COMPARISON BETWEEN HEXA-TYPE AND CONVENTIONAL E-TYPE CORE THREE-PHASE TRANSFORMERS

ABSTRACT

The concept of power transformer design with a symmetric core construction (the hexa-transformer) provides more compact solution compared to traditional technology based on an E-type core. This paper evaluates parameters of two 100 kVA three-phase transformers built according to both concepts. The evaluation includes calculations of induced voltages, inductances, core losses and weight differences. Further, the calculated parameters are compared with measured values. It is shown that, for the investigated transformer size and ratings, the compact design of the hexa-transformer yields up to 25% lower core losses, 40% smaller magnetization current and 12% lower core weight compared to the conventional E-core transformer.

Keywords: core, hexa-transformer, core losses, magnetization current

1 INTRODUCTION

The manufacturing of three-phase transformers with the core arranged in a triangular shape was attempted already in the 1880’s. However, at that time this technology was too complex to be broadly commercialized. Much later, at the beginning of the 1990’s, engineers succeeded to implement the idea with some modification and the resulting product was introduced as a hexa-transformer.

Figure 1 Arrangement of the hexa-transformer construction
The hexa-transformer is a three-phase transformer with a specially shaped core, as illustrated in Figure 1. The core consists of nine rolls of laminated steel bands and the core legs have a cross-sectional shape of a hexagonal.

Transformers built according to this concept are characterised by higher energy efficiency, lower weight and volume, lower vibrations and noise level, lower electromagnetic stray field, inrush current and lack of third harmonic. In addition, compared to the traditional technology of power transformer production that involves a large amount of manual labour, the new technology allows automating the production process to a large extent.

The aim of this paper is to evaluate a hexa-transformer in comparison with a conventional three-phase E-core transformer. Thus, two 100 kVA units of the same ratings, winding design, turn numbers, materials, as well as similar cross-sectional areas of the core legs, are compared. The comparison is based on calculated induced voltages, inductances, core losses and weights and the results are verified with measured values.

2 THE MEASUREMENTS AND SIMULATION MODELS

2.1 Measurements and transformer data

The rated values of the compared transformers are provided in Table 1. The main core dimensions of the hexa-transformer and E-core transformer, respectively, are also given as well as the windings and material data of the hexa-transformer. The construction of the hexa-transformer core is further illustrated in Figure 2. The three rolls/yoke are named A, b and c where roll A has twice the width of roll b and c. Measured no-load voltages, \(U_0\), magnetization currents, \(I_m\), and core losses \(P_0\) are shown in Table 2.

| Table 1 Rated values, core material and winding parameters of the compared transformer |
|-----------------------------------|-------------------------------|
| Rated Power                       | 100 kVA                       |
| Voltage levels                    | 11000/420 V                   |
| Current levels                    | 5.25/137.5A                   |
| Connection                        | Dyn                           |
| Coil Length                       | 345 mm                        |
| Coil outer diameter               | 236 mm                        |
| Number of turns                   | 3180/67                       |
| Hex-core leg cross section radius | 33/66 mm                      |
| Hex-core leg height               | 350 mm                        |
| E-core leg cross section radius   | 53 mm                         |
| E-core leg height                 | 440 mm                        |
| Winding material                  | copper                        |
| Core material                     | GO Unisil-H M103-27P          |

| Table 2 Rated values, core material and winding parameters of the compared transformer |
|-----------------------------------|-------------------------------|
| Type                              | \(U_0\) (V) | \(I_m\) (A) | \(P_0\) (W) |
| E-core                            | 420            | 0.46        | 191          |
| Hexa-core                         | 420            | 0.27        | 156          |
| % difference                      | 0              | 41          | 18           |
2.2 E-core and hexa-transformer models

3D model geometries (Figures 1 and 3) were created directly in a finite element (FEM) software package [4] in accordance with the measured dimensions of the transformers with some modifications, as described below. The magnetic properties of the cores were assumed to be nonlinear and anisotropic. The permeability of the core material was characterised by its normal ($\mu_n$, $\mu$) and tangential ($\mu_t$) components with respect to core surfaces. The normal direction is thus in the rolling direction of the lamination sheet, see Figure 4. The permeability components are specified as follows [5]:

$$\mu_n = (1-k_{Fe}) + \mu_{Fe} k_{Fe}, \quad \mu_t = \mu_{Fe} / ((1-k_{Fe}) \mu_{Fe} + k_{Fe})$$

(1)

where $\mu_{Fe}$ is the relative permeability of the laminated steel described as a non-linear function of the flux density ($B(H)$-curve), $K_{Fe}$ is the stacking factor assumed here to be equal to 0.95.

The permeability functions are given by measured magnetization curves for the rolling direction and for the transverse direction (in this case the material is grain oriented Cogent steel). However, direct use of these two functions led to poor convergence of the resulting non-linear problem. Therefore, the permeability of the transverse direction was approximated to be one tenth of the permeability of the normal direction. In the model, the permeability in normal ($\mu_n$, $\mu$) and tangential ($\mu_t$) directions were implemented as components of the total permeability tensor.
The vectors $\mathbf{n} = (n_x, n_y, n_z)$, $\mathbf{r} = (r_x, r_y, r_z)$, and $\mathbf{t} = (t_x, t_y, t_z)$ are unit vectors following the shape of the core, so that for a bend (hexa-core case), $\mathbf{n}$ is in the rolling direction, $\mathbf{t}$ is in the axial (transverse) direction, and $\mathbf{r}$ is in the radial direction of the bend, as shown in Figure 4. In the conventional E-core transformer, the geometry of the core is drawn in Cartesian co-ordinate system. Hence, if the core slices are stacked in z-direction, then the components of permeability can be expressed simply by using (3) where the expressions for $\mu_n$, $\mu_r$, and $\mu_t$ are defined in (1) and the directions are shown in Figure 5.

$$\mu = \begin{bmatrix} \mu_n & 0 & 0 \\ 0 & \mu_t & 0 \\ 0 & 0 & \mu_r \end{bmatrix}$$

In the real transformers, the primary (high voltage and low current) and secondary (low voltage and high current) windings are located on each core leg and are separated by an insulation barrier of 8 mm.
The secondary windings are the closest to the core leg, and they are made of conductors with a rectangular cross section. The primary windings are made of conductors with circular cross sections. The windings are wound in layers with paper-insulation between layers.

In the model, the windings are represented as hollow cylinders with circular inner cross sections and evenly distributed current densities. The currents in the primary windings are set as rotating according to (4) and (5) with no current component in the axial direction of the coil (in this case the z-direction which is the case of the hexa-core model):

\[ J_x = -J_k \frac{(y - y_k)\sqrt{(x - x_k)^2 + (y - y_k)^2}}{x - x_k} \]  

\[ J_y = J_k \frac{(x - x_k)\sqrt{(x - x_k)^2 + (y - y_k)^2}}{y - y_k} \]  

where \((x_k, y_k)\) is the center of coil \(k\), \(J_k\) is the current density in coil \(k\), \(k = 1\) to \(3\), and 

\[ J_1 = J_0 \cos(\omega t) \]  

\[ J_2 = J_0 \cos(\omega t + 2\pi/3) \]  

\[ J_3 = J_0 \cos(\omega t + 4\pi/3) \]  

where \(J_0\) is the current density amplitude, \(\omega\) the angular frequency and \(t\) stands for time. For the E-core model, which has the axial direction along the y-axis, (4) and (5) must be changed accordingly, yielding \(J_x\) and \(J_z\). The paper-insulation between layers is neglected in the model. However, the insulation barriers between primary and secondary windings are implemented as narrow air gaps.

2.3 Magneto-static simulations

The model settings and material characteristics described above were utilized for solving 3D magneto-static problem using corresponding application mode in the finite element package [4]. The equation (7) for magnetic vector potential \(A\) was solved providing time-dependent distributions of magnetic fluxes and fields in the computational domain.

\[ \nabla \times (\mu_a \mu_r \nabla \times A) = J \]  

The domain contained half of the transformer geometry (see Figure 6) enclosed in an air box. In this way leakage fluxes could be resolved. The magnetic insulation boundary conditions (Neuman boundary condition) were used on the outer boundaries of the air box. These conditions set the normal component of the vector potential on the boundary to zero:

\[ n \times A = 0 \]  

Since one half of the transformer is modeled, the boundaries on the bottom cross section in Figure 6 were set to electric insulation condition that specifies the tangential component of the field intensity to be zero:

\[ n \times H = 0 \]  

In this way, symmetry has been attained.

The meshing of the hexa-transformer model is problematic due to the long thin spaces between the yokes and between the rolls. The closer the parts are to each other, the more problematic is the meshing. In many cases the meshing was impossible, as far as too long thin elements were needed to be generated, mostly in the air regions between bends. Due to this, even though the mesh was configured to handle long thin finite elements, the spacing between the bends had to be slightly exaggerated to be able to mesh and to solve the model. Also, the yokes where modeled as semi-circles instead of the flattened yokes of the real hexa-core. This, of course introduced discrepancies between the model and the actual shape of the hexa-transformer, e.g. the total path for the main flux was longer giving a slightly larger reluctance as well as the reluctance of the leakage flux path in air. Further, in order to reduce computational time, the three rolls per yoke of the real hexa-transformer were represented by one roll of lamination (with the cross section of half a hexagonal). The resulting model is shown in Figure 6. The simplifications made for the hexa-core model were justified by comparing
the results for the complex and simplified core constructions (with non-linear and isotropic core permeabilities) which yielded small differences (<5%) in the computed induced voltages and core loss.

The most interesting numerical results obtained from the simulations are induced voltages, inductances of the windings and core losses. The induced line-to-line rms voltages, \( V_{\text{rms}} \), are found from the well-known transformer formula (for the primary coil):

\[
V_{\text{rms}} = \sqrt{2\pi f N_2 \phi} = \sqrt{2\pi N_2 f \int B_n dA}
\]

Here, \( N_2 \) is the number of turns in the secondary winding, \( f \) is the frequency, \( \phi \) is the peak magnetic flux, and \( B_n \) is the flux density in the normal direction to the cross-sectional area \( A \). The inductances of the windings are found by integrating the normal component of the magnetic flux density over the cross-sectional area \( A \) of a coil:

\[
L_{11} = \frac{1}{i_1} (N_1 \int B_n dA)
\]

Here, \( L_{11} \) is the self inductance, \( i_1 \) is the current and \( N_1 \) is the number of turns in coil 1.

Core losses are obtained based on material data provided by the manufacturer and computed values of the flux density from the magneto-static solution. If the core laminations are modeled accounting for anisotropy of the permeability, the losses can also be calculated separately for the different directions (rolling and transverse directions). The following equation is thus used to find core loss \( P_0 \) from a model of half a transformer:

\[
P_0 = 2\rho \int_{V_r} P(|B_n|) \phi dV, W
\]

Here, \( \rho \) is the material density (mass density), and \( P(|B_n|) \) is the specific total loss as a function of peak magnetic polarization in the normal (rolling) direction. Factor 2 is used only if a half transformer is modeled. The specific loss for the transverse direction is also given by the manufacturer and it may be found from the calculations considering anisotropic permeability using the flux density value in the transverse direction; \( P(|B_t|) \).

The core weight \( m \) is easily found by integrating over the core volume and multiplying with the material mass density.

\[
m = 2\rho \int_{V_r} dV, \ kg
\]

## 3 CALCULATION RESULTS AND DISCUSSION

The magnitudes of the measured magnetizing currents (see Table 2) were used as input parameters for the simulations performed for no-load conditions. Note (Table 1) that the no-load magnetizing current of the hexa-transformer is smaller than the one of the E-core transformer. The reason to this can be explained as follows.

Figure 6 The model used for simulations of the hexa-transformer
In the E-core, the flux from the middle winding has reluctance different from (and lower than) that of the outer windings [6]. This is shown in Figure 7 where one can observe that some of the flux from the outer winding has to travel a longer distance than the flux from the middle coil.

Figure 7 E-core with the magnetic flux generated by a coil placed on (a) outer limb, and (b) middle limb

Figure 8 Arrow plots of the magnetic flux density for a) hexa-core transformer, and b) E-core transformer
There are no such unsymmetrical conditions in hexa-transformers and all windings have equal reluctances with equal (shorter) lengths of flux paths. This contributes to a higher magnetic flux for the same magneto-motive force, or in other words, the magnetizing current will be smaller in the hexa-transformer even though it will give the same no-load voltage as the E-core transformer. The difference between the transformer types is also illustrated in Figure 8, where computed magnetic fluxes are shown for both the hexa-transformer and conventional transformer.

Further, in the hexa-transformer core, flux paths are always closed and in order to be so, the flux has to pass one insulation sheet as the core is built up by rolls of laminations as it is shown in Figure 9. This is not the case for the E-core transformer where the core is built up as staples of lamination sheets with the borders distributed over the core to avoid short circuits. An example of this is shown in Figure 7 (the dotted lines show lamination borders) where one layer of lamination is shown. As can be seen in the figure, the magnetic flux needs to pass at least four borders. However, these borders contain no insulation. The effect on the reluctance, depending on the different borders the flux has to pass, is presumably small for both the E-core and the hexa-core transformer. This effect is consequently not modeled in detail and is only considered by (for both transformer types) choosing a stacking factor slightly lower than the specified by the manufacturer (0.95 instead of 0.96). Normally, the stacking factor considers only the fact that the insulation between lamination sheets is restricting the cross-section area of the steel core but in this paper we thus also include the fact that the flux is restricted by borders in the assembled core.

Thus, the reluctance of the hexa-core is expectedly smaller than that of the E-core, mainly due to the fact of the symmetry of the hexa-core and, consequently, smaller magnetizing current should be needed for the same electro-motive force. Hence, the path followed to make a closed loop of the magnetic flux is in a more natural and shorter way for the hexa-core leading to less flux leakage in the core and less reluctance for the flux. Moreover, as the amount of material is less for the hexa-core compared to the conventional transformer, the core loss of the hexa-transformer should be less.

The results of the magneto-static calculations at time equal to zero in (6) are shown in Table 3. By comparing with the data in Table 2, one can observe that the values of the measured and computed voltages $U_0$ agree well (~5% difference). Such good agreement has been achieved only if a proper description of the properties of the material of the laminated core was provided, including its anisotropy and non-linearity.

![Figure 9](image)

**Figure 9  A part of a roll of laminated steel bands with one coil and the path of the magnetic flux**

<table>
<thead>
<tr>
<th>Table 3 Results of magneto-static calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>E-core</td>
</tr>
<tr>
<td>Hexa-core</td>
</tr>
<tr>
<td>% difference</td>
</tr>
</tbody>
</table>

Looking at the calculated core loss $P_0$ values in Table 3, it is clear that magneto-static calculations do not give the total core loss (compare with Table 2). The core loss due to eddy currents
could not be considered in magneto-static calculations. Therefore, the comparison of calculated core losses concerns mainly the hysteresis loss and they are lower for the hexa-transformer.

Further, the calculated self-inductances \( L \) on primary side (referred to secondary side) are shown in Table 3. The inductance of the E-core winding is that of an outer winding. For the middle winding, the calculated self-inductance is slightly higher (1.63 H) which is realistic and in agreement of the discussion around Figure 7. Also, the higher inductance of the hexa-transformer is in accordance with the lower magnetizing current.

The 12% differences in core weight \( m \) (Table 3) comes from the fact that the hexa-yoke carries the flux in a more symmetric and efficient way. Therefore, the hexa-core yoke will always demand less volume than the E-core yoke. If the core is short and wide (short legs and long yoke); the hexa-core weight may be only 80% of the E-core (with the same outer dimensions). However, the investigated E-core is long and narrow (thus a relatively short yoke) and the weight difference is therefore not so pronounced (only 12% difference).

Figure 10 Magnetic flux density at no-load conditions obtained from hexa-transformer model with non-linear and isotropic core properties

Figure 11 The simulated magnetic flux density at no-load at one time-instant (\( t \) equals zero in (6)) for the half-hexa transformer-simplified model (non-linear and anisotropy of the core considered)
The well distributed flux in the yoke of the hexa-core transformer is illustrated in Figure 10. It is shown for no-load case at a single time instant (\( t \) equals to zero in (6)) for the half-hexa-transformer model with the complicated core construction (non-linear and isotropic representation of the permeability of the core). The flux density is similar in all three bends that are in the same rolling direction. This is due to saturation and a constant cross sectional area along the flux path. When looking at the solution for the simplified geometry, see Figure 11, where also the anisotropy of the permeability of the core was implemented according to (2), the flux density is no longer so evenly spread out in the core. The flux is now more concentrated towards the inner parts of the lamination rolls. The flux distribution in the E-core is however even more uneven, as seen in Figure 12, meaning that the yoke in the E-core is not used in a material-economic way. Observe in Figures 10 and 11 that the upper yoke of the hexa-core contains three bends with cross-section areas equal to half of the core leg cross-section area. The upper yoke of the E-core-transformer, however, contains two parts (connecting the core legs) with each cross-section area similar to the core leg cross-section area. Therefore, the yoke material of the hexa-core need only be approximately \( \frac{3}{4} \) of the E-core yoke material.

4 CONCLUSIONS

Two 100 kVA tree-phase transformers with hexa- and E-cores have been evaluated. It has been shown by both measurements and computer simulations that the compact design of the hexa-transformer yields significant improvements of the parameters, e.g., up to 25% lower core losses, 40% smaller magnetization currents, 12% lower core weight, etc. These are results of the symmetric hexa-core construction providing low core reluctance.

5 LITERATURE