Comparative Study of Single-phase Shell & Core Type Transformers in GIC Temperature Rise Effect

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Abstract. Geomagnetically induced currents (GICs) flowing through transformers may cause temperature rise which could result in permanent damage. As the single-phase-set transformers are widely used in the bulk power transmission, this paper investigates the temperature rise effect both in shell type transformers and core type transformers. Based on the designing parameters of the 500kV single-phase shell type and core type transformer, a 3D finite element model including the transformer iron core, tank and supporting parts has been established, so that the temperature rises in the iron cores and supporting parts are all taken into account. Through calculation with different values of GIC excitations, the different temperature rise characteristics between shell transformer and core transformer are investigated. The simulation results of the temperature rise at different positions in the supporting parts can provide references for the designing of Chinese UHV (ultra-high voltage) transformers to mitigate the temperature rise due to DC bias.

Introduction

It is called DC magnetic bias when DC or quasi DC current flows through power transformers, the transformer and the power grid can be threatened by the severe DC bias. There are two main reasons for the serious DC magnetic bias: one is the effect of the HVDC (high voltage direct current) grounding electrode current [1], another is the impact of geomagnetically induced currents (GIC) in the power grid caused by the geomagnetic storms [2]. DC magnetic currents up to 210A have been monitored at the transformer neutral point in Zhexi Converter Station [3]. During the severe geomagnetic storms on November 9 to 10, 2004, the maximum GIC at the Ling’ao Nuclear Power Plant reaches up to 75.5A [4]. The1000kV UHV (ultra high voltage) power grid in China, which has been under construction since 2009, adopts 500 mm² eight-bundled conductors for the transmissions lines which has smaller DC resistance than that of 500kV power grid, plus the terminal substation effect of GIC, the GIC in the1000kV Shanghai Substation is estimated to be 346.62A at maximum [5]; and the GIC in transformers in Ximeng Substation which is included in the planning Sanhua UHV Grid could reach 442.9A [6]. These data show that the DC bias prevention and mitigation of the effects have become an important task in the construction and operation of China's power grid with the development of UHVDC and continuous reduction of DC resistance of the transmission lines.

Transformers suffer the same interference, though the two causes of DC bias are different. The DC bias result in abnormal vibration, noise, harmonics, reactive power loss and temperature rise [7]. As for the influence of geomagnetic storms, in addition to the blackout [8], there have been a large number accidents where transformers were severely damaged due to the temperature rise [9-11]. In reference [9], where the accident on March 13, 1989 has been introduced, geomagnetic storms encroached New Jersey Salem nuclear power plant and caused damage to the 500kV/1200MVA transformer. The reasons for which the transformer windings were burned and the GIC values were also analyzed. The accident caused by the GIC in South African Power Grid destroyed several 400 kV transformers during the geomagnetic storms in October to November, 2003 [10]. In reference [11], the tank model of the transformer leakage flux distribution and the temperature rise was established, and the values of leakage flux and temperature rise were calculated. The previous
researches on the transformer temperature rise due to GIC are very limited for the probable reasons that the GIC does not exist in all countries and the transformer designing is related to commercial secrets.

In the EHV/UHV transmission system of high power, single-phase transformers are usually used. There are two types of different iron cores: the core type and the shell type. In references [12] and [13], the leakage flux distribution of the 500kV single-phase transformer with core type has been studied, however it was studied with a 2D model. The main transformers widely used are single-phase shell type transformers, typically in both China's EHV power grid (750kV power grid constructed from 2005) and the UHV power grid (1000kV constructed from 2009). Due to the different core structures between the shell type and the core type transformers, the leakage flux distribution and the temperature rise effect of the two type transformers are different, which lead to difference in the distribution of temperature rise. Based on the work in [12, 13], this paper makes further study on the GIC effect, employing the core type transformer with similar capacity as in [12, 13], but targeting at the single-phase shell type transformer, to determine the temperature rise position in the supporting members and the corresponding GIC threshold values which can provide references both for the designing of the Chinese EHV and UHV transformers and mitigation the temperature rise due to the DC bias.

Parameters & Modelling

Transformer Parameters

In this paper, the core type transformer reference to [12-13], and with similar capacity the single-phase shell type transformer is introduced.

The relevant data of two transformers are given in table 1, and figure 1 shows the B-H curves of the materials of the core and tank [12]. As for materials, the core uses M095-27S silicon steel, and the tank material is A3 steel, the winding wire uses copper, and the material for magnetic shunt is the same as the core. Where, M095-27S silicon steel and the A3 steel are nonlinear magnetic materials, the conductivity of which are \(4.8 \times 10^6 \text{S/m}\) and \(5.6 \times 10^6 \text{S/m}\). The relative permeability of the copper is approximately to 1, and its conductivity is \(5.8 \times 10^7 \text{S/m}\).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Descriptions</th>
<th>Shell transformer value</th>
<th>Core transformer value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S_N)</td>
<td>rated capacity</td>
<td>224 MVA</td>
<td></td>
</tr>
<tr>
<td>(f)</td>
<td>frequency</td>
<td>60 Hz</td>
<td></td>
</tr>
<tr>
<td>(V_{\text{h}}/V_{\text{l}})</td>
<td>rated voltage</td>
<td>500 / 230 kV</td>
<td>512.5 / 24 kV</td>
</tr>
<tr>
<td>(R_1/R_2)</td>
<td>resistance of series / common winding</td>
<td>0.179 / 0.125 (\Omega)</td>
<td>0.790 / 0.003 (\Omega)</td>
</tr>
<tr>
<td>(N_1/N_2)</td>
<td>winding turns</td>
<td>261 / 222</td>
<td>715 / 58</td>
</tr>
<tr>
<td>(Z_%)</td>
<td>short-circuit impedance%</td>
<td>12 %</td>
<td>16.54 %</td>
</tr>
<tr>
<td>(I_0%)</td>
<td>no-load current%</td>
<td>0.063 %</td>
<td>0.127 %</td>
</tr>
</tbody>
</table>

Table 1. Parameters for shell and core transformers.
Modelling

According to basic parameters in figure 1 and table 1, the geometric model of the transformer is established in ANSOFT-Maxwell, and the mesh generation is applied to the model afterwards, by applying the excitation, the simulation is tested, as described below:

1) Geometric model established

According to the structure size, and since the feature of the transformer symmetry, 1/4 3D element model is established for the shell type transformer, as well as the 1/8 model for core type transformer, as shown in figure 2. In geometric model, there should have magnetic shunt in the inner surface of the tank and the T beam, but didn’t map in this paper, for the magnetic shunt is small thickness, and not easily observed in the graph.

2) Define material properties

Transformer tank, T beam and core clamping have the same material, A3 steel; core, magnetic shunt uses M095-27S silicon steel sheet; winding conductor material is copper; the core rod and core clamping a and b are all using non isoperm (stainless steel). The parameters of material properties can be defined by B-H curve in ANSOFT.

3) Applied excitations

Based on the theory of J-A [14], the excitation current under different GICs is obtained, and then the load current and the exciting current are applied to the transformer winding together.

The current \( i_1 \) applied on the series winding and the current \( i_2 \) applied on the common winding for shell transformer are:
where \( i_e \) is the excitation current with DC bias that obtained by J-A theory; \( i_{1L}, i_{2L} \) are load currents on series winding and common winding, respectively; and \( N_1, N_2 \) are numbers of the series winding and common winding turns.

The current \( i_1 \) applied on low-voltage winding and the current \( i_2 \) applied on high-voltage winding for core type transformer are described as:

\[
i_1 = i_{1L} + i_e
\]

\[
i_2 = i_{2L} + i_e
\]

4) Mesh generation

Firstly, the grid generator is used to divide the transformer model adaptively, and then the grid is refined in the area of the tank, iron core, T-beam and so on. Due to the small penetration depth of the tank, T-beam and core clamping, it is necessary to refine the surface of these structural parts. Maxwell 3D automatically calculates the penetration depth of the tank by defining the properties of the tank material (A3 steel) in the mesh generator. The mesh generator can refine the mesh of the material surface according to the penetration depth.

**Hotspots Heating Effect of GIC**

An increase of the losses in transformer metal structures results in an increase in the temperature rise of transformer components. Statistics show that the GIC could attain up to 100A per phase for 1 min and 50A per phase for 5 minutes during magnetic storms [15], and in large transformers, time constant of windings is in the range of 5 - 6 minutes and it is up to 15 - 30 minutes for the core, tank, and other structural parts, therefore, temperatures corresponding to GIC pulses reach a fraction of the steady state values, and we assume the GIC only has magnitude influence. Additionally, it needs 10 to 18 hours for the transformer oil to achieve a stable temperature [16], thus, when discussing the transformer losses caused by the GIC, we suppose that the temperature of metal structures rises quickly enough to reach a stable temperature, and the temperature of transformer oil is basically unchanged because it changes too slow.

The temperature rise of the transformer metal structure under GIC can be obtained by ANSOFT - ePhysic software and ANSOFT-Maxwell software co-simulation. With the step presented in Chapter II, the temperature distribution of the shell type transformer and core transformer metal structure can be obtained, as shown in figure 4, figure 5 (GIC=40A).

From figure 4 to figure 5, the simulation results show that the hot spot position of the core transformer is different from that of core transformer. On the shell type transformer, after DC bias occurs, the hot spot of the tank is located at the intersection of the bottom and the lower T-beam; the hot spots of the upper and lower T-beam are at their center; and the hot spot of core clip is at the intersection of upper T-beam. As for core type transformer, the hot spot of the tank is located in the center area of the top and the bottom of the tank; the hotspot of the core clamp is located in the center region of the bottom end of the core clip; but the core rod temperature rise is very small.
The Analysis of Supports Temperature Rise

Besides the simulation with a single GIC value, the temperature of each supporting members of shell and core transformers with different GIC values is simulated, and GIC has different effects on different support, as showed in figure 6. Since temperature distribution of a transformer is dominated by the loss of the transformer, the average loss of different components of both shell type and core type transformer in FEM modelling are given in table 2.
Table 2. The average loss of different components.

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>$\Delta P$ (kW)</th>
<th>GIC (A)</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta P$ of the shell type transformer</td>
<td>tank</td>
<td></td>
<td>29</td>
<td>63</td>
<td>93</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td>T-beam</td>
<td></td>
<td>13</td>
<td>32</td>
<td>45</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>core clamp</td>
<td></td>
<td>7</td>
<td>19</td>
<td>33</td>
<td>43</td>
</tr>
<tr>
<td>$\Delta P$ of the core type transformer</td>
<td>tank</td>
<td></td>
<td>21</td>
<td>56</td>
<td>84</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>core clamp and tie rod</td>
<td></td>
<td>5</td>
<td>12</td>
<td>20</td>
<td>26</td>
</tr>
</tbody>
</table>

As showed in figure 6 (a), the temperature of the shell transformer tank, T-beams and core clamping increase with the increasing GIC, and the upper and lower T-beam earliest appeared remarkable local overheating. When the GIC is up to 30A, the maximum of T-beam would exceed 115 °C, the maximum temperature rise would exceed 75°C; and when the GIC is up to 40A, the maximum of local tank temperature would exceed 115°C, the maximum temperature rise would exceed 75°C, the temperature rise of iron core clamping will exceeds the standard limit values while GIC continues to increase. Similarly, as showed in figure 6 (b), when GIC up to 30A, the temperature rise of the core transformer tank exceeds the limit, obviously.

A comparison of the allowable temperature rise limit of the transformer can be seen, when the GIC reached to 30A, the tank will be local overheating; and when it up to 45A, the core clamping will also be local overheating. Compared with core type transformer, shell type transformer are more seriously affected by GIC, the temperature rises faster, and the temperature rise is greater.

Conclusion and Discussion

Based on the work in [16-17], the further research is made in this paper, and the differences in temperature rise effect caused by GIC of the single-phase shell type transformer and core type transformer are comparative analyzed, the main conclusions are obtained as follows:

1) When DC magnetic bias occurs, the results show that there is a big difference between shell transformer and core transformer in the hotspot locations. As for shell transformer, the obvious hotspot of the tank locates at the junction of the bottom of the tank and the T-beam, while in core transformer that locates in the center area of the top tank and the central bottom of the tank; and the iron core clamping’s hotspot in shell transformer locates at the junction of the clamping and the upper T-beam, but in core transformer that locates in the center region of the bottom end of the core clamping.

2) As we consider the GIC effect, the temperature rise exceeds the IEEE standard’s limit values for local T-beam and the tank, when the GIC reaches up to 30A and 40A in shell type transformer. And different in core type transformer, the tank is the sensitive component in temperature rise with GIC.

3) The iron core structure has great influence on transformer GIC temperature rise effect. In this paper, we assume that once the designing parameters are determined, the temperature rise effect is determined, therefore, the precise model isn’t necessary, so that the hotspot can be found with engineering software.

4) Compared with the temperature rise effect of single-phase core type transformer, the influence of the same GIC on the temperature rise of the shell transformer is more serious. Because four or five limb single-phase shell type is widely used in UHV Transformer (750kV or 1000kV) in China, a particular attention should be paid on the temperature rise caused by GIC. On the other hand, whether slot on the T-beam or adopting non-magnetic material could restrain the GIC temperature rise still requires further research.

References