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CALCULATION OF HOT SPOT TEMPERATURE AND AGING OF A TRANSFORMER

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***Abstract*— Temperature is one of the prime factors that affect the Transformer life. In fact increase temperature is a major cause of reduce Transformer life. Further the cause of most transformer failuren is breakdown of insulation system, so anything that adversely affects the insulation properties inside the transformer reduces its life. Such things as overloading of transformer, moisture in transformer, poor quality oil and insulating material, extreme temperature affect the insulating properties of the transformer.**

Key words – transformer, insulation, hot spot temperature, aging.

I. Introduction

A transformer has many components that require maintenance. The insulating system is a truly vital part, consisting of the oil and the solid insulation. The solid insulation may not be so readily accessible, but the oil certainly is. Oil can be kept in a good condition for a very long time and with proper care, probably for an indefinite period of time. However, poorly maintained oil will significantly reduce the technical life of the transformer

It is sometimes stated that the end of life of a transformer is ultimately decided by the end of life of the solid insulation. Even though it is true that many transformers are taken out of service before the solid insulation is so severely degraded, it is still true that the condition of the cellulosic insulation sets a limit for how long a transformer can be safely and reliably operated. For this reason alone, it is wise to carry out preventive maintenance.

II. Effect of Moisture in Insulating Oil

Moisture and oxygen cause the oil to decay much faster than the normal rate and form acid and sludge. Sludge settles on windings and inside the structure, causing transformer temperature rises. If temperature increases then conductor resistance increases and consequently transformer Output voltage and load voltage decreases. So under voltage occurs if transformer temperature rises.

Moisture lowers the dielectric strength of oil. Thus insulating property decreases. So breakdown voltage also decreases with increase of moisture content in oil, which is shown in Fig.1.

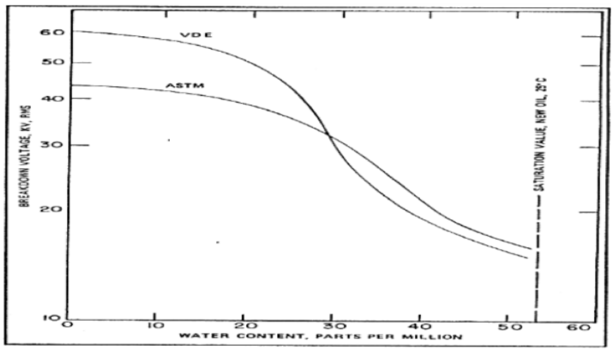

Fig 1. Moisture vs Dielectric Breakdown.

III. Effect of Moisture in Insulation

Moisture rises temperature and lowers the dielectric strength of solid insulation.

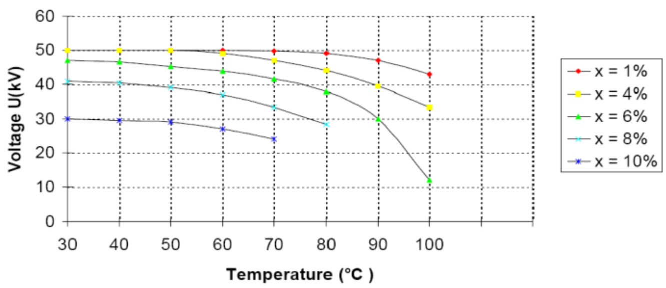

Fig 2.Temperature vs Breakdown Voltage curve for insulating material.

Moisture raises the temperature and hence dielectric power factor and increases the risk of thermal breakdown of solid insulation.

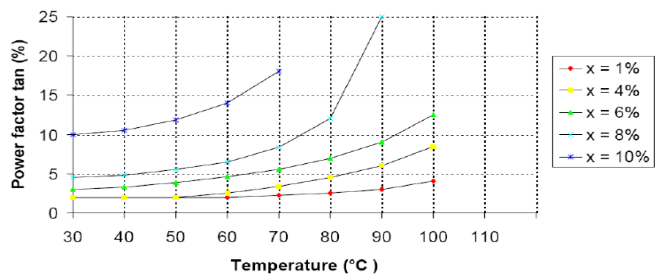

Fig 3. Temperature and hence Dielectric power factor curve.

Moisture accelerates thermal aging of paper insulation [1].

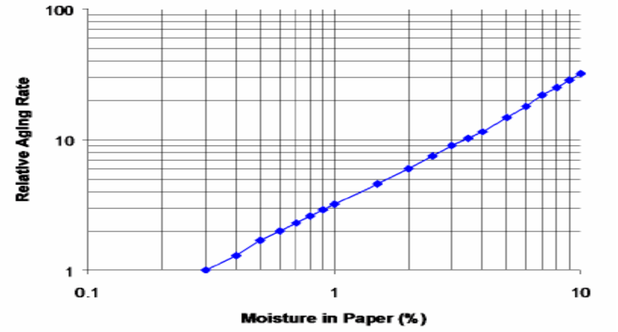

Fig 4. Linear relation between Moisture content in paper and aging rate.

IV. CALCULATION OF HOT SPOT TEMPERATURE IN 154KV TRANSFORMER

The heat run test is conducted to determine whether the temperature rise limits of the top liquid and the average winding satisfy to the specification or not. The heat run test is mostly used for the routine test in the factory. Test methods of the heat run test are actual loading method, loading back method and short circuit method. In the factory test, however, the heat run test is measured by the short circuit method. The heat run test by the short circuit method makes the secondary winding short and applies voltage to the primary winding, supplying current equivalent to loss.

A. Specification of the 154 kv transformer

Table 1. Specification of the 154 kv transformer

Classification		Specification
Loss	No-load	11,280W
	Load	78,956W
	Total	90,236W
Rated voltage		154/22.9kV
Rated capacity		Single-phase, 15/20MVA, 60Hz
Core type		Shell
Temperature rise limits		Top liquid 60^0C
		Average winding 65^0C
Cooling method		ONAN/ONAF
% impedance		20%
Liquid volume		11,000 liters

B. Specification got from heat run test and temperature rise test

The power transformer uses a heat run test to measure top liquid temperature rise and average winding temperature rise by the factory test, which is specified in its specification [2].

Table 2. Specification got from heat run test and temperature rise test

Classification		Specification
oil	Top liquid temperature rise($\Delta\theta_0$)	50^0C
	Radiator upper temperature(θ_u)	66^0C
	Radiator bottom temperature(θ_b)	40^0C
Transformer winding	Measured winding resistance After shutdown of the power supply	HV - 0.924Ω
		LV - 0.0201Ω
	Cold resistance measured(R_1)	HV - 0.793Ω
		LV- 0.017228Ω
	θ_{u1}	20^0C
	θ_{b1}	19^0C
	θ_{01}	20^0C

C. Calculation of average temperature of oil

Primary rated voltage = lowest voltage under the rated phase voltage = $\frac{154}{\sqrt{3}}$ ± 12.5% =77798 V

The rated current (I_r), equivalent to load loss is

$$= \frac{rated\ capacity}{primary\ rated\ voltage} = \frac{15\ MVA}{77798\ V} = 192.8\ A$$

The ratio of the current transformation is 400/5A

Rated current at secondary (I_r) = $\frac{192.8}{400/5}$ =2.41 A

Total loss current (I_l) = Rated current × $\sqrt{\frac{total\ loss}{load\ loss}}$

$$= 192.8 \times \sqrt{\frac{90236}{78956}} = 206\ A$$

Total loss current (I_l) at secondary = $\frac{206}{400/5}$ = 2.575 A

The top liquid temperature is the temperature of the insulating liquid at the top of the tank, representative of top liquid in the cooling flow stream. The top liquid temperature is conventionally determined by thermocouple immersed in the insulating liquid at the top of the tank.
Top liquid temperature rise ($\Delta\theta_0$) = 50^0C
Let Ambient temperature (θ_a) = 25^0C
Top liquid temperature (θ_0) = Ambient temperature (θ_a) + Top liquid temperature rise ($\Delta\theta_0$) = (25 + 50) = 75^0C

Average liquid temperature (θ_{om}) = Top liquid temperature(θ_0) – $\frac{radiator\ upper\ temperature(\theta_u) - radiator\ bottom\ temperature\ (\theta_b)}{2}$

$$= 75 - \left(\frac{66-40}{2}\right) = 62^0C$$

Average liquid temperature rise ($\Delta\theta_{om}$) = Average liquid temperature – Ambient temperature (θ_a) = (62 – 25) = 37^0C

D. Calculation of average temperature of winding

The measured winding resistance after shutdown of the power supply was 0.925Ω on the high voltage winding; and was 0.0201Ω on the low voltage winding. The average winding temperature shall be determined using the value of resistance at the instant of shutdown. In Heat Run Test when making power shutdown, connecting the DC power supply and measuring the winding resistance, the winding temperature goes down, resulting in the lower measurement of the winding resistance compared to the instant of power shutdown.

The decay of the winding resistance with time t after shutdown of the power supply can be expressed with the relation

$$R\,(t) = A\,(t) + \Delta R \times e^{-t/T}$$

Where T is an estimate for the time constant of the winding cooling down to the liquid with an exponential decay. Thus, the winding resistance at the instant of shutdown (t = 0) is as follows $R_w = A_0 + \Delta R$

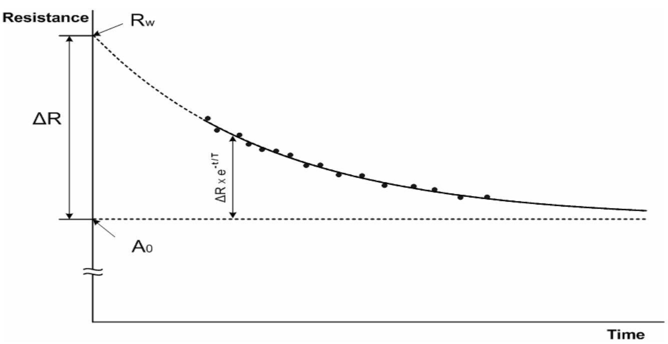

Fig 5. Average winding temperature variation after shutdown

The fall of the resistance from power shutdown to measuring winding resistance is calculated by the extrapolation method. The fall of the resistance (ΔR) measured by the extrapolation method was 0.06575Ω on the high voltage winding and 0.001371Ω on the low voltage winding.

Thus, the winding resistance at the instant of shutdown (R_w) was (0.925Ω + 0.06575Ω) = 0.991Ω on the high voltage winding And (0.0201Ω + 0.001371Ω) = 0.02147Ω on the low voltage winding.

Average winding temperature (θ_w) is the winding temperature determined at the end of temperature rise test from the measurement of winding resistance.

Average winding temperature (θ_w) = $\frac{R_w}{R_1}(235 + \theta_1) - 235$

Where, reference measurement R_1 and θ_1 are the winding resistance and the liquid temperature before the heat run test.
Cold temperature (θ_1) was $\theta_1 = \theta_{01} - (\theta_{u1} - \theta_{b1})/2$
$= 20 - (20\text{-}19)/2 = 19.5\ ^0C$

Cold resistance (R_1) measured is 0.793Ω on the high voltage winding and 0.017228Ω on the low voltage winding.

The average winding temperature (θ_w) on the high voltage winding = (0.991/0.793) (235 + 19.5) – 235 = 83.04 ^{0}C
The average winding temperature (θ_w) on the low voltage winding = (0.02147/0.017228) (235 + 19.5) – 235 = 82.16 ^{0}C

E. Calculation of Hot Spot Temperature (HST)

The hot spot temperature is calculated by the winding resistance for reference which is detected during the heat run test. If the hot spot temperature calculated by the winding resistance is different to the actual hot spot temperature, the life of transformer will be estimated a big error [3].

The average winding to liquid temperature gradient (g) = average winding temperature (θ_w) ~ Average liquid temperature (θ_{om})

So average winding to liquid temperature gradient (g) for high voltage winding = (83.04 – 62) = 21.04^{0}C And average winding to liquid temperature gradient (g) for low voltage winding = (82.16 – 62) = 20.16^{0}C
Corrected average winding to liquid temperature gradient (g_c)

$$= g \times \left(\frac{I_r}{I_l}\right)^{1.6}$$

g_c for high voltage winding = $21.04 \times \left(\frac{2.41}{2.575}\right)^{1.6} = 18.92^0C$

g_c for low voltage winding = $20.16 \times \left(\frac{2.41}{2.575}\right)^{1.6} = 18.13^0C$

Hot spot temperature (θ_h) = top liquid temperature (θ_0) + (h × g_c), Where H=1.3(for power transformer) or 1.1(for distribution transformer).

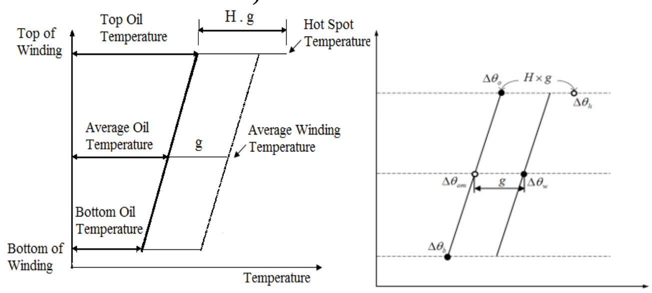

Fig 6. Temperature rise distribution model

Hot spot temperature (θ_h) for high voltage winding = 75 + (1.3 × 18.92) =99.6^{0}C and Hot spot temperature (θ_h) for low voltage winding = 75 + (1.3 × 18.13) =98.57^{0}C

The hot spot temperature rise ($\Delta\theta_h$) = Hot spot temperature (θ_h) – Ambient temperature (θ_a) = (99.6 – 25) = 74.6^{0}C for high voltage winding and (98.57 – 25) = 73.57^{0}C for low voltage winding.

F. Aging calculation of transformer

The standard normal lifetime for oil-immersed power transformer for continuous HST of 110^{o}C based on and other IEEE standards.

IEEE Loading guide shows that insulation life is an exponential function of HST:

% of Insulation life = A × exp (B/ (θ_h+273))

Here θ_h is the HST (^{0}C), A and B are constants that are determined according to insulation material and HST reference defined for normal insulation life. This Equation can be used for both distribution and power transformers because both are manufactured using the same cellulose insulation. For instance, suppose HST reference for insulation life to be 110^{0}C. It means that if the transformer works continuously with this HST, its life will be 1 per unit (life in hour can be determined according to the used insulation) [3]. Using above assumptions above equation would be

Per Unit Life = 9.8 × 10^{-18}× exp (15000/ (θ_h+273))

This Equation yields a value of 1 per unit life for the reference HST of 110^{o}C.

For HV winding Per Unit Life = 9.8 × 10^{-18}× exp (15000/ (99.6+273)) = 2.98 pu

For LV winding Per Unit Life = 9.8 × 10^{-18}× exp (15000/ (98.57+273)) = 3.33 pu

Aging Acceleration Factor (F_{AA}) is the rate at which a transformer insulation aging is accelerated compared with the aging rate at 110 ^{o}C. F_{AA} is given as

F_{AA}= exp (15000/ (110+273)) - (15000/ (θ_h+273))

= 0.3351 For HV winding

= 0.2997 For LV winding

F_{AA} is greater than 1 when the HST is over 110 ^{o}C and less than 1 when the HST is below 110 ^{o}C. Some F_{AA} values at different temperatures are presented in Table

Table 3. F_{AA} values at different temperatures

HST (^{o}C)	F_{AA}	HST (^{o}C)	F_{AA}
60	0.0028	130	6.9842
70	0.0104	140	17.1995
80	0.0358	150	40.5890
90	0.1156	160	92.0617
100	0.3499	170	201.2294
110	1	180	424.9200
120	2.7089	190	868.7719

A curve of F_{AA} vs. HST is shown in Fig. 7. And the conclusion is that the loss of life of transformer insulation is related to the HST exponentially.

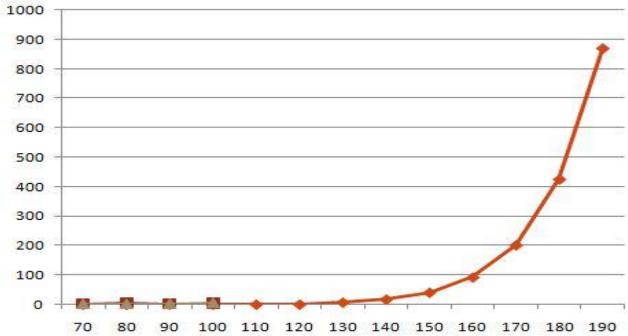

Fig 7. Curve of F_{AA} vs. HST

G. Percentage Loss of Life

The HST is varying according to load and ambient temperature. The equivalent aging acceleration factor at the reference temperature in a given time period (F_{EAA}) for n=1 to N for the given temperature cycle is defined as

$F_{EAA} = \sum (F_{AA,n} . \Delta t_n) / \Delta t_n$

Where N is total number of time intervals. Δt_n is nth time interval and $F_{AA,n}$ is aging acceleration factor for the temperature which exists during the time interval Δt_n.

The equivalent loss of life in the total time period is determined by multiplying the equivalent aging by the time period (t) in hours. In this case total time period used is 24 hours. Therefore, the equation of percent loss of life equation is as follows

% Loss of Life = (F_{EAA}×t×100)/normal insulation life

Hence we can say, if HST raises then Aging Acceleration Factor (F_{AA}) increase and F_{EAA} increase. So % Loss of Life will be higher.

V. CONCLUSION

The Hot Spot Temperature (HST) value depends on the ambient temperature, the rise in the top oil temperature (TOT) over the ambient temperature, and the rise in the winding HST over the top oil temperature. Moisture management in power transformers is a persistent concern especially for aging units. Extensive drying procedures are applied at the manufacturing stage and sustained efforts are deployed in service to maintain high dryness. The effect of moisture on insulation aging is well documented along with the detrimental effect on insulation strength and partial discharge inception level.

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