Transformer Loss of Life Monitoring

A review of in-service highlighting achieved benefits

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I INTRODUCTION

Most protection relays detect abnormal conditions or an existing fault in the primary equipment as fast as possible and isolate the minimum portion of the electric system. However, some protection elements like thermal overload, for instance, are intentionally delayed and will trip the breaker when the operation condition is close to permanent damage.

Current and temperature measurements will give the operator a good indication of how the transformer operates, but it is hard to estimate how much an overload jeopardizes a transformer's life.

This paper will highlight how novel monitoring techniques can aid the operator on their routine and asset management to make investment decisions based on protection relay data.

The standards IEEE Std C57.91-2011 and IEC 60076-7:2017 provide a guideline for overloading a power transformer and calculating the aging of transformer insulation. However, the aging calculation methodology is complex, and the standards recommend the use of a computer program to process the various data needed to calculate the hot spot temperature, insulation aging rate, and loss of life.

Computing data collected by multiple sources imposes some degree of complexity. In addition, processing non-real-time data requires time-synchronization and data-matching techniques. All these challenges restrict the accuracy of monitoring.

Modern relays utilize transformer information from nameplate, heat run tests, and acquire field data locally, e.g., load, tap changer position, cooling status, ambient and top-oil temperature to calculate the hot spot temperature, insulation aging rate, total transformer loss of life, and remaining life. These results provide valuable information to the operator, allowing them to make quicker and more conscious decisions.

II OVERVIEW OF TRANSFORMER AGING

The transformer's specification defines the operation regime, and the expected lifetime, e.g., IEEE Std C57.12.00-2010 has adopted an insulation life of 180,000 hours at 110℃.

IEEE C57.91-1995 standard has developed four different loading conditions beyond nameplate to explain the risk involved in the higher operating temperatures:

- Normal life expectancy:

  • Normal life expectancy loading: The transformer loading is continuous at the rated output when operated under usual conditions.

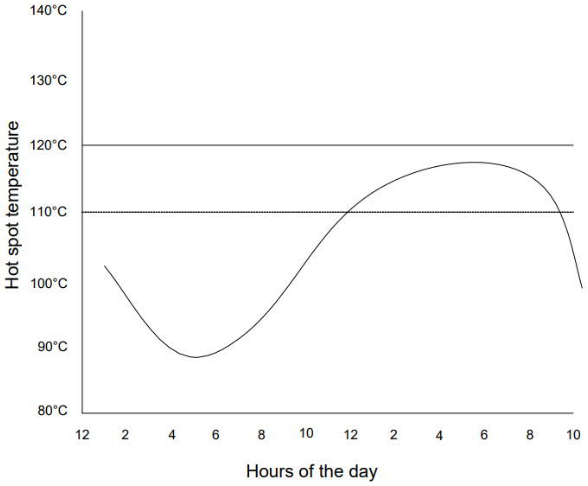

Figure 1: Normal life expectancy loading

- Sacrifice of life expectancy

  • Planned loading beyond nameplate: Restricted to short time overload.

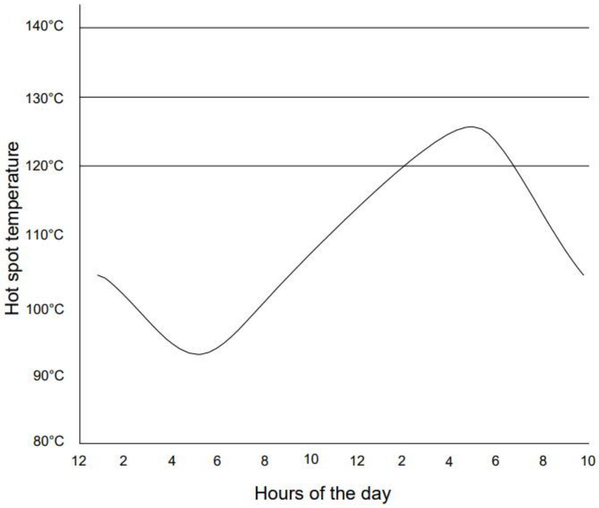

Figure 2: Planned loading beyond nameplate rating

- Long time emergency loading: Loading results from the prolonged outage of some system element. This loading profile is not a normal operating condition but may persist for some time.

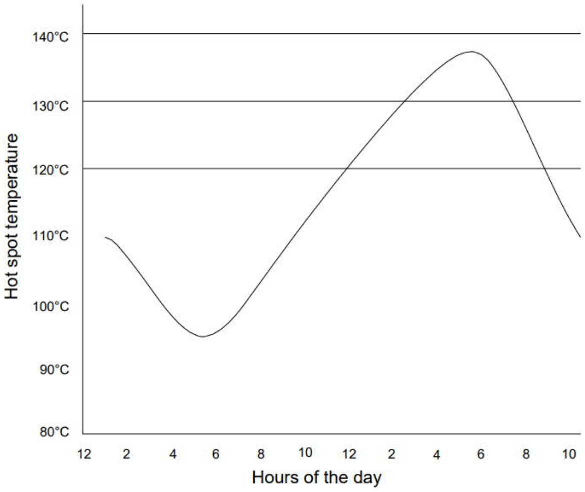

Figure 3: Long time energy loading

- Short time emergency loading: Unusually heavy loading for a short time due to one or more unwanted events that seriously disturb the normal system loading.

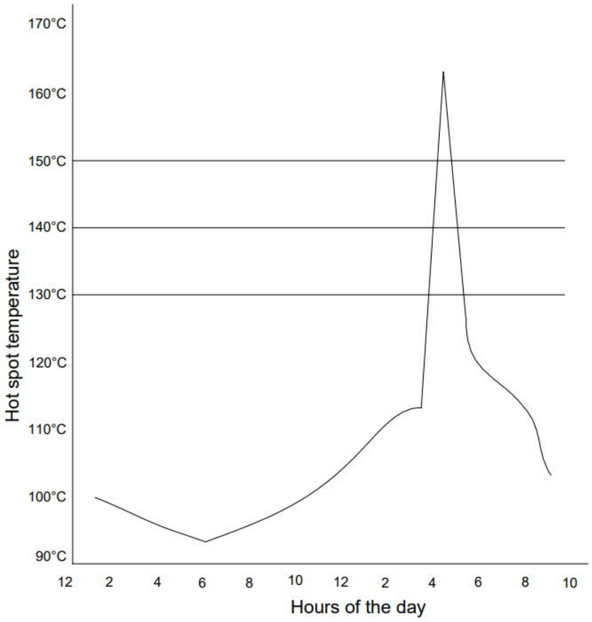

Figure 4: Short time energy loading

Chemical reactions degrade the insulation paper characteristics causing the transformer insulation to age. The three main components of these reactions are moisture, oxygen, and temperature.

The oil preservation system minimizes the oxygen and moisture present in the transformer and can be monitored online by dedicated devices or during regular maintenance.

Temperature is the most accessible controllable variable of the aging effect, and it is mainly affected by the load.

The temperature effect on a chemical reaction speed can be calculated based on the Arrhenius equation. This equation describes the dependence of the chemical reaction rate over the temperature. In practice, the aging rate increases exponentially with increasing temperature.

The aging rate is calculated for non-upgraded and upgraded paper insulation by the following equations:

$$V = 2^{(\theta_h - 98)/6}$$

$$V = e^{\left(\frac{15\ 000}{110+273} - \frac{15\ 000}{\theta_h + 273}\right)}$$

V = aging rate
θ_h = hot spot temperature in °C

An aging rate greater than one means the insulation is aging prematurely, and on the other hand, if it is smaller than one, the insulation is being spared. As shown in Table 1, the aging rate is susceptible to the hot spot temperature, meaning small temperature changes can significantly affect the aging or lifesaving.

	Paper insulation	
	Non-upgraded	Upgraded
θ_h (°C)	V	V
80	0,125	0,036
86	0,25	0,073
92	0,5	0,145
98	1,0	0,282
104	2,0	0,536
110	4,0	1,0
116	8,0	1,83
122	16,0	3,29
128	32,0	5,8
134	64,0	10,1
140	128,0	17,2

IEC 60076-7:2017

Table 1: Relative aging rates caused by hot spot temperatures

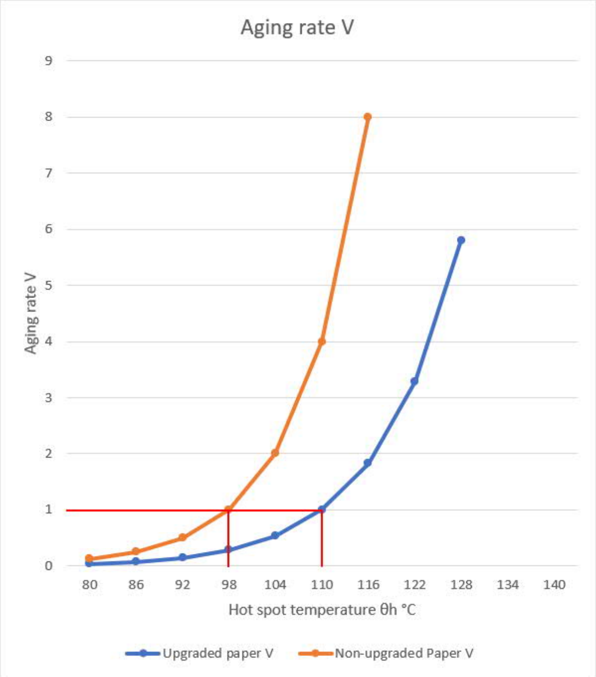

Figure 5: Graphical representation of relative aging rates caused by hot spot temperatures

III LOSS-OF-LIFE CALCULATION

Cumulative aging rate over time defines the loss-of-life, and the equation calculates it:

$$L = \int_{t_1}^{t_2} V \, \mathrm{d}t \quad \text{or} \quad L \approx \sum_{n=1}^{N} V_n \times t_n$$

V_n = relative aging rate during interval n
t_n = nth time interval
n = number of each time interval
N = total number of intervals during the period considered

IV HOT SPOT TEMPERATURE CALCULATION

Several factors in the transformer construction cause the temperature distribution to be very complex and uneven inside the transformer. Since the temperature is not uniform, the maximum aging will happen at the highest temperature location, also known as the hot spot. Unfortunately, measuring the hot spot temperature is complex and expensive. It would often require special sensors, fiber optics, or a laser. These complexities make measuring impractical for most transformers, therefore calculating the winding hot spot temperature is more appealing for long-time-in-service or new transformers.

Hot spot temperature rise may increase the risk of gas bubbles formation, reducing the dielectric strength and exposing the transformer to failure. Therefore, it is vital to pay special attention to rising hot spot temperature, and it is advisable to use hot spot temperatures for alarms.

The IEEE C57.91-2011 provides only an exponential equation to calculate the hot spot temperature. This method is helpful for transformer tests, and it takes into consideration load steps only. The IEEE equation provides a good result if the load is steady for a long time.

In the standard IEC60076-7, there are two methods to calculate the hot spot temperature: exponential equations, like the standard IEEE C57.91-2011, and the differential equations method.

The differential method is more suitable for online monitoring applications, and its equation is:

$$\theta_h = \theta_o + \Delta\theta_h$$

θ_h = hot spot temperature
θ_o = top-oil temperature
$\Delta\theta_h$ = hot spot temperature rise above top-oil temperature

V HOT SPOT TEMPERTURE RISE

The hot spot temperature rise above top-oil temperature ($\Delta\theta_h$) is calculated from the hot spot to top-oil temperature gradient ($\Delta\theta_{hr}$).

$$\Delta\theta_{hr} = \left(T_{HR} - T_{TOR}\right)/\left(i_t/i_r\right)^y$$

$\Delta\theta_{hr}$ = Hot spot to top oil temperature gradient
T_{HR} = Hot spot temperature rise
T_{TOR} = Top-oil temperature rise
i_t = Current measured in the winding during type test
i_r = Winding rated current
y = Empirical winding exponent. Represents the effect of change in resistance and oil viscosity with change in load

The following diagram is a simplified transformer thermal distribution.

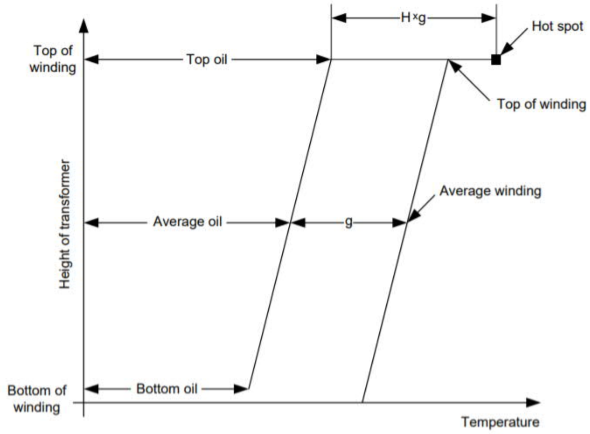

Figure 6: Simplified transformer thermal distribution

The simplified diagram assumes the following considerations:

- Oil temperature increases linearly from bottom to top.
- Winding temperature rise is parallel to the oil temperature rise with constant difference 'g' (average winding to average oil temperature gradient).
- The hot spot temperature rise is higher than the top winding temperature rise by the Hot Spot Factor (H) factor.

The following equations calculate the hot spot:

$$\Delta\theta_{h(n)} = \Delta\theta_{h1(n)} - \Delta\theta_{h2(n)}$$

$$\Delta\theta_{h1(n)} = \Delta\theta_{h1(n-1)} + D\Delta\theta_{h1(n)}$$

$$\Delta\theta_{h2(n)} = \Delta\theta_{h2(n-1)} + D\Delta\theta_{h2(n)}$$

$$D\Delta\theta_{h1(n)} = \frac{Dt}{\left(k_{22}\times\tau_w\right)}\times\left(k_{21}\times\Delta\theta_{hr}\times K^y - \Delta\theta_{h1(n-1)}\right)$$

$$D\Delta\theta_{h2(n)} = \frac{Dt}{\left(\left(1/k_{22}\right)\times\tau_o\right)}\times\left(\left(k_{21}-1\right)\times\Delta\theta_{hr}\times K^y - \Delta\theta_{h2(n-1)}\right)$$

k_{21} and k_{22} are constants
τ_w = Winding time constant
τ_o = Oil time constant
K = load factor

VI TOP-OIL TEMPERATURE

Top-oil temperature plays an enormous influence on hot spot temperature calculation; hence it is vital to have a good quality top-oil temperature measurement.

In case the top-oil temperature is not available either because the transformer is not equipped with a sensor or because of a failure in measuring the temperature, the relay will use these equations to calculate top-oil temperature:

$$\theta_{0(n)} = \theta_{0(n-1)} + D\theta_{0(n)}$$

with,

$$D\theta_{0(n)} = \frac{Dt}{\left(k_{11}\times\tau_o\right)}\times\left(\left[\frac{1+\left(K^2\times R_{(tap)}\right)}{1+R_{(tap)}}\right]^x\times\Delta\theta_{or} - \left[\theta_{o(n-1)} - \theta_a\right]\right)$$

$R_{(tap)}$ = Loss ratio at the current tap position
$\Delta\theta_{or}$ = Top oil temperature rise
x = Empirically oil exponent. Represents the effect of change in resistance with a change in load.
k_{11} = constant

VII TAP CHANGER

Transformer losses influence the top-oil temperature and, consequently, hot spot temperature. Furthermore, the losses vary for each tap position; therefore, transformers equipped with tap changers need to have the losses corrected for each tap position.

The heat run test report informs the losses for a few different tap positions.

A good solution to calculate the loss for each tap position is to interpolate the losses at rated, minimum, and maximum tap position in a linear equation.

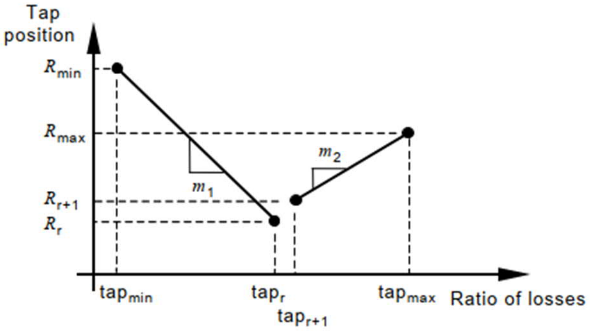

Figure 7: Losses as a function of the tap position

$$m_1 = \frac{R_r - R_{\text{min}}}{\text{tap}_r - \text{tap}_{\text{min}}} \qquad m_2 = \frac{R_{\text{max}} - R_{r+1}}{\text{tap}_{\text{max}} - \text{tap}_{r+1}}$$

The tap losses for each tap position above the rated tap changer position is calculated by the equation:

$$R(\text{tap}) = R_{r+1} + (\text{tap} - \text{tap}_{r+1}) \times m_2$$

and at or below rated tap position is calculated according to this equation:

$$R(\text{tap}) = R_r + (\text{tap} - \text{tap}_r) \times m_1$$

VIII LOSS OF LIFE TESTING CONSIDERATIONS

The time it takes for the transformer to heat up and cool down is determined by winding and oil time constants τ_W and τ_o and because the mass of transformer is big, the time for the temperature to stabilize for a given load is very long.

This equation defines the winding time constant:

$$\tau_W = \frac{(m_w \times C \times g)}{1000 \times P_w}$$

τ_W = winding time constant
m_w = Winding mass
C = Conductor material specific heat
g = Winding to oil gradient at rated load
P_w = I^2R loss of a winding at rated load and rated temperature

This equation defines the oil time constant:

$$\tau_o = \frac{(3.6 \times C \times \Delta\theta_{om})}{P}$$

τ_o = oil time constant
C = Thermal capacity based on the cooling medium
$\Delta\theta_{om}$ = Average oil temperature rise at the load considered
P = Supplied losses (NoloadLoss + LoadLoss)

The long time the transformer takes to heat and cool is mimicked by the relay, leading the relay testing for FAT or commissioning to last for several hours or even days.

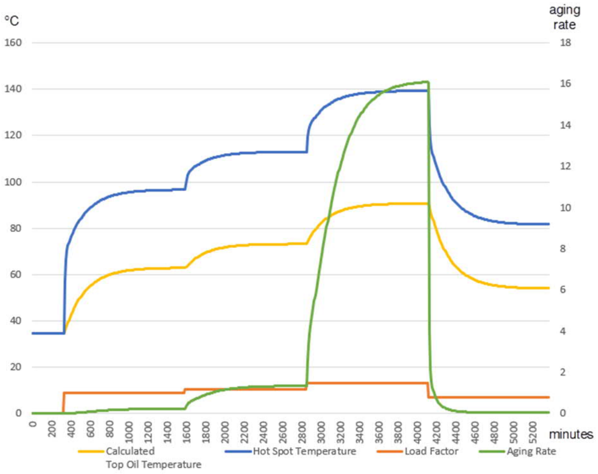

Figure 8: Hot spot and top-oil temperature, load, and aging rate at nominal time constant

Load factor 0; 1; 1.2; 1.5; 0.8
τ_W = 600s
τ_o = 12600s

The alternative to reducing the test duration is to temporarily decrease the winding and oil time constant to the lowest settings. Testing the relay quicker can also play an essential role in increasing personal safety as injecting high secondary currents to the relay with a test set for long hours may impose an unnecessary risk.

It is essential to mention that time constant will not affect the final hot spot temperature calculation for the given period, but it will only affect the time it takes to reach the final temperature. This can be seen by comparing the Figure 8 and 9.

The reduced time constants of the settings used for testing will cause the hot spot temperature and aging rates to change fast after the load step change. Consequently, it can be challenging to verify the results precisely when the values change fast. Therefore, it is recommended to keep the load injection steady until the hot spot temperature and the aging rate stabilizes approximately six times longer than the time of the oil time constant.

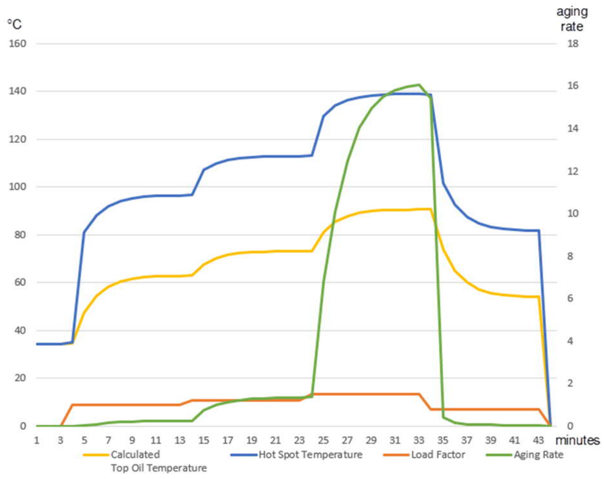

Figure 9: Hot spot and top-oil temperature, load, and aging rate at reduced time constant

Load factor 0; 1; 1.2; 1.5; 0.8

τ_W = 10s

τ_o = 100s

When testing the function using actual winding and oil time constant in a laboratory, instead of injecting secondary current to the relay, it is safer to test injecting digital sampled values according to IEC61850-9-2LE. Since it takes hours for the hot spot temperature and aging rate to stabilize, it is desirable to integrate the relay into SCADA, making it easier to monitor the trends evolution and compare them with expected results later.

A significant factor to be considered during the test is the top-oil temperature. When the relay is being tested on site with top-oil temperature sensor connected, the actual top-oil temperature measured will not change with current injected to the relay. Therefore, you must disconnect the sensor from the relay and let the function calculate the top oil temperature evolution based on injected current, ambient temperature, cooling status, and tap position.

IX BENEFITS

This case study analyzed a 3-phase transformer 150/75/75MVA, 161/13.8/13.8kV. The primary winding has a de-energized tap changer (DETC). The secondary and tertiary windings have an on-load tap changer (OLTC). As tap changer position influences the losses, for better accuracy of loss of life calculation, the relay was configured with three instances of loss of life function, one per winding.

As top-oil temperature information is vital for loss-of-life calculation, the algorithm will calculate the temperature, maintaining the function reliability if the top-oil temperature sensor fails.

The cooling fans' control uses hot spot temperature information to optimize the wear and tear and diminish the periodic test and system maintenance effort.

Embedding the monitoring function with traditional transformer protection, tap control, and fan control in one relay improves the footprint savings and spare parts management.

Calculated hot spot temperatures are used to set alarms in conjunction to the traditional thermal overload protection resulting in a better protection scheme.

The weather effect over the transformer loading capability became more visible to the operator as hot spot temperature is calculated in real time. Consequently, the operators can adapt the maximum load for hot or cold days.

A deeper analysis of the aging trends may be helpful to understand how the transformer is being sacrificed or spared over time. In addition, the aging rate trends analysis allows the transformer owner to correlate the overloading into cost in dollar amount, supporting the decision-making process for accepting contingency loading, planning of the load balancing, retrofitting, or investment on plant expansion, to name a few.

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