Finite Element Analysis of Thermal Performance Behavior in Medium Voltage Current Transformer

Nihat Pamuk

Zonguldak Bulent Ecevit University, Faculty of Engineering, Electrical and Electronics Engineering, Zonguldak, Turkey

Abstract – Current transformers reduce large current values to measurable current values in electrical systems and provide isolation of various measuring instruments and relays from the main electrical system. Voltage current transformers are produced according to the tests defined in national and international standards during the production phase. In order for the relays used for protection in electrical systems to work correctly, medium voltage current transformers must be within the verified operating range. For this reason, it becomes very important for current transformers to work correctly. In case the main current has a harmonic structure, the operating range of the protection type medium voltage current transformers can change significantly. In this paper, it the steady-state thermal performance behaviour in a medium voltage current transformer is studied and analysed. The study was carried out considering four different loads. The numerical results of the temperature distribution were obtained using a 2D finite element software package. The iron losses in the core region were calculated using the maximum flux density that was obtained with a 2D finite element software package. The numerical solutions were compared with measured experimental results that were obtained in tests. Some conclusions are remarked.

Keywords – current transformer, measurement, finite element analysis, thermal performance.

1. Introduction

A reliable operation of the electric power system requires, among others, accurate information from the medium voltage current transformer to the protective relays and to the SCADA system [1]. So, in the design stage of a medium voltage current transformer, electromagnetic and thermal studies should be performed.

In this paper was studied and analyzed the steady-state temperature distribution of a medium voltage current transformer with five primary current ratings (25 A, 10 A, 5 A, 2.5 A, and 1 A) and a 5 A secondary rating. For each one of these ratings, the study was carried out considering four different loads. The numerical results of the temperature distribution were obtained using a 2D finite element software package. The iron losses in the core region were calculated using the maximum flux density that was obtained with the 2D finite element software package CADdyMAG [4], [5]. These computer programs were also implemented by the author to solve the electric and the magnetic field problems.

The finite element analysis of thermal performance behavior solutions was compared with the temperatures that were measured experimentally with two thermocouples installed inside the medium voltage current transformer.

2. Definition of the Thermal Problem

The steady-state heat transfer problem in a domain D is described by the following partial differential equation [6].

\[ \nabla \cdot (k \nabla T) + f_T = 0 \]  \hspace{1cm} (1)
∇ (nabla) is defined as differential operator, \( k \) is defined as thermal conductivity \([\text{W/(m}^\circ\text{C})]\), \( T \) is defined as temperature \((^\circ\text{C})\), and \( f_t \) is defined as thermal sources \([\text{W/m}^3]\) in equation 1. The thermal sources \( f_t \) in the medium voltage current transformer windings can be defined by the following expression equation 2 [7], [8].

\[
f_t = p_0 [1 + \alpha (T - T_0)] J^2
\]

(2)

\( J \) is defined as current density \([\text{A/m}^2]\), \( p_0 \) is defined as electric resistivity at \( T_0 \) temperature \([\Omega\text{m}]\), \( \alpha \) is defined as linear expansion coefficient \([\text{K}^{-1}]\) in equation 2. In the core region, \( f_t \) was assumed as constant. These thermal sources were evaluated considering the maximum flux density value that was obtained from the finite element solution and can be defined by the following Poisson expression equation 3 [9], [10].

\[
\nabla^2 A = -\mu J
\]

(3)

\( A \) is defined as magnetic potential vector \([\text{Wb/m}]\), \( \mu \) is defined as magnetic permeability \([\text{H/m}]\) in equation 3. Using the finite element formulation to solve equation 1, a discretization of the domain \( D \) was made and then the condition of stationarity applied to the respective functional [11], [12]. With the following equation 4, the calculation is made for each first-order triangular finite element of the matrix network.

\[
([S]_e + [G]_e + [H]_e) [T]_e = [F]_e + [P]_e
\]

(4)

\( [S]_e \) is defined as thermal conductivity matrix, \( [G]_e \) is defined as resistivity temperature dependency matrix, \( [H]_e \) is defined as convection matrix, \( [T]_e \) is defined as temperature vector, \( [F]_e \) is defined as heating sources vector, and \( [P]_e \) is defined as convective vector in equation 4. These matrices are described in [13]. In the elements of the outside surface of the medium voltage current transformer, a natural convective heat transfer coefficient \( h_n \) was considered [14]. Assembling all the finite element matrices corresponding to equation 4, the global matrix equation given in equation 5 is obtained.

\[
[S][T] = [F]
\]

(5)

In order to get a unique solution of the above algebraic equations system, the temperature of some nodes must be specified, and then the system of equations solved to get the numerical nodal temperature distribution.

3. Application Example

The steady-state temperature distribution of a medium voltage current transformer with five primary current ratings \((25 \text{ A}, 10 \text{ A}, 5 \text{ A}, 2.5 \text{ A}, 1 \text{ A})\) was studied and analyzed and a 5 A secondary rating.

The study was carried out considering four different loads \((50\%, 80\%, 100\% \text{ and } 110\% \text{ of nominal load})\). The medium voltage current transformer used is shown in Figure 1. In Figure 2, is presented the zoom of the outline of the model. In Figure 3, is presented the finite element mesh model with 975 nodes and 1930 elements.
In order to reduce the complex geometry of the device to a two dimensional problem, a detailed investigation was made. This study suggested a reduction in the thermal sources related to the heat flow in the outside surfaces of the medium voltage current transformer. The convective heat transfer coefficient was made equal to 16 W/(K.m²). The experimental results were obtained in tests with two thermocouples (T_c1 and T_c2) located in the device as it is shown in Figure 2.

4. Heat Transfer Research in Medium Voltage Current Transformer

The main change in the amount of temperature rise in the medium voltage current transformer is due to the processes in the production phase of the transformer. The heat energy generated during the production phase is calculated by converting the temperature distribution of the transformer [15]. The heat energy generated is transmitted in the form of radiation and convection propagation until the heat distribution reaches equilibrium. In case the heat generation and distribution reach equilibrium, the transformer temperature will remain constant [16].

The main heat sources in medium voltage current transformers are the guide rods in the transformer coil and the secondary coil. In normal operation, the current between 100 A and 1000 A can flow through the guide rods in the primary coil of the transformer. In this case, the current amount in the secondary coil of the transformer is usually at the level of 5 A [17]. For this reason, the losses on the secondary coil of the medium voltage transformer are neglected. Joule heat energy generated on the guide rod in the primary coil of the transformer should be considered. In addition, some additional losses occur in medium voltage current transformers. These additional losses are eddy current, leakage and stray losses. The amount of these additional losses is quite small and difficult to calculate.

The main heat transfer in medium voltage current transformer takes place in the form of convection, radiation and conduction. The real heat conduction in the medium voltage current transformer occurs in the guide rod of the primary coil and the insulating bushing [18]. Heat conduction is transferred from high temperature values to lower temperature values. The convection heat transfer in the medium voltage current transformer is transmitted to the environment through the transformer's outer insulation hardware made of epoxy resin. The heat transfer in the interior of the transformer is transmitted from the air-contact surfaces of the hardware part made of carbon steel material. In the temperature field distribution characteristic of the transformer, the ventilation area in the high voltage coil of the transformer should be adjusted considering the convection heat transfer coefficient of the lower and upper rod connection units [19]. Radiant heat transfer in the medium voltage current transformer occurs on the outer wall of the transformer, which is in contact with the air. The main factor that allows the heat in the transformer to spread to the environment is the surface emission [20].

5. Experimental and Finite Element Analysis

The thermal analysis of the medium voltage current transformer was performed with an ambient temperature of 20 °C. All the errors ε presented in this study are referred to the experimental temperatures that were obtained in the tests. In Table 1. are shown the finite element numerical results with and without the thermal influence of the iron losses, considering the nominal operating conditions. In Figure 4. are shown the isothermal lines corresponding to the 25A / 5A load situation.

![Figure 4. Zoom of the isothermal lines model for the 25A/5A situation](image)

<table>
<thead>
<tr>
<th>Primary Current Winding [A]</th>
<th>Without Iron Losses</th>
<th>With Iron Losses</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_c1</td>
<td>T_c2</td>
<td>T_c1</td>
<td>T_c2</td>
</tr>
<tr>
<td>1</td>
<td>40.3</td>
<td>40.5</td>
<td>35.5</td>
</tr>
<tr>
<td>2.5</td>
<td>40.7</td>
<td>40.9</td>
<td>35.0</td>
</tr>
<tr>
<td>5</td>
<td>42.3</td>
<td>42.5</td>
<td>39.5</td>
</tr>
<tr>
<td>10</td>
<td>46.5</td>
<td>46.7</td>
<td>43.0</td>
</tr>
<tr>
<td>25</td>
<td>44.8</td>
<td>45.0</td>
<td>48.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ε [%]</th>
<th>Tc1</th>
<th>Tc2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5A</td>
<td>1.56</td>
<td>1.62</td>
</tr>
<tr>
<td>9.99</td>
<td>1.02</td>
<td></td>
</tr>
<tr>
<td>1.01</td>
<td>1.04</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Finite element temperatures with/without considering the iron losses for nominal load
In Table 2 are shown the finite element temperatures and experimental temperatures for the 1 A primary winding conditions. In Table 3 are shown the finite element temperatures and experimental temperatures for the 2.5 A primary winding conditions. In Table 4 are shown the finite element temperatures and experimental temperatures for the 5 A primary winding conditions. In Table 5 are shown the finite element temperatures and experimental temperatures for the 10 A primary winding conditions. In Table 6 are shown the finite element temperatures and experimental temperatures for the 25 A primary winding conditions. All of the tables present the experimental and the numerical spot temperatures corresponding to the two thermocouples location. For each one of the primary windings, four different load situations were analyzed. As the temperature rise of the medium voltage current transformer produced by the iron losses is quite small, they were not taken into account in the finite element solutions.
6. Conclusion

From the above results the following conclusions can be extracted:

- A 2D heat transfer simulation of the medium voltage current transformer can be performed if an adequate reduction of the thermal sources is made in order to accommodate the influence of the heat flow through the two non modelled outside surfaces.

- As it was expected the temperature rise due to the iron losses is quite small, since the current medium voltage current transformer core is manufactured with grain-oriented steel and consequently operates with a small value of the flux density.

- The thermal finite element analysis is a very important tool for the medium voltage current transformer designer, since it allows to predict the temperature distribution particularly in severe load conditions without damage or destroying the device.

References


