THERMAL SIMULATION FOR DISTRIBUTION TRANSFORMERS IN UNDERGROUND VAULTS

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ABSTRACT

This paper presents the thermal simulation of the load behavior of a transformer in an underground vault, so as to establish maximum loading without loss of life. In that way, it optimizes the utilization factor of transformers in underground distribution systems. The simulation is carried out using a set of differential equations that relate heat flow from the transformer to the vault and the forced extraction of air from the vault to the environment. The software supports different daily loads and ambient temperature cycles, vault configurations and amounts of air extraction, forced or natural. The results of the simulations were matched with field measurements in existing vaults and the results obtained were extremely positive, thus the program optimizes the utilization factor of transformers in underground vaults.

INTRODUCTION

This paper presents the equations used in a computer model to study the loss of life of transformers installed in vaults. Its goal is to establish the daily loss of life for a transformer installed in a vault loaded with the demand for normal and emergency conditions. The program is able to study transformers in free air and in a vault. For transformers in free air the equations are those of the Brazilian Standard (ABNT) NBR 5416/1981. Two methods were developed for transformers in vaults. In the first one, called model I, the temperature of the vault is determined by the balance between the heat produced in the transformer, by losses, and the heat transferred to the environment by the ceiling, the walls and the air extraction. Next, the temperature of the oil and the hot spot are established considering the transformer in free air, with the temperature of the environment equal to the vault temperature. In the second method, called model II, the oil temperature is determined by a set of differential equations of heat transfer from the transformer to the air in the vault. A sensitivity analysis of the numeric values of the parameters involved in the equations of heat transfer was made. This analysis was based on field measurements of the transformer load current and temperature, as well as of the temperature in the vault. The temperatures measured were those of: air input and output in the vault, transformer oil and radiators.

DEFINITION OF TERMS

Q_{Trans} - heat produced by losses in transformer, W;
Q_{wall} - heat transferred to ground through the walls, W;
Q_{ceiling} - heat transferred to external ambient through the vault ceiling, W;
Q_{vent} - heat extracted from the fault by forced ventilation, W;
A_{wall} - total area of walls, m²;
A_{ceiling} - total area of ceiling, m²;
H_{wall} - heat transfer coefficient to walls, W/m² × K;
H_{ceiling} - heat transfer coefficient to ceiling, W/m² × K;
T_{vault} - vault average temperature, °C;
T_{Soil} - ground average temperature, °C;
T_{Amb} - ambient temperature in air external to vault, °C;
V_{Air} - air flow, m³/s;
C_{Air} - thermal capacity of air, J/kg × K (1015 J/kg × K);
ρ_{Air} - air density at 20 °C, kg/m³ (1.18 kg/m³);
m_{Air} - maximum flow of air m_{Air} = V_{Air} × ρ_{Air}, kg;
P_{Vent} - power consumption of the fan, W;
P_{no-load} - transformer no-load losses, at nominal voltage, W;
P_{Cupc} - transformer full load losses, in W;
s - transformer load in per unit of nameplate kVA;
m_{Trans} - transformer weight, kg;
C_{Trans} - unitary thermal capacity of transformer, Wh/kg × °C;
C_{Total} - total thermal capacity of transformer, Wh/°C (C_{Trans} = m_{Trans} × C_{Trans});
T_{Trans} - transformer temperature, °C;
Q_{Ger} - total heat generated in the transformer by losses, W;
Q_{TR} - heat transferred from the transformer to the air in the vault, W;
Q_{conv} - heat transferred from the transformer to the air by convection, W;
Q_{rad} - heat transferred from the transformer to the air by irradiation, W;
A_{Trans} - transformer external area, m²;
I_{Trans} - coefficient of heat transfer by convection, W/m² × K;
T_{Trans} - transformer external temperature, K;
T_{Air} - average temperature of air in the vault. It will be taken as the average between input and output of air in the vault, T_{Air} = 0.5 (T_{in} + T_{out});
σ - Stefan Boltzman constant, 5.67 × 10⁻⁸ W/m² × K⁴;
T_{C} - average temperature of walls and ceiling of the vault. It will be taken as the average between wall and ceiling temperatures;
ε_{Trans} - coefficient of emissivity of the surface of the transformer;
ε_{C} - average coefficient of emissivity of the surface of walls and ceiling of the vault;
HEAT TRANSFER EQUATIONS

Transformer Immersed In Free Air

The equations on which the computer program is based are essentially those of the Brazilian Standard (ABNT) NBR 5416/1981, and those in [1]. The daily loss of life is established by equations in that standard and depends on the temperature of the hottest spot and the time it stays at that temperature.

Model I

The equations on which the computer program is based are essentially those of a transformer in free air, except for the fact that the temperature of the air in the vault will correspond essentially those of a transformer in free air, except for the vault temperature. The daily cycle, the average temperature of the vault, \( T_{\text{avg}} \), is obtained using the temperature at the vault in is obtained using the temperature \( T_{\text{avg}} \) at the vault in is obtained using the temperature \( T_{\text{avg}} \) at

\[
\begin{align*}
Q_{\text{Trans}} & = Q_{\text{wall}} + Q_{\text{roof}} + Q_{\text{vent}} \\
results from the set of equations: \\
Q_{\text{wall}} & = P_{\text{fe}} + s^2 P_{\text{c Cu}} \text{pc} \\
Q_{\text{wall}} & = 0.7 \times h_{\text{wall}} \times A_{\text{wall}} (T_{\text{wall}} - T_{\text{amb}}) \\
Q_{\text{roof}} & = h_{\text{roof}} \times A_{\text{roof}} (T_{\text{wall}} - T_{\text{amb}}) \\
Q_{\text{vent}} & = m_{\text{air}} \times C_{\text{air}} (T_{\text{wall}} - T_{\text{amb}})
\end{align*}
\]

and also from:

\[
\begin{align*}
P_{\text{fe}} + s^2 P_{\text{c Cu}} & = 0.7 \times h_{\text{wall}} \times A_{\text{wall}} (T_{\text{ambient}} - T_{\text{soil}}) \\
& + (h_{\text{roof}} + m_{\text{air}} \times C_{\text{air}}) (T_{\text{wall}} - T_{\text{ambient}})
\end{align*}
\]

The temperature of the vault for a demand 's' is determined from this set of equations. In that way the program calculates, for each transformer load condition, at instant "i", during the daily cycle, the average temperature of the vault, \( T_{\text{avg}} \). It also calculates the temperatures of the oil and the hot spot in the same way it would for a transformer in air, with an ambient temperature \( T_{\text{avg}} \).

Model II

The heat flow from the transformer to the air in the vault obeys the following differential equation:

\[
m_{\text{Trans}} C_{\text{Trans}} \frac{dT_{\text{Trans}}}{dt} = C_{\text{Trans}} \frac{dT_{\text{Trans}}}{dt} = Q_{\text{G}}(t) - Q_{p}(t) \quad (1)
\]

The heat transfer is done by convection and irradiation. The air extracted from the vault by forced convection results in an absolute heat balance as follows: part of the heat produced is transferred to the walls and the ceiling of the vault and part is removed to the exterior of the vault by the air extraction. Then:

\[
\begin{align*}
\text{temperature of output air, } T_{\text{out}} \text{, } ^{\circ} \text{C}; \\
Q_{\text{conv}} & = h_{\text{Trafo}} A_{\text{Trafo}} (T_{\text{Trafo}} - T_{\text{Air}}) \\
Q_{\text{rad}} & = \sigma A_{\text{Trafo}} (T_{\text{Trafo}}^4 - T_{\text{Air}}^4) \quad (2)
\end{align*}
\]

The final equation to obtain the temperature of the transformer is:

\[
C_{\text{Trans}} \frac{dT_{\text{Trans}}}{dt} = P_{\text{vent}} + \frac{1}{R} \sigma A_{\text{Trans}} (T_{\text{Trans}}^4 - T_{\text{Air}}^4) \quad (3)
\]

On the other hand, considering forced ventilation:

\[
\begin{align*}
m_{\text{air}} C_{\text{air}} (T_{\text{out}} - T_{\text{in}}) & = P_{\text{vent}} + \frac{1}{R} \sigma A_{\text{Trans}} (T_{\text{Trans}}^4 - T_{\text{Air}}^4) \\
& - h_{\text{ceiling}} A_{\text{ceiling}} (T_{\text{Air}} - T_{\text{ceiling}}) \quad (4)
\end{align*}
\]

Considering temperature \( T_{\text{Air}} \) equal to the ambient average temperature, and the output air temperature:

\[
T_{\text{Air}} = \frac{T_{\text{Amb}} + T_{\text{Amb}}}{2} \quad \text{ou} \quad T_{\text{out}} = 2 T_{\text{Air}} - T_{\text{Amb}}
\]

Substituting this value in (4):

\[
T_{\text{Air}} (2 C_{\text{Air}} + h_{\text{Trans}} A_{\text{Trans}} + h_{\text{wall}} A_{\text{wall}} + h_{\text{ceiling}} A_{\text{ceiling}}) = \frac{P_{\text{vent}} + h_{\text{Trans}} A_{\text{Trans}} T_{\text{Trans}} + h_{\text{wall}} A_{\text{wall}} T_{\text{wall}} + h_{\text{ceiling}} A_{\text{ceiling}} T_{\text{ceiling}} + 2 C_{\text{air}} T_{\text{Amb}}}{R} \quad (5)
\]

At each time interval of the daily load cycle, the absolute temperature of the top oil is determined by the numerical integration of (3), following a step-by-step process. In the first step of an interval of the daily cycle, the temperature in the vault is obtained using the temperature \( T_{\text{Air}} \) of the preceding step and assuming \( T_{\text{wall}} \) and \( T_{\text{ceiling}} \) are equal to the vault temperature. \( T_{\text{Air}} \) is used according to the Euler method of numerical integration of (3). The process is continued until two consecutive estimates for \( T_{\text{Trans}} \) are equal within the desired tolerance.

RESULTS

Sensitivity Analysis

To make the sensitivity analysis for both models the parameters used were:

- 500 kVA transformer: 45.0 °C rise in the temperatures at full-load of top oil and 20.0 °C of full-load hot-spot; 3.0 h thermal time constant, 4.42 ratio of full-load loss to no-load loss, 1200 W no-load loss.
- Vault dimensions (m): 2.25 width; 5.4 length; 2.75 height.
- Heat transfer coefficient (W/m²/K): Transformer 20.0; walls 2.8; ceiling 1.30.
− Emissivity of surfaces: Transformer 0.60 walls/ceiling 0.60.
− Forced ventilation: mass flow of air 1.650 kg/s; power of fan 0.500 kW; specific heat of air 1015.0 J/kg.

TABLE 1 – Daily cycle of load and ambient temperature

<table>
<thead>
<tr>
<th>Time interval (h)</th>
<th>Start</th>
<th>End</th>
<th>Load (pu)</th>
<th>Amb.Temp. (^\circ)C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>3.0</td>
<td>0.2</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>12.0</td>
<td>1.0</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>12.0</td>
<td>24.0</td>
<td>0.2</td>
<td>25.0</td>
<td></td>
</tr>
</tbody>
</table>

Heating Transfer Coefficient of Transformer

The values for parameter \( h_{\text{trans}} \) were considered to be between 2.0 and 40.0 W/m\(^2\)/K. As shown in Table 2 and Fig.1, when such values vary within this range, the life of the transformer varies between 0.01 and 49.40 years respectively, according to the ABNT equations. As the life of the transformer depends greatly on \( h_{\text{trans}} \) and this value must be set with great accuracy, it is also important to research the dependence between \( h_{\text{trans}} \) and the transformer temperature.

TABLE 2 – Heat transfer coefficient of the transformer

<table>
<thead>
<tr>
<th>Coef. ( h_{\text{trans}} ) (W/m(^2)/K)</th>
<th>Life (years)</th>
<th>( ABNT )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>15.0</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td>2.76</td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td>7.31</td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td>15.85</td>
<td></td>
</tr>
<tr>
<td>35.0</td>
<td>29.60</td>
<td></td>
</tr>
<tr>
<td>40.0</td>
<td>49.40</td>
<td></td>
</tr>
</tbody>
</table>

Fig.1 - Parameter “\( h_{\text{trans}} \)"

Heat Transfer Coefficient to Walls and Ceiling

The heat transfer coefficient to the walls and ceiling does not present any effect on the estimated life of the transformer.

Emissivity of Transformer Surface

The influence of the value of emissivity of the transformer surface in the estimated life of the transformer is shown in Table 3.

TABLE 3 – Emissivity of transformer

<table>
<thead>
<tr>
<th>Transformer emissivity</th>
<th>Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1.15</td>
</tr>
<tr>
<td>0.4</td>
<td>1.85</td>
</tr>
<tr>
<td>0.6</td>
<td>2.76</td>
</tr>
<tr>
<td>0.8</td>
<td>3.92</td>
</tr>
<tr>
<td>1.0</td>
<td>5.35</td>
</tr>
</tbody>
</table>

TABLE 4 – Emissivity of walls/ceiling

<table>
<thead>
<tr>
<th>Emissivity</th>
<th>Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>2.30</td>
</tr>
<tr>
<td>0.4</td>
<td>2.66</td>
</tr>
<tr>
<td>0.6</td>
<td>2.76</td>
</tr>
<tr>
<td>0.8</td>
<td>2.82</td>
</tr>
<tr>
<td>1.0</td>
<td>2.86</td>
</tr>
</tbody>
</table>

Flow of Air Blown by Fan

Varying the flow out of the fan from 0.1 to 2.5 kg/s the life estimate had variations as shown in Table 5. This factor presents great influence in the estimate of life and was considered for both models.

TABLE 5 – Flow out of fan

<table>
<thead>
<tr>
<th>Flow of air</th>
<th>Life estimate (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model II</td>
<td>Model I</td>
</tr>
<tr>
<td>0.1</td>
<td>0.23</td>
</tr>
<tr>
<td>0.5</td>
<td>1.48</td>
</tr>
<tr>
<td>1.0</td>
<td>2.14</td>
</tr>
<tr>
<td>1.5</td>
<td>2.63</td>
</tr>
<tr>
<td>1.65</td>
<td>2.76</td>
</tr>
<tr>
<td>2.0</td>
<td>3.08</td>
</tr>
<tr>
<td>2.5</td>
<td>3.55</td>
</tr>
</tbody>
</table>

Conclusions

The estimated life of a transformer is greatly influenced by the value of the heat transfer coefficient for the transformer; thus, it should be analyzed using the field measurement for an existing vault.

ANALYSIS OF FIELD MEASUREMENTS

Introduction

The field measurements were taken at a vault located at Al. Santos, CT 3182, during the period between July 24, 2003 and August 14, 2003, with a time interval of 5 minutes. The load current in the transformer and the temperature at several points were measured. The points of measurement were: air input and output, surface of transformer, radiators, network protector and walls and ceiling. The program plots, in a graphic output, the cycle of estimated absolute temperature of top-oil and the corresponding value measured on the field. On
the other hand, the value of the heat transfer coefficient was calculated based on the current and temperature measured.

**Estimate of Heat Transfer Coefficient of the Transformer**

Considering in (1), the time variations \( \Delta t = t(i) - t(i-1) \), the resulting temperature variations in the transformer are:

\[
\Delta T_T = T_{\text{Trans}}(i) - T_{\text{Trans}}(i-1),
\]

thus:

\[
\Delta T_T = A_{\text{Trans}}(T_{\text{Trans}} - T_{\text{Air}}) \Delta t - \sigma A_{T_{\text{Tr}}}(T_{\text{Tr}} - T_{\text{Air}}) \Delta t + h_{\text{Traf}} A_{\text{Traf}} (T_{\text{Traf}} - T_{\text{Air}}) \Delta t - \frac{A_{T_{\text{Tr}}}}{R} \Delta t + \frac{\Delta T_{\text{Tr}}}{R} - \Delta T_{\text{Tr}} = \Delta t.
\]

The value of \( h_{\text{Traf}} \) is determined by adjusting the linear and exponential functions, as follows:

\[
h_{\text{Traf}} = \frac{(P_{\text{still}} + s^2 P_{\text{cu}}) \Delta t - C_{\text{Trans}} \Delta T}{A_{\text{Traf}} (T_{\text{Traf}} - T_{\text{Air}}) \Delta t - \sigma A_{T_{\text{Tr}}}(T_{\text{Tr}} - T_{\text{Air}}) \Delta t - \frac{A_{T_{\text{Tr}}}}{R} \Delta t + \frac{\Delta T_{\text{Tr}}}{R} - \Delta T_{\text{Tr}}}
\]

Applying (5) to all available measurements, the value of \( h_{\text{Traf}} \) was determined and the probability curve of \( h_{\text{Traf}} \) is plotted in Fig. 5.

**Fig. 5 – Distribution of \( h_{\text{Traf}} \)**

The dependence of \( h_{\text{Traf}} \) vs. \( I \) is established by adjusting the linear and exponential functions, as follows:

\[
h_{\text{Traf}} = 15.067 + 0.01911 I \quad h_{\text{Traf}} = 16.758 e^{0.00071 I}
\]

The program was improved to support the variation of \( h_{\text{Traf}} \) with the current. The value of \( h_{\text{Traf}} \) was considered not to exceed 32 W/m²/K. With those improvements it was possible to determine, at each time interval of the daily load cycle, the deviation between the temperatures of top oil measured and the estimate: \( \Delta T = T_{\text{Oil,Meas}}(i) - T_{\text{Oil,Est}}(i) \) and to determine the average and standard deviation of error:

\[
\mu = \frac{\sum_{i=1}^{N} \Delta T(i)}{N} \quad s = \sqrt{\frac{\sum_{i=1}^{N} (\Delta T(i) - \mu)^2}{N}}
\]

The values observed are presented in Table 6, and the linear function (is slightly more accurate):

**TABLE 6 – Error in top oil temperature**

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Linear</th>
<th>Expon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>1.911</td>
<td>2.066</td>
</tr>
<tr>
<td>Maximum</td>
<td>6.553</td>
<td>6.552</td>
</tr>
<tr>
<td>Average (µ)</td>
<td>3.211</td>
<td>3.359</td>
</tr>
<tr>
<td>Standard dev. (σ)</td>
<td>1.259</td>
<td>1.117</td>
</tr>
</tbody>
</table>

**LOSS OF LIFE WITH LOAD**

**Introduction**

Using the transformer of the preceding section and the daily load and temperature curve of Table 7, the daily loss of life was estimated in percentage terms, and the life in years, for the maximum demand varying from 0.7 pu to 1.2 pu, with and without forced ventilation. The results are presented in Table 8.

**TABLE 7 – Daily load and temperature**

<table>
<thead>
<tr>
<th>Time interval (h)</th>
<th>Demand (pu)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 9</td>
<td>0.30</td>
<td>27</td>
</tr>
<tr>
<td>9 - 18</td>
<td>1.00</td>
<td>30</td>
</tr>
<tr>
<td>18 - 21</td>
<td>0.60</td>
<td>26</td>
</tr>
<tr>
<td>21 - 24</td>
<td>0.30</td>
<td>25</td>
</tr>
</tbody>
</table>

**Test case 1 – Fault in forced ventilation**

This test case considers that the transformer works at a maximum demand of 0.95 pu, during "n" days per year, without ventilation due to a fault in the fan. The life of the transformer may be calculated as follows:

\[
\text{Life}(n) = \frac{100.0}{(365 - n) \text{LLD}_{\text{normal}} + n \times \text{LLD}_{\text{without}}(n)}
\]

where:

- \( \text{Life}(n) \) - transformer life with "n" days yearly without ventilation, years;
- \( \text{LLD}_{\text{normal}} \) - daily loss of life with transformer demand of 0.95 pu with forced ventilation, %;
- \( \text{LLD}_{\text{without}} \) - daily loss of life with transformer demand of 0.95 pu without forced ventilation, during 'n' days per year, %;

**TABLE 8 – Loss of life with and without ventilation**
The resulting life is presented in Figure 6.

**Figure 6 - Transformer life**

```
Days without forced ventilation
0 1 2 3 4 5 6
0 5 10 15 20 25 30

Life (years)

0 10 20 30 40
```

### Test case 2 – Transformer with overload due to faults

For this test, the transformer is expected to work at a maximum demand of 0.95 pu, during “n” days per year at a maximum demand of 1.2 due to faults in the network. The transformer always works with forced ventilation. The life of the transformer may be calculated as follows:

\[
\text{Life}(n) = \frac{1000}{(365-n)\, \text{LLD}_{0.95} + n \times \text{LLD}_{1.20}(n)}
\]

The resulting life is shown in Figure 7.

**Figure 7 - Transformer life in overload**

```
Days of fault
0 1 2 3 4 5 6
0 10 20 30 40

Life (years)

0 10 20 30 40
```

### Conclusions

The software that was developed is able to study the loading of the transformer with regard to loss of forced ventilation and with operation in overload. More field tests are needed to improve the accuracy of the coefficient of heat transfer and to analyze the faults in the forced ventilation system. (It will be improved, also, t) The methodology used in the definition of the external area of the transformer must also be improved.

### References


