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A Strategy for Replacement of Oil-Cooled Power Transformer

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ABSTRACT

Estimation of the remaining life of a power transformer in service has been of a big concern to most owners, especially when it is known to have been overloaded either continuously or intermittently over long periods. Therefore, to make economical decisions for such transformer replacement, it is critical to estimate the remaining life expectancy. This paper discusses, in detail, the insulation aging and life expectancy estimation of oil-filled transformers and also provides a simplified transformer overloading guidelines.

1. INTRODUCTION

Emergency and/or planned overloading capability of power transformers beyond their nameplate rating is primarily limited by the winding hottest-spot temperature. It depends on several factors including design and operating characteristics, daily load curve, historical loading data, testing and maintenance program, and specific applications. Determining accurately the hottest-spot temperature is very critical to the transformer overall life expectancy assessment.

Most transformer failures can be related to the thermal deterioration of insulation which is known to be a function of both time and temperature. For liquid-filled transformers, the traditional winding insulation system is thermally upgraded oil-impregnated (cellulose) paper. Over time, the paper loses mechanical (tensile) and electrical strength (surge withstand capability) and becomes brittle when exposed to elevated operating temperatures causing the deterioration of the insulating properties. Oxygen and water are the primary agents that degrade cellulose insulation. Heat acts as catalysts and accelerates the reactions in producing various oil-degradation products.

The winding (I^2R) losses, the core losses, and the stray losses in the tank and metal support structures are the principle sources of heat that cause the oil and winding temperature rises. Individual temperature rises taken at different locations may vary due to local eddies. However, there may be significant differences between top and bottom oil rises, and this depends on the design of the cooling systems and winding construction. The difference between the top and bottom oil rises with forced oil cooling (FOA) will be in the order of only a few degrees, whereas, this difference will be several times larger for forced air cooled (FA) transformers. A typical simplified transformer cooling model used for analysis is illustrated in Fig. 1.

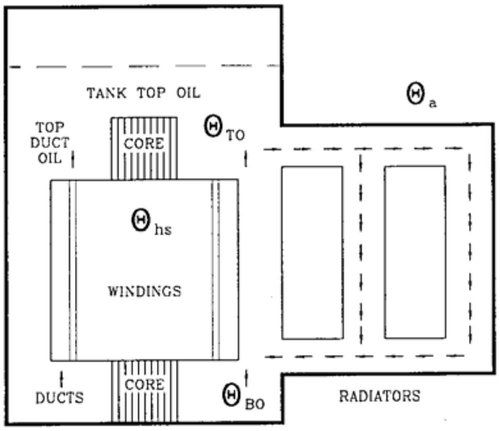


Fig. 1 Transformer Fluid Flow

2. UNDERSTANDING TRANSFORMER NAMEPLATE RATING

The transformer nameplate MVA rating is the continuous apparent power which can be delivered under normal operating conditions without exceeding the specified temperature limits, and normal loss-of-life. Currently thermally upgraded oil-paper and enamel insulation systems are utilized in the design of large power transformers and they are rated for the single 65°C average winding temperature rise. However, 55°C temperature rise rating (with a 65°C highest rating) is still widely used in the industry. For 130°C (Old Class B) insulation system, Hottest-Spot Temperature (θ_{hs}) = 30°C (ambient) + 65°C (average winding temperature rise) + 15°C (hot-spot margin) = 110°C.

Transformer ratings under forced cooling systems are also based on the type of cooling employed. There exist some relationships between the base rating (OA) and the corresponding increase in rating due to the added cooling systems. Transformer overloading above the nameplate capacity without any additional sacrifice of life may be possible for short periods of time during low ambient temperature conditions and lower initial loads. Unless done with proper evaluation, this may cause damage which is not always readily apparent. Such damage increases the probability of failure when abnormal electrical stresses, such as those associated with switching surges, and abnormal mechanical forces associated with through fault currents, are encountered.

3. TRANSFORMER FAILURE MODES

There are basically two failure modes occur during overloading. (The failure due to bad designs and quality control is not taken into consideration here).

- The *first mode is the long-term failure*. The dielectric strength of conductor insulation deteriorates slowly under normal loading. Mechanical properties, such as, retained tensile strength (RTS) and/or retained degree of polymerization (RDP) are the most acceptable criteria used to measure the insulation integrity. The corresponding correlation with the loss-of-life is discussed in reference [1].
- The *other failure mode is the short-term* and is attributed to bubble formation (or gassing) in the oil. This is common when there is a rapid growth of heat generation as it happens during the short circuit.

Impulse test [2] on transformers under overload has revealed that at 180°C impulse strength reduces up to 30% compared with the value at room temperature. In power transformer winding model test [3], at temperature greater than 150°C, a sharp drop of 60 Hz dielectric strength has also been reported. The actual age of insulation under normal operating conditions, on the other hand, has relatively minor effect on dielectric strength. The model tests reported just 10% reduction in dielectric strength under normal operating conditions over a life span of 30 years.

4. OVERLOADING, TEMPERATURE RISE AND INSULATION LIFE CHARACTERISTICS

Historically, the loss-of- life of insulating paper has been determined by the reduction of its tensile strength. A 50% reduction of tensile strength has been used as the criteria for a long period of time and this has produced very conservative results. More recently, an alternative method using the retained degree of polymerization (RDP) of the insulating paper has been used to determine the electrical insulation life. The relative dielectric constant and loss tangent method are also being investigated by monitoring changes in capacitance and conductance as a function of frequency to determine the thermal age of a power transformer [4].

As stated in the IEEE Standard C57.91-1995 [5], transformer insulation deteriorates as a function of time and temperature and the aging is determined by the hottest-spot temperature (θ_{hs}). Normal life expectancy is said to occur when transformers with a rated average winding rise of 65°C are operated continuously with hottest spot temperatures of 110°C. Various temperatures such as top oil, radiator surfaces, and cooling medium can be measured directly to estimate the transformer hottest spot temperature. This value, θ_{hs}, can be expressed in two different ways. It is based on the sum of the ambient temperature (θ_a), the average winding temperature rise ($\Delta\theta_w$) and the hottest spot temperature rise margin above the average winding temperature rise ($\Delta\theta_1$).

$$\theta_{hs} = \theta_a + \Delta\theta_w + \Delta\theta_1 \tag{1}$$

where, $\Delta\theta_1$ = 15°C for 65°C average winding temperature rise.

The alternate form that is used recently is given by:

$$\theta_{hs} = \theta_a + \Delta\theta_{TO} + \Delta_g \tag{2}$$

where, $\Delta\theta_{TO}$ = Average top-oil temperature rise above ambient, and
$\Delta\theta_g$ = Hottest-spot winding temperature rise over the top oil.

There are also several other semi-empirical equations available to predict the hottest spot temperature rise at rated full load. Fig. 2 depicts a commonly used simplified model of the transformer temperature rise quantities that is used to calculate the hot-spot temperature.

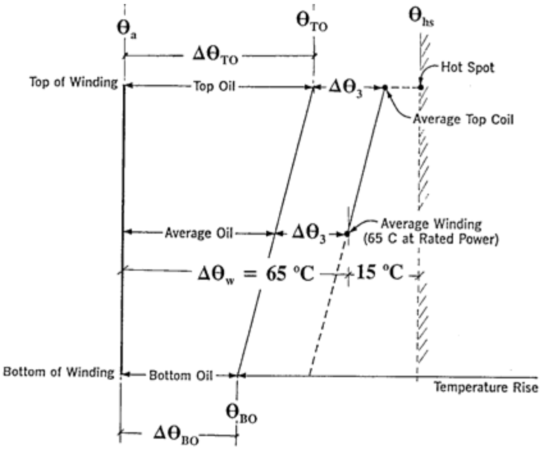


Fig. 2 Transformer Thermal Diagram

5. TRANSFORMER'S THERMAL MODEL

There are two transformer's thermal models in the IEEE guide: the classical thermal model as discussed in Clause 7 is simple and requires minimum information, whereas, the alternative thermal model discussed in Annex G is more complex and requires more detailed information. In this paper, we focus on Clause 7 model. The detailed calculation of Annex G can be found in reference [6] and also in the IEEE loading guide.

The hottest-spot temperature of Clause 7 (IEEE Standard) is calculated from Eq. (2). The top-oil temperature rise under steady-state condition is proportional to the total transformer loss and is given by:

$$\Delta\theta_{TO} = \Delta\theta_{TOR} \cdot \left(\frac{K^2 R + 1}{R + 1} \right)^n \tag{3}$$

where, $\Delta\theta_{TOR}$ = the top-oil temperature rise at rated load,
K = the per-unit loading,
R = the loss ratio, and
n = an exponent (oil).

The hottest-spot rise over top-oil temperature ($\Delta\theta_g$) is also proportional to winding loss and is given by:

$$\Delta\theta_g = \Delta\theta_{gr} \cdot (K^2)^m \tag{4}$$

where, $\Delta\theta_{gr}$ = the hottest-spot rise over top-oil temperature at rated load, and
m = an exponent (winding).

The transient equation for temperature rise can be written as:

$$\tau_{TO}\frac{d\Delta\Delta_{TO}}{dt}=-\Delta\theta_{TO}+\Delta\theta_{TO,u} \tag{5}$$

where, τ_{TO} = oil time constant, and

$\Delta\theta_{TO,u}$ = the ultimate top-oil rise from Eq. (3).

By applying Laplace Transform to the above equation:

$$\tau_{TO}s\Delta\Delta_{TO}(s)=-\Delta\theta_{TO}(s)+\Delta\theta_{TO,u}(s) \tag{6}$$

$$\Delta\theta_{TO}(s)=\frac{1}{1+\tau_{TO}s}\cdot\Delta\theta_{TO,u}(s) \tag{7}$$

The hottest-spot rise over top-oil temperature ($\Delta\theta_g$) can be found in the same manner using the winding time constant. The transient equation is written as:

$$\Delta\theta_g(s)=\frac{1}{1+\tau_g s}\cdot\Delta\theta_{g,u}(s) \tag{8}$$

From Eqs. (3), (4), and (5), the block diagram of IEEE Std. Clause 7 transient equation is shown in Fig. 3. When the load curve, *K(t)*, is discretized into small time period, the solutions to the first-order differential Eqs. of (7) and (8) then are:

$$\Delta\theta_{TO}=(\Delta\Delta_{TO,u}-\Delta\theta_{TO,i})(1-e^{-t/\tau_{TO}})+\Delta\theta_{TO,i} \tag{9}$$

$$\Delta\theta_g=(\Delta\Delta_{g,u}-\Delta\theta_{g,i})(1-e^{-t/\tau_g})+\Delta\theta_{g,i} \tag{10}$$

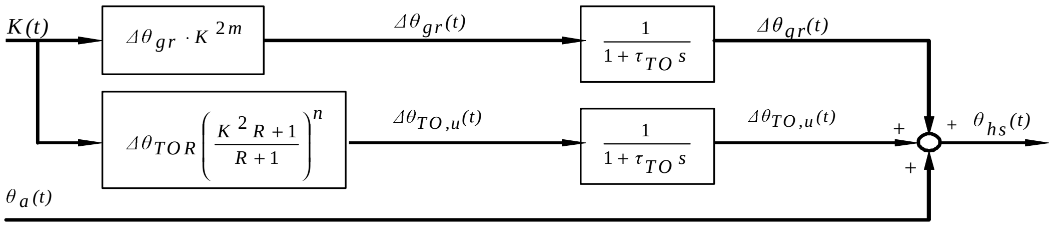
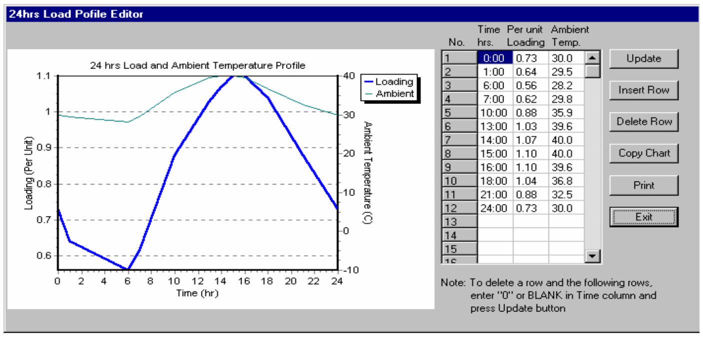


Fig. 3 Block Diagram of IEEE Clause 7 Transient Equations

6. COMPUTER PROGRAM

A PC based computer program has been written to calculate transformer temperatures and loss-of-life based on any load and ambient profiles. The program provides users with easy interface by graphic user interface (GUI). Users can save, open file, print, and copy text and graph results to clipboard.

The program can calculate temperatures and loss-of-life on either daily basis or for any life cycle study with load growth. The estimated remaining tensile strength and degree of polymerization are also printed out. Figs. 4 to 8 illustrate some typical results (self-explanatory) from the program. Additional information is also provided in the Appendices 9.1 and 9.2.



No.	Time hrs.	Per unit Loading	Ambient Temp.
1	0:00	0.73	30.0
2	1:00	0.64	29.5
3	6:00	0.56	28.2
4	7:00	0.62	29.8
5	10:00	0.88	35.9
6	13:00	1.03	39.6
7	14:00	1.07	40.0
8	15:00	1.10	40.0
9	16:00	1.10	39.6
10	18:00	1.04	36.8
11	21:00	0.88	32.5
12	24:00	0.73	30.0
13			
14			
15			

Note: To delete a row and the following rows, enter "0" or BLANK in Time column and press Update button

Fig. 4 Load and Ambient Temperature Profiles Data

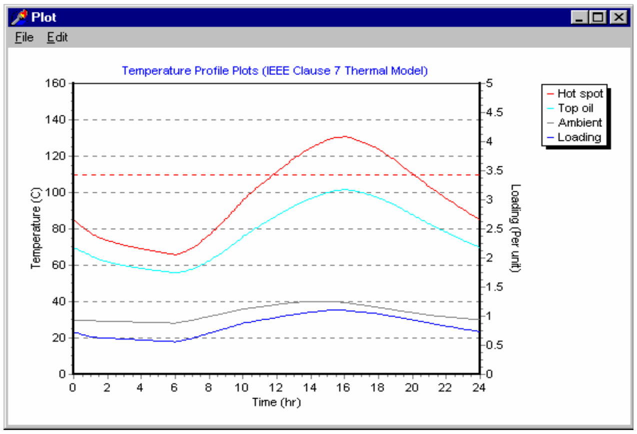


Fig. 5 Temperature Plots from Computer Program

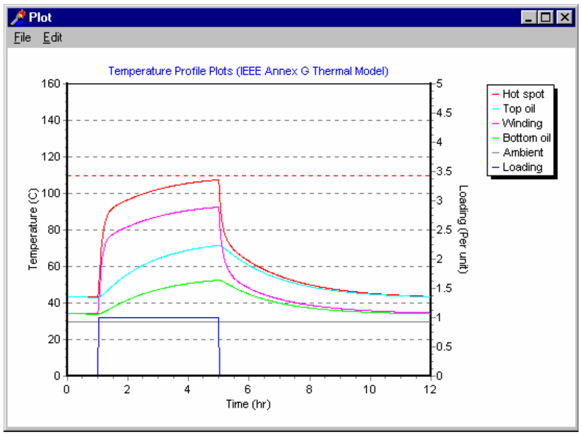


Fig. 6 Step Load Response from Annex G Model

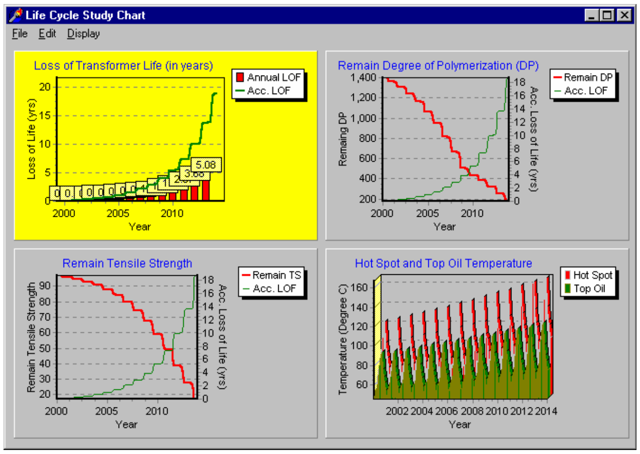


Fig. 7 Life Cycle Study Plots

7. CONCLUSIONS

For several reasons, overloading of power transformers beyond their nameplate rating has been routinely practiced by the utilities. However, in order to achieve greater profit (mainly in the form of deferred capital cost for transformer replacement), more and more utilities now are aggressively pursuing overloading the power transformers at the cost of loss-of-life. Overloading can take place in different forms, such as, continuous, intermittent, planned, short or emergency. Depending on the application considerations, some form of overloading of transformers may not cause any damage and hence, reduced life expectancy and may be acceptable. In other applications, overloading may cause severe damages. In order to find the optimum most cost effective operation, it is essential for the utilities to be able to predict with reasonable accuracy the transformer remaining life under certain overloading conditions.

Because of the complex nature of this problem, it is very difficult to determine the total effects of overloading on transformers. A simplified overloading guideline, considered to be a good and acceptable practice, is developed in this paper. This paper has also presented a general, yet in depth, discussion on the transformer overloading capabilities, the corresponding loss-of-life and simple method of estimating the remaining life expectancy. The technique presented in this paper is simple and requires a sample of paper and testing for RDP and RST. Currently, there are other methods, such as analysis of dissolved gas in oil or other on-line monitoring devices, are also being developed for future applications.

8. REFERENCES

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9. APPENDICES

9.1 Loss-of-Life Estimation

To estimate accurately the hot-spot, winding and oil temperatures, one needs to consult the loading guides. The IEEE standard utilizes the top-oil temperature and the temperature rise over top-oil for the calculation of the hot-spot temperature and assumes a 30°C ambient temperature.

The IEEE loading guide also utilized the concept of "the relative aging rate" and "per-unit life". The per-unit life equation for 65°C average winding temperature rise transformer is defined by:

$$\textit{Per-Unit Life} = 9.80 \, x \, 10^{-18} e^{\left[\frac{15{,}000}{\theta_{hs}+273}\right]} \tag{11}$$

For, $\theta_{hs} = 110^{\circ}\text{C}$ (= 30+65+15), the per-unit life = 1.00.

The idea of relative aging rate is defined by the Relative Aging Factor (F_{AA}):

$$F_{AA} = e^{\left[\frac{15{,}000}{383} - \frac{15{,}000}{\theta_{hs}+273}\right]} \tag{12}$$

The value of F_{AA} is greater than 1, when the hot-spot temperature exceeds 110°C, suggesting loss-of-life (from normal aging) and less than 1 when the hot-spot temperature is less than 110°C, meaning life extension.

Eq. (12) may be used to calculate equivalent aging of the transformer in hours at any other temperature which will be consumed in a given time period (T) and is given by:

$$F_{EQA} = \frac{1}{T} \int_{0}^{T} F_{AA} \, dt \tag{13}$$

The % loss of life, when the normal insulation life is known, can be calculated as:

$$\%Loss\ of\ Life = \frac{F_{EQA}\ x\,T}{Normal\ Insulation\ Life} \times 100 \tag{14}$$

IEEE standard provides some commonly used values for the "normal insulation life" as shown in Table 1. The expected transformer life used commonly in the industry is estimated between 20-30 years. However, depending on transformer operating conditions, 40 years (or more) of service life is not uncommon. This, however, is based on the assumption of long periods of light loads and lower ambient temperatures.

Table 1 Normal Insulation Life per IEEE C57.91-1995

End of Life Criteria	Hours (Yrs.)
50% retained tensile strength (RTS)	65,000 (7.42)
25% retained tensile strength (RTS)	135,000 (15.41)
200 retained RDP or 20% (RTS)	150,000 (17.12)
Distribution Transformer Functional Life Test Data	180,000 (20.55)

9.2 Estimation of Remaining Life Expectancy [1]

Transformer life is closely related to the insulation life. The insulation end-of-life criteria of 50% RTS (or life span of 7.42 yrs.), initially utilized by the IEEE, was very conservative. RDP of 200 (or equivalent to 20% RTS) seems to be preferred by recent investigators since this provides with realistic numbers in life expectancy (approx. 17 years). The direct measurement of RTS or RDP on paper sample retrieved from transformer is the most accurate way to estimate the remaining life of transformer. Utilities generally may do it where appropriate opportunity is available such as schedule maintenance and repair. Reference [7] published the results of % RTS and RDP of thermally upgraded paper aged in seal tube at an elevated temperature of 160°C. In order to provide some estimation, the discrete data available from reference [7] were fit to the exponential curve by least square method.

If the 20% RTS and/or 200 RDP are used as end-of-life criteria, the time (*T*) in per-unit life and the retained tensile strength curve can be written as:

$$Retained\ Tensile\ Strength\ (RTS) = 97.05e^{-1.58T} \tag{15}$$

$$Retained\ Degree\ of\ Polymerization\ (RDP) = 622e^{-1.135T} \tag{16}$$

Then, the transformer remaining life can be estimated from the following Eqs. (17) and (18), when the RDP or RTS of the insulation can be measured:

$$Remaining\ Life\ = 1 + 0.633\ln\left(\frac{RTS}{97.05}\right) \tag{17}$$

$$Remaining\ Life\ = 1 + 0.881\ln\left(\frac{RDP}{622}\right) \tag{18}$$

Finally, there should be a correction for the moisture content. The IEEE recommended end-of-life value assumes low oxygen and 0.5% moisture level. The paper must be well dried with 0.5% water content by weight. If the moisture content increases, the insulation life further reduces according to the following equation:

$$Normal\ Life = \frac{Normal\ Life@0.5\%H_2O}{2\times\%H_2O} \tag{19}$$

9.3 Simplified Transformer Overloading Guidelines

A simplified transformer overloading guidelines (suitable for practicing engineers) including some of the key features are depicted in Fig. 8 and summarized in Table 2.

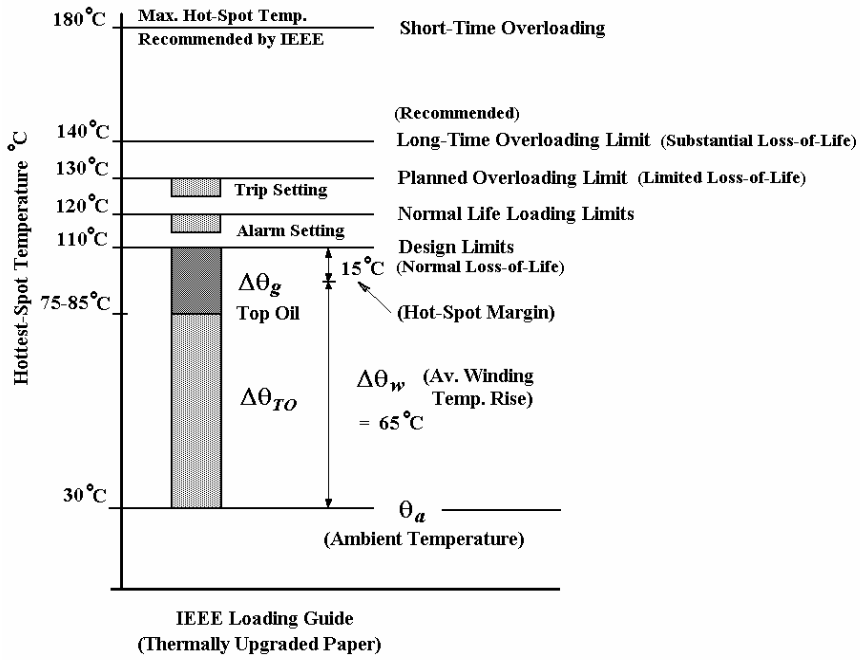

Fig. 8 IEEE Temperature Limits for Various Types of Loading

Table 2 The Thermal and Electrical Limits for Various Types of Loading

Type of Loading	IEEE		
	Current (pu.)	Winding Hot-spot	Top-oil Temp.
Normal Life Expectancy Loading	2	120	105
Planned Loading beyond the Nameplate Rating	2	130	110
Long-Time Emergency Loading	2	140	110
Short-Time Emergency Loading	2	180	110

- *Understand Transformer Nameplate Rating and Design Fundamentals* - Transformer Classification (Distribution and Power); Cooling; Average Winding Temperature Rise; Insulation Type (thermally upgraded vs. *kraft* paper) and Class; Allowable Hot-Spot Temperature and Design Limits, Insulation Life vs. Transformer Life.
- *Determine End-of-Insulation Life Criteria and the "Normal" Insulation Life Value* - Retained Tensile Strength (RTS); Retained Degree of Polymerization (RDP), or other. Typical industry standards for transformer life is between 20-40 yrs. 30 yrs., is a commonly used number.
- *Moisture Content* - Every 0.5% increament of moisture content reduces insulation life by half.
- *Normal Life Expectancy Loading* - Average (24 hrs.) maximum hot-spot temperature of 110°C without exceeding the maximum value of 120°C. No limit for loading beyond nameplate rating, as long as the average hot-spot temperature doesn't exceed 110°C.
- *Planned Loading Beyond the Nameplate Rating* - Average (24 hrs.) maximum temperature of 110°C without exceeding the maximum value of 130°C with limited loss-of-life. Aging rate is doubled for every 6-8 °C continuous hot-spot temperature increment.
- *Long-Time Emergency Loading* - May last for weeks and months. It is recommned that the maximum hot-spot temperature should not exceed 140°C in order to avoid substantial loss-of-life. Aging is doubled for every 6-8 °C continuous hot-spot temperature increment.
- *Short-Time Overloading* - Usually last for a short-time (less than half-an-hour), and the hot-spot temperature may go up to 180°C with severe loss-of-life. Transformer failure is expected due to the bubble and gas formation in the oil.
- *Maximum Overloading at Any Time* - Limited to 2 times the highest rating.
- *Ambient Temperature* - Worst possible condition over a 24 hrs. period. For every 1°C ambient temperature decrement, loading capacity can be increased by 1% without any loss-of-life and vice versa.
- *Maximum Allowable Absolute Temperature* - 180°C as per IEEE.
- *Bushing Overloading Capacities* - 150°C maximum bushing hot-spot temperature and/or 2 times rated bushing current (per IEEE).
- *Bushing-Type Current Transformer* – Bushing-type current transformers have the top-oil as their ambient, which is limited to 105°C.
- *Recommended Practice* – For normal operation, for the winding hot-spot temperature, in case of OA/FA or OA/FA/FA, set the alarm between 115°C - 120°C and trip between 125°C - 130°C. For FOA cooling, it is recommended that both alarm and trip should be set at lower values by 5-10°C. At higher operating temperatures, expect significant loss-of-insulation-life depending on the duration, frequency, and the moisture content.
- In case of unavailable winding hot-spot temperature values, *recommended values for the top-oil temperatures gauge settings* (OA/FA, OA/FA/FA) 100°C for alarm and 110°C for trip. For FOA, again the alarm and trip settings are lowered by 5-10°C. It is also highly recommended to consult with the manufacturer.