of transformer oil against temperature (in per unit).

C_1 is given in Eqn. 2 and can be taken constant.

$$C_1 = C \times \left[\rho_{oil}{}^2 \times g \times \beta_{oil} \times k^{\left(\frac{1-n}{n}\right)} \times L^{\left(\frac{3n-1}{n}\right)} \times c_{oil} \right]^{(n)} \tag{3}$$

The transformer top-oil thermal model given in Fig. 2 is derived from the thermal-analogy and heat transfer theory. The differential equation corresponding to Fig. 2 is as Eqn. 4.

$$q_{fe} + q_l = C_{th-oil} \times \frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil} - \theta_{amb})}{\frac{1}{h \cdot A}} \tag{4}$$

Substituting the heat transfer coefficient (*h*) (*h* is obtained by substituting C1 from Eqn. 3 into Eqn. 2) in Eqn. 2 gives Eqn 5.

$$(q_{fe} + q_l) \times \left(\frac{\mu^n}{C_1 \cdot A}\right) = \left(\frac{\mu^n}{C_1 \cdot A}\right) \times C_{th-oil} \times \frac{d\theta_{oil}}{dt} + (\theta_{oil} - \theta_{amb})^{1+n} \tag{5}$$

$R_{th\text{-}oil\text{-}air,rated}$ which is the non-linear thermal resistance at rated power is obtained from Eqn. 6.

$$R_{th-oil-air,rated} = \frac{1}{C_1 \cdot A} \times \left(\frac{\mu_{rated}}{\Delta\theta_{oil,rated}}\right)^n \tag{6}$$

3.2 Indoor situation

Due to limited ventilation in indoor operation the thermal resistance and thermal capacitance of indoor and outdoor transformers are different.

The heat transfer between bodies is as follows:

1. From winding to oil
2. From oil to surrounding air
3. Air inside the room is cooled by natural ventilation and convection heat transfer from the air to room parts (door, walls and ceiling).

4. The heat transfer through the door

The extended model and analogues circuit presented in [2]. According to presented model, the first cooling component which is dominant is represented by thermal resistance of room to ambient, $R_{room\text{-}amb}$. The initial form of this thermal resistance is derived from the Hoppner formula [2, 5].

The extended model of [2] can be simplified as fig. 4. When the $R_{room-amb}$ calculated as Eqn. 7

$$R_{room-amb} = R_{ven} \,\|\, \left(R_{indoor-w\&c} + R_{w\&c-amb}\right) \| \left(R_{indoor-door} + R_{door-amb}\right) \quad (7)$$

C_{indoor} is equal to 0.022 times of weight of the prefabricated transformer substation [2].

From solving thermal model given in Fig. 4 the following equations are derived.

$$q_{fe} + q_l = C_{th-oil} \times \frac{d\theta_{oil}}{dt} + \frac{\left(\theta_{oil} - \theta_{air-room}\right)}{R_{th-oil-room}} \quad (8)$$

$$q_{fe} + q_l + q_{cabin} = C_{indoor} \times \frac{d\theta_{air-room}}{dt} + \frac{\left(\theta_{air-room} - \theta_{amb}\right)}{R_{room-amb}} \quad (9)$$

The thermal model that presented in [2] can be simplified as Fig. 4.

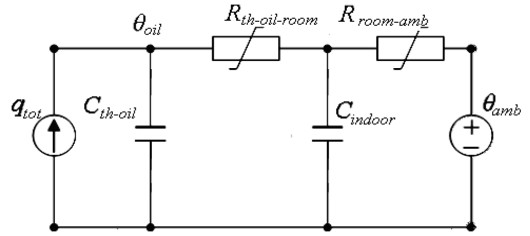


Fig. 4. The equivalent top-oil thermal model for indoor situation.

3.3 Hot Spot Temperature rise modeling

Similar to the theory given for the top-oil temperature model, the hot-spot temperature model is also represented as a thermal circuit (Fig. 5)

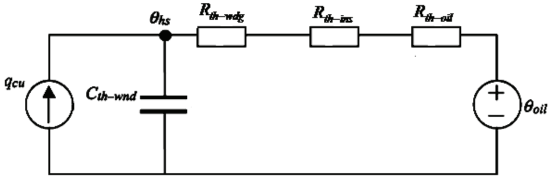


Fig. 5. Hot-spot temperature model.

The heat generated by load losses is represented as an ideal heat source and the top-oil temperature forms an ideal temperature source [6]. The nonlinear thermal resistance is defined by the heat transfer theory, which has already been applied to the top-oil thermal model as explained below. The nonlinear winding to oil thermal resistance is given by the following equation:

$$R_{th-hs-oil} = R_{th-wdg} + R_{th-ins} + R_{th-oil} \quad (10)$$

Where $R_{th\text{-}wdg}$ is the winding thermal resistance, $R_{th\text{-}ins}$ is the insulation thermal resistance, and $R_{th\text{-}oil}$ is the oil thermal resistance.

Comparing the resistances given in (10) gives the following thermal correlations [6].

$$R_{th-oil} \rangle\rangle R_{th-wdg} \quad (11)$$

$$R_{th-oil} \rangle\rangle R_{th-ins} \quad (12)$$

The simplified thermal model of hot-spot temperature obtained from Fig. 5 considering the above given thermal correlations is shown in Fig. 6 [6]. Thus, the final equation for the nonlinear winding to oil thermal resistance is as;

$$R_{th-hs-oil} = R_{th-oil} = \frac{1}{h \cdot A} \quad (13)$$

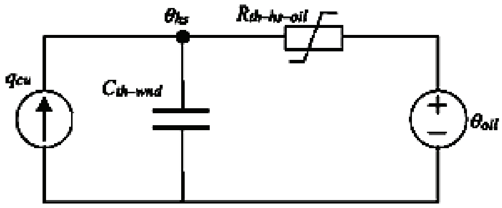


Fig. 6. Simplified Hot-spot temperature model.

Equation (13) is similar to (1) for the top-oil temperature model; therefore, the derivation of the heat transfer coefficient (*h*) for hot-spot temperature is completely similar to that of the heat transfer coefficient given in (2).

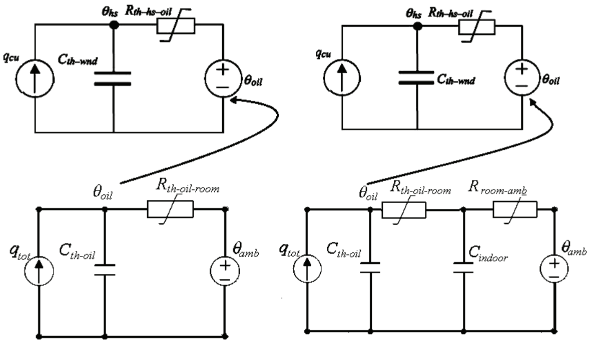
$$h = C_1 \times \left(\frac{\Delta\theta_{hs}}{\mu}\right)^n \quad (14)$$

The viscosity, μ depends on the hot-spot temperature. Equation (15) is the result obtained from applying the energy balance theorem to the thermal circuit shown in Fig. 5.

$$q_{cu} = C_{th-wdg} \times \frac{d\theta_{hs}}{dt} + \frac{(\theta_{hs} - \theta_{oil})}{R_{th-hs-oil}} \quad (15)$$

Substituting heat transfer coefficient, h obtained from Equation (14) into (13) gives $R_{th\text{-}hs\text{-}oil}$, which is used in Equation (15) to obtained Equation (16).

$$q_{cu} = C_{th-wdg} \times \frac{d\theta_{hs}}{dt} + \frac{(\theta_{hs} - \theta_{oil})}{C_1 \times \left(\frac{\Delta\theta_{hs}}{\mu}\right)^n \cdot \frac{1}{A}} \quad (16)$$



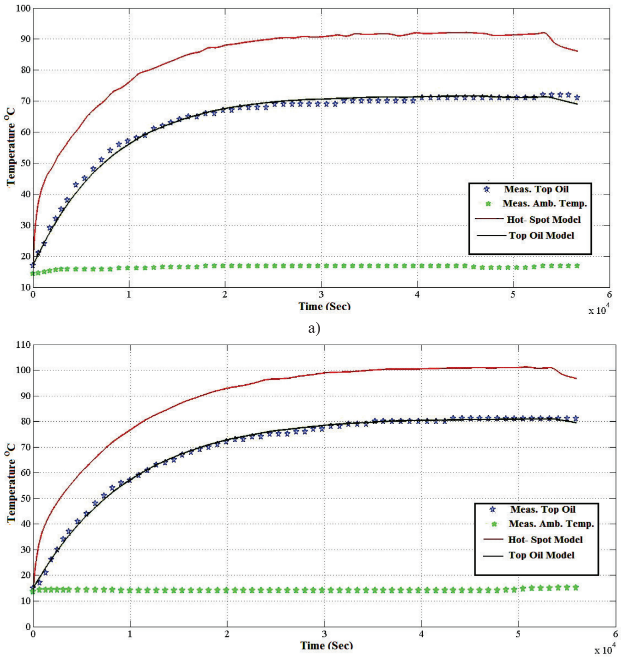
a) b)

Fig. 7. Hot-spot temperature model a) Outdoor situation b) Indoor situation .

The simplified form of Equation (16) is given as:

$$q_{cu} \cdot \left(\frac{\mu^n}{C_1 \cdot A}\right) = \left(\frac{\mu^n}{C_1 \cdot A}\right) C_{th-wdg} \times \frac{d\theta_{hs}}{dt} + (\theta_{hs} - \theta_{oil})^{1+n} \quad (17)$$

To verify the models derived for outdoor and indoor transformers the experiments were carried out on a transformer under indoor and outdoor situations. The temperature rise results obtained from experimental tests and theoretical study for indoor and outdoor transformers are shown in Fig. 8. In these tests power injected to the primary windings of the transformer (secondary windings are short circuited) [1, 4, 7] are equal. The figures verify the fact that for the same load and the same conditions the top-oil and hot-spot temperatures of indoor transformer are higher than those for outdoor transformer.



a)

b)

Fig. 8. Comparing experimental and theoretical results of the top-oil and hot-spot temperature rise for a) outdoor and b) indoor situations.

4. Insulation aging equations

Montsinger in the 1930s publish the first study on insulation failure as a reduction in the insulating material tensile strength. The aging of the transformer insulation was presented as the reduction in insulation strength by 50% for *XºC*, where *X* varied based on the range of operating temperatures of the insulating material. 1Typical values of *X* vary from 6ºC–10ºC. The International Electrotechnical Commission (IEC) loading guide [1, 10] uses a value of 6ºC for X; i.e., the aging rate doubles every 6ºC in insulation temperature. A loss of life formulation based on the 6-degree rule is given by

$$R_A = 2^{\left(\frac{\theta_{hst}-110}{6}\right)} \tag{18}$$

The transformer aging methodologies in this section are also based on IEEE C57.91-1995, as discussed in [1]. The winding hottest spot temperature is used to determine the transformer equivalent aging. The following equation for an aging acceleration factor, FAA, is based on the equation for aging acceleration factor from:

$$R_{A,l} = e^{\left[\left(\frac{15000}{(\theta_{hsts,R})+273}\right)-\left(\frac{15000}{\theta_{hsts,l}+273}\right)\right]} \tag{19}$$

The aging acceleration factor will have a value of 1.0 for continuous transformer operation at rated winding hottest spot temperature. For transformer operation above rated winding hottest spot temperature, the aging acceleration factor is greater than one, indicating accelerated aging. Eq. 20 estimates the total equivalent aging time, EQA, over the entire PHEV demand profile:

$$EQA = \int_{t_i}^{t_u} R_{A,1}\,dt \tag{20}$$

Eq. 21 estimates the equivalent aging factor, FEQA, for the entire PHEV demand profile:

$$LOL = \frac{\int_{t_i}^{t_u} R_A(t)dt}{\int_{t_i}^{t_u} dt} \tag{21}$$

The insulation rate of aging is expected to double for every 6˚C rise in insulation hottest-spot temperature. The LOL in percent can be computed by

$$LOL = \frac{\sum_{i=1}^{N} R_A(i)\Delta t_i}{\sum_{i=1}^{N} \Delta t_i} \tag{22}$$

where *N* is the number of intervals over which the LOL is to be computed, and Δt_i is the duration of the *i* th interval.

5. Failure rate

The bath-tub curve is used for estimating the frequency of the failure incidents likely to be expected. Figure 9 shows a typical failure rate bath-tub curve for transformers.

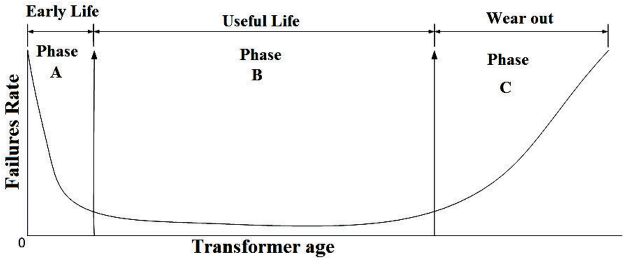


Fig. 9. Typical transformers failure rate bath-tube curve.

There are three different regions on the cure as:

Phase A: This region is corresponding to new transformers. This period is approximately, 1-3 years after commissioning. During this period, the number of failures will drop to a very few incidents per annum, even to zero incidents; any failures occurring during that period are caused mostly by production or design errors (e.g. small leaks, incorrect sensor settings etc.)

Phase B: This region is for normal operation and depends on the type, loading and maintenance of contemporary transformers. In this phase, no major failures are likely to occur and may last between 20 and 30 years.

Phase C: During this period the number of incidents increases and the problems mainly are caused by ageing.

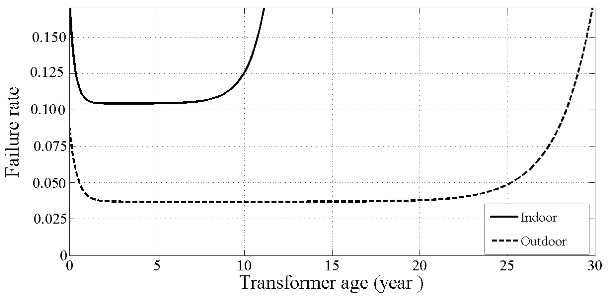


Fig. 10. Transformers failure rate for indoor and outdoor operating situations.

Figure 10 shows the failure rate for indoor and outdoor transformers loaded at the same conditions and power. This curve has been derived considering the conditions of the test the result of which is shown in figure 8.

6. Conclusions

The dynamic and steady-state responses of indoor and outdoor transformers are different according to the theoretical and experimental results. The steady-state values of top-oil and hot-spot temperature rises of indoor transformer are higher than those for outdoor situations.

Figure 10 verifies the fact that for the same load and the same conditions the failure rate and the loss of life of indoor transformer are higher than those for outdoor transformer.

The results of this study show that the loading of transformer is very important and affects deeply the loss of life of a transformer. In addition, for the same loss of life, the indoor transformer should be loaded below that for outdoor situation.

7. Acknowledgments

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8. References

[1] Guide for Loading Mineral-Oil-Immersed Transformers, IEEE Standard C57.91, 1995. 12 June 2003.

[2] I. Iskender, A. Mamizadeh, “An improved nonlinear thermal model for MV/LV prefabricated oil-immersed power transformer substations”, Electrical Engineering (Archiv fur Elektrotechnik), Springer Berlin / Heidelberg, Volum : 93 Issue: 1 pages : 9-22, Mar 2011, DOI: 10.1007/s00202-010-0186-y

[3] G. Swift, T. Molinski, W. Lehn, and R. Bray, “A fundamental approach to transformer thermal modeling—Part I: Theory and equivalent circuit,” IEEE Trans. on Power Delivery, vol. 16, no. 13, 2001.

[4] IEC 60076-2 power transformer part 2 temperature rise, IEC standard 60076-2

[5] Z. Radakovic, S. Maksimovic, " Non-stationary thermal model of indoor transformer stations ", Electrical Engineering 84 (2002) 109–117 _ Springer-Verlag 2002 , DOI 10.1007/s00202-001-0111-5

[6] D. Susa, M. Lehtonen, H. Nordman, "Dynamic Thermal Modeling of Power Transformers" , Ieee Transactions On Power Delivery, Vol. 20, No. 1, January 2005.

[7] High-voltage switchgear and controlgear – Part 202: High-voltage/low-voltage prefabricated substation , IEC Standard 62271-202 , 06 2006

[8] IEEE C57.100-1999, IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers.

[9] I. Iskender, A. Mamizadeh, "Thermal Capacitance Calculation of Top-Oil Temperature for Power Transformers", International Review Of Electrical Engineering-IREE, VOL. 4, NO. 5, Part A, Page 882-886, September – October 2009

[10] V. V. S. S. Haritha, T. R. Rao, A. Jain, M. Ramamoorty, “Thermal Modeling of Electrical Utility Transformer”, Third International Conference on Power Systems (ICPS 2009), Report No: IIIT/TR/2009/209, Hyderabad , INDIA, December 2009

[11] Daniel J. Tylavsky, Xiaolin Mao, Gary A. McCulla, “Transformer Thermal Modeling: Improving Reliability Using Data Quality Control”, IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 21, NO. 3, Pages 1357-1366 JULY 2006

[12] M. Ali, C. Eley, A. M. Emsley, R. Heywood, and X. Xaio. Measuring and understanding the ageing of kraft insulating paper in power transformers. IEEE Electrical Insulation Magazine, 12(3):28–34,May 1996.

[13] van Schijndel A., Wetzer J.M., Wouters, P.A.A.F., “Remaining lifetime modelling for replacement of power transformer populations”, International Conference onCondition Monitoring and Diagnosis, 2008. CMD 2008.

[14] Cigré Working Group 12.05. An international survey on failures in large power transformers in service. Electra, 88:21–48, 1983.

[15] M. K. Pradhan, T. S. Ramu, “On the Estimation of Elapsed Life of Oil-Immersed Power Transformers.”, Ieee Transactions On Power Delivery, Vol. 20, No. 3 pages: 1962-1969, July 2005.

[16] P. Agoris, P. Cichecki, S.Meijer, and J. J. Smit. “Building a transformer defects database for UHF partial discharge diagnostics”, In 2007 IEEE Lausanne Power Tech, pages 2070–2075, Lausanne, Switzerland, July 2007. IEEE.

[17] A. M. Emsley and G. C. Stevens. Review of chemical indicators of degradation of cellulosic electrical paper insulation in oil-filled transformers. IEE Proceedings Science, Measurement and Technology, 141(5):324–334, September 1994.

[18] Abu-Siada, A., Lai Sin Pin, Islam, S., “Remnant life estimation of power transformer using oil UV-Vis spectral response”, Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES

[19] IEEE C57.100-1999, IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers.

[20] Stebbins, R.D., Myers, D.S., Shkolnik, A.B., Furanic compounds in dielectric liquid samples: review and update of diagnostic interpretation and estimation of insulation ageing, The 7th International Conference on Properties and Applications of Dielectric Materials, 2003. Volume 3, 1-5 June 2003 Page(s):921 - 926 vol.3