Automated Dry-type Transformer Aging Evaluation: A Simulation Study

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Abstract — Transformer operation conditions are quite crucial for industry as they have significant influence on transformer remained lifetime. This influence becomes even more significant once transformer operates at high ambient temperature. Hence, development of an intelligent system that able to monitor the effect of environmental conditions on remained lifetime together with aging rate, and provide information in real time is substantial. This study is focused on an online system forecasting transformer aging rate and remained life. To evaluate the proposed model, simulation results are compared to calculations proposed by IEC standards. Moreover, system’s behavior under real life conditions is analyzed and results suggesting possible industry enhancements are provided.

Keywords — Aging rate, Dry type transformer, Hot-spot temperature, Online monitoring system, Transformer efficiency.

I. INTRODUCTION

Based on current industry trends, it is becoming preferable to invest in intelligent predictive assessment systems rather than restoration of asset after failure [1]. In other words, investing money in prevention of accidents than dealing with accident consequences is more preferential way. Indeed, some of the vital challenges for entire industries are extension of system’s service life, reduction of maintenance cost and decrease in failure rate. These issues also relate to energy supply systems and especially to transformers which is considered as the most substantial component in transmission of energy.

Through its life transformer operates at different ambient temperature conditions and at different altitudes, whereas it is mostly designed to work at temperature of 30 or 40 °C and 1000 meters altitude from the sea level. Especially in environment with extreme temperature fluctuations from -50°C in winter and +40°C in summer, transformers operating conditions are considerably different from standard conditions. Besides differences between manufacturer’s lifetime expectations with real life results, fluctuating environmental conditions have other negative effects. High temperature conditions cause damage to insulation media which consequently leads to transformer lifetime reduction. Moreover, at ambient temperature less than 0 °C transformer becomes underloaded which results in its insufficient utilization [2].

Dry-type transformers are designed to operate in conditions where flammable characteristics of oil immersed transformers are not suitable [3]. However, as a result of limited cooling capacity and inability of partial repair, the analysis of their thermal behavior becomes particularly important.

Several researches have been previously conducted on thermal analysis of cast-resin dry-type transformers. One of the earliest researches was conducted by Halacsi in [4]. He proposed methods of calculating average temperature rise of dry-type transformers. In [5]-[6], Pierce worked on a dry type transformer and conducted tests with imbedded thermocouples to compare the thermal parameters on certain overloading conditions. His prediction model of hot-spot temperature was supported by experimental results. In [7]-[8], Bagheri et al. studied the influence of the temperature and loading on transformer characteristics. Based on analytical and different analysis methods such as frequency response analysis, they tried to identify the influence of parameters that mostly effect on hot-spot temperature and aging rate of insulation. Rahimpour and Azizian [3] used finite difference method to analyze the heat transfer of dry type transformer under environmental conditions.

Two key parameters in transformer’s thermal analysis are loading and ambient temperature. To avoid transformer overload, operator should be provided with information on how much load should be decreased, once ambient temperature rises. This study focuses on mathematical thermal modeling of cast-resin dry-type transformer and real-time application of this model. The proposed system is able to predict aging rate and remained lifetime of the dry type transformer based on operational load and ambient temperature. This system will be identified with statically developed empirical equations. Obtained results will be assessed by the comparison with results provided in IEC standards [9]. Based on input values, system could also provide the most optimal operational load, which could be especially beneficial for industry purposes.

II. METHODOLOGY

A. Thermal Model

Transformer thermal model system was developed based on IEC [9] and IEEE standards [10]. These standards are providing the guidelines for the loading of dry-type transformers based on transformer thermal model. Thermal
model yields aging rate as a function of operating temperature, loading and time constant for different dry-type transformer thermal classes.

The expected lifespan at constant hot-spot thermodynamic temperature of the transformer varies according to Arrhenius’ law and is obtained by,

$$L = a \times \exp(b/T)$$  \hspace{1cm} (1)

where, $a$ and $b$ are the Arrhenius’ equation constants based on the thermal class of the transformer, and $T$ is the hot-spot temperature or maximum temperature measured in Kelvin.

Manufacturers typically assume that normal lifetime of transformer is equal to 20 years or 180000 hours. Aging rate is a consumption of lifetime-hours per one hour of operation time. Aging rate $k$ calculates as ratio of expected lifetime $L$ to normal lifetime by (2). The lifetime consumption shows consumption of lifetime-hours during certain time period $t$ in hours and calculates by (3) [9].

$$k = 180000 \times a^{-1} \times \exp(-b/T_{HS})$$  \hspace{1cm} (2)

$$L_C = 180000 \times a^{-1} \times \exp(-b/T_{HS}) \times t$$  \hspace{1cm} (3)

Hot-spot temperature is primary variable used in aging rate and lifetime consumption calculations. Equation (4) demonstrates dependence of the ambient temperature $T_{AMB}$ and hot-spot temperature rise over the ambient $\Delta \theta_{HS}$.

$$T_{HS} = 273 + T_{AMB} + \Delta \theta_{HS}$$  \hspace{1cm} (4)

where $T_{AMB}$ is the ambient temperature in degrees Celsius ($^\circ$C) and $\Delta \theta_{HS}$ is the hot-spot temperature rise above the ambient temperature.

Hot-spot temperature rise $\Delta \theta_{HS}$ can be calculated either for the steady state load or for transient state during the load change. After single step change in load system tends to achieve steady state and hot-spot temperature reaches certain ultimate hot-spot temperature if allowed to stabilize. Ultimate hot-spot temperature rise over ambient $\Delta \theta_{HSu}$ is the calculated as a function of loading change [9].

$$\Delta \theta_{HSu} = Z \times \Delta \theta_{Wrated} \times I^q$$  \hspace{1cm} (5)

where $I$ is the loading factor per unit, $\Delta \theta_{Wrated}$ is the average winding temperature rise over the ambient temperature at rated load ($I = 1$ p.u.), $q$ is the empirical constant that is equal to 1.6 for air natural cooling (AN) and to 2 for air forced cooling (AF), $Z$ is a constant factor that equals to 1.25 [9].

Hot-spot temperature reaches the ultimate hot-spot temperature by the path that can be described by the equation (6). It is used to calculate momentary values of the hot-spot temperature at any time $t$ when temperature changes from initial to ultimate value.

$$\Delta \theta_{HS} = (\Delta \theta_{HSu} - \Delta \theta_{HSi}) \times (1 - e^{-\tau t}) + \Delta \theta_{HSi}$$  \hspace{1cm} (6)

where $\Delta \theta_{HSu}$ is the hot-spot temperature rise over the ambient at time $t$ in minutes, $\Delta \theta_{HSi}$ and $\Delta \theta_{HSi}$ are the ultimate and initial hot-spot temperature rise values, and $\tau$ is the time constant.

Time constant is a time for hot-spot temperature rise to change 63.2\% after a step change in transformer load. After five time constant, the steady state condition is obviously achieved. Time constant is calculated according equation (7) [9].

$$\tau = \tau_R \times \frac{\Delta \theta_{HSu} - \Delta \theta_{HSi}}{\Delta \theta_{HSr} - \Delta \theta_{HSi}}$$  \hspace{1cm} (7)

where, $\Delta \theta_{HSr}$ is the hot-spot temperature rise over the ambient temperature at rated load ($I = 1$ p.u.), $m$ is an empirical constant that is equal to 0.8, $\tau_R$ is the rated time constant that is calculated by data provided from manufacturer, and usually equals to 0.5.

Equations (4) and (2) demonstrate dependence of the aging rate on the ambient temperature. Usually, manufacturers design transformers to operate under rated ambient temperature with permanent loading capability. However, fluctuations of the ambient temperature can lead to underloading or overloading conditions. Then, it is important to find dependence of the loading capability from the ambient temperature. Limit of the aging rate for transformer normal operation is one ($k = 1$). Transformation of (2), (4), and (5) yields to equation (8) that shows loading capability when $k = 1$ as a function of ambient temperature.

$$I_{optimal} = \frac{T_{HSr} - T_{AMB}}{Z \times \Delta \theta_{Wrated}}$$  \hspace{1cm} (8)

where $T_{HSr}$ is the rated hot-spot winding temperature in degrees Celsius ($^\circ$C) and it can be found by (9) for every transformer’s insulation thermal class.

$$T = \frac{-b}{\ln(a/180000)} - 273$$  \hspace{1cm} (9)

B. Computational Algorithm

The base of the system is computational algorithm. System follows purposes to predict remained lifetime and propose optimal operational loading that correspond to the energy security. Optimal operational loading has dependence on ambient temperature and can be different from rated load. The risks of mechanical and electrical damage are higher in case of inaccurate operation of the system. Therefore, accuracy requirement is very critical and algorithm must consider all possible scenarios. High accuracy is reached by system operation in real time. Algorithm considers timing issue; design includes start-finish time and order of priorities for every operation. Algorithm flowchart is displayed on Figure 1 which shows order of priorities and decision mechanism.

Algorithm is flexible for different dry-type transformers, because of manual adjustment of empirical constants. Initially, system uses constants provided by standards; later, constants must be derived according to practically obtained data.
Constants calibration will increase prediction accuracy of the system. Final system is open-loop and does not regulate itself. However, future improvements conclude management of loading and cooling system that depends on momentary loading capability.

III. SIMULATION RESULTS

Algorithm is tested for four case studies to demonstrate opportunities and accuracy of the system. Case studies are ordered based on input parameters complexity. Simulation results are compared with examples provided by standards to evaluate the error.

A. Step Change in Loading

First case study is simulated according to IEC standard. Transformer insulation thermal class is H with AN cooling system, ambient temperature is 30 °C, time sample is 6 minutes. Input load demonstrates single step change from 0.8 to 1.2 p.u. Figure 2 displays behavior of (a) input load, (b) hot-spot temperature rise and (c) aging rate for 2.2 hours. When load change is detected, hot-spot temperature rise is calculated (6). Hot-spot temperature rise and time constant are equal to \( \Delta \theta_{Hsu} = 133.872 \text{ K} \) and \( \tau = 0.399 \text{ hours} \). Figure 2 shows that temperature stabilizes after 2 hours that corresponds to 5 time constants. Temperature reaches ultimate hot-spot temperature rise. Hot-spot temperature and aging rate demonstrate exponential behavior for single step change in the load. Transformer lost 9.5809 hours of lifetime during 2.2 hours of operation.

![Figure 2](image2.png)

Figure 2. The effect of (a) loading factor rise on (b) hot-spot temperature and (c) aging rate.

B. Varying Loading

Second case study is also simulated according to IEC standard. Transformer insulation thermal class is H with AN cooling system, ambient temperature is 30 °C, time sample is 60 minutes. Figure 3 shows behavior of (b) hot-spot temperature rise, (c) aging rate and (d) remained lifetime. Input load gradually increases from 0.7 p.u. to 1.2 p.u. for 15 hours, then decreases until 0.7 p.u. for 9 hours.

![Figure 3](image3.png)

Figure 3. The effect of (a) loading factor fluctuations on (b) hot-spot temperature, (c) aging rate and (d) remained lifetime.

Time sample is less than five time constants, meaning that at each time sample, when system derives ultimate temperature rise and time constant (6) it is not at steady state.
Initial temperature for this equation is hot-spot temperature rise during the previous time sample. Hot-spot temperature behavior follows variations in loading factor. Aging rate sharply increases at highest value of the hot-spot temperature, remained lifetime falls at this moment. Finally, transformer lost 50.9218 hours of lifetime for 24 hours of operation.

C. Error Evaluation

Figure 4 displays relative error for calculation of hot-spot temperature and aging rate in comparison to IEC standard. It can be mentioned that for both cases (a) and (c), uncertainty in hot-spot temperature is mostly less than 0.15%. Zero error in (a) first case and high error in (c) second case can be explained by the fact that system did not reach stable operation on first time samples. Aging rate becomes inaccurate at low loading, but at high loading relative error decreases until 1%. Errors are mostly a result of rounding made in standards. For instance, in second case ultimate temperature rise in IEC is chosen as 134 K, while the real value utilized by simulation is 133.872 K. Similarly aging rate of the first time sample taken by IEC as 0 h/h, while the real value is 0.000059 h/h. Resultant error calculated by the system is equal to 4.2% and 5.3% for the first and second cases respectively. Compared to transformer’s lifetime, such error is equal to 9540 inaccurately calculated hours or one year error. This error analysis demonstrates importance of online monitoring for transformer and perfunctory format of the examples provided by standards.

D. Loading Capability for Varying Ambient Temperature

For the third case, (8) was utilized to find the dependency of loading capability from ambient temperature. All thermal classes were analyzed for AN and AF cooling. Ambient temperature was chosen to vary from -50°C to +50°C. Variables introduced in (8) such as ΔT_{IRated}, q, and Z were taken from IEC standard [9], but the last value Δθ_{IRated} was not introduced in this standard. This value was assessed based on information provided in IEEE standard [10]. According to this standard, Δθ_{IRated} is the difference between thermal class and maximum rated ambient temperature. In this case, maximum rated ambient temperature is 40°C. Loading capability for different thermal classes with different cooling is shown on Figure 5.

Based on manufacturer’s suggestions, optimal ambient temperature is 30°C. At this ambient temperature loading capability is equal to 1. For lower ambient temperatures, loading capability is higher, showing the overloading potential. For instance, for 180°C (H) AN case, the loading capability of transformer is equal to 1.5, revealing that transformer load can be increased by 50%. On the other hand, the loading capability is lower than 1 for ambient temperature higher than 30°C, indicating that load should be decreased to reach the optimum operational state.

Simulation results were compared with IEEE standard. This comparison is summarized in Tables I and II. It can be mentioned that results are rather similar for middle (+10°C to +40°C) and different for extreme (0°C & +50°C) temperatures. Moreover, it can be also seen that loading capability range is higher for simulation than for IEEE. For instance, for AN type transformer, loading capability range for IEEE is equal to 0.22 p.u, while for simulation it is 0.5467 p.u. These differences arise from the discrepancy of approaches utilized. In IEEE loading capability is assigned based on average temperature. For instance, if it was measured that average ambient temperature is equal to 20°C and the average loading capability for this day is equal to 1.04 p.u., then this loading capability is assigned for 20°C. In contrast, proposed
simulation calculates loading capability for every ambient temperature, resulting in a more accurate outcome. As a result of this averaging, loading capability range decreases values measured at extreme temperatures approach mean value.

Table I. IEEE and simulation results for loading capability for 180°C (H) AN transformer at different ambient temperatures.

<table>
<thead>
<tr>
<th>Ambient temperature</th>
<th>IEEE result</th>
<th>Simulation result</th>
<th>Error evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 °C</td>
<td>1.130</td>
<td>1.267</td>
<td>10.810 %</td>
</tr>
<tr>
<td>10 °C</td>
<td>1.090</td>
<td>1.192</td>
<td>8.550 %</td>
</tr>
<tr>
<td>20 °C</td>
<td>1.040</td>
<td>1.105</td>
<td>5.880 %</td>
</tr>
<tr>
<td>30 °C</td>
<td>1.000</td>
<td>1.000</td>
<td>0</td>
</tr>
<tr>
<td>40 °C</td>
<td>0.950</td>
<td>0.874</td>
<td>8.680 %</td>
</tr>
<tr>
<td>50 °C</td>
<td>0.910</td>
<td>0.720</td>
<td>18.970 %</td>
</tr>
</tbody>
</table>

Table II. IEEE and simulation results for loading capability for 180°C (H) AF transformer at different ambient temperatures.

<table>
<thead>
<tr>
<th>Ambient temperature</th>
<th>IEEE result</th>
<th>Simulation result</th>
<th>Error evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 °C</td>
<td>1.100</td>
<td>1.215</td>
<td>9.465 %</td>
</tr>
<tr>
<td>10 °C</td>
<td>1.070</td>
<td>1.154</td>
<td>7.279 %</td>
</tr>
<tr>
<td>20 °C</td>
<td>1.040</td>
<td>1.083</td>
<td>3.970 %</td>
</tr>
<tr>
<td>30 °C</td>
<td>1.000</td>
<td>1.000</td>
<td>0</td>
</tr>
<tr>
<td>40 °C</td>
<td>0.960</td>
<td>0.903</td>
<td>6.320 %</td>
</tr>
<tr>
<td>50 °C</td>
<td>0.930</td>
<td>0.788</td>
<td>18.090 %</td>
</tr>
</tbody>
</table>

E. Varying Load and Ambient Temperature

In the fourth case simulation was tested for real life conditions to reveal the load capability for different load factor and ambient temperature values. To test the simulation under real life conditions, April temperature values were chosen for Astana city in Kazakhstan. Temperature was measured for the first week of the month and measurements were done for an hourly time periods. Transformer insulation class was chosen to be 180°C (H) and it was assumed that it has AN cooling system.

In Figure 5, for the time period between 15 to 20 hours, when instant ambient temperature rise is mentioned, loading capability of the system faces immediate decrease. Similarly, for time period between 70 to 85 hours, loading capability significantly increases as a result of decreased ambient temperature. Hence, it can be mentioned, that relationship between loading capability and ambient temperature can be described as inverse. On the other hand, the aging factor of the system depends both, from the loading factor and ambient temperature. It can be seen from the aging rate peak that happened from 30 to 50 hours time period for simultaneous rise of loading factor and ambient temperature.

IV. FUTURE IMPROVEMENTS

The computational algorithm is developed for hardware system. System integrates to the dry-type transformer through the set of sensors to read input variables. Developed analytical method is based on statistical data which is described in IEC [9] and IEEE standards [10]. Future research includes examination of the system with hardware implementation and transformers of different insulation classes. Basically, the indicator of operation must be temperature values. Several methods for practical measuring of hot-spot temperature are described in [3], [5]-[6] and [11]-[12]. One of these approaches can be used to confirm, calibrate developed system and establish new constants for insulation classes. In addition, the further improvements will be developing system to intelligent by allowing the system to control loading of transformer and cooling according to current ambient temperature.
V. CONCLUSION

Transformer aging rate and life reduction was discussed. The hot-spot temperature and thermal modelling of transformer were also presented. An algorithm was developed to perform automated dry-type transformer aging evaluation for different environmental and load conditions. This algorithm was simulated and the results were compared with standard data. The simulation results show that as compare to the data in Standard which were conducted manually (via calculator); more accurate ageing rate and life consumption can be achieved through automated evaluation system for dry-type transformer through a real-time computer based program. This discrepancy between manual calculation and computer program comes through rounding of digits during transformer ageing rate calculation. These rounding errors will collect and become significant for long time transformer lifetime estimation. Furthermore, using automated evaluation program; the transformer loading capability for different insulation classes and cooling systems under different ambient temperatures was calculated. This information is quite beneficial for industry.

VI. REFERENCE


