Comparison of the Efficiency of Superconducting and Conventional Transformers

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Abstract. For a transformer, the annual energy loss depends on the load-dependent efficiency of the transformer and the characteristic load curve at the specific location in the grid or elsewhere. The goal of this work is the comparison of the efficiency and the annual energy losses of a superconducting (from 2G high temperature superconductors) and conventional transformer. The calculations of the load-dependent efficiency for both transformers are performed referring to a real case application of a power transformer in a power plant which defines the load curve of the device. For the conventional transformer the data base of an industrial product was used, whereas for the superconducting transformer a conceptional design for the selected specific application was developed and used for the calculations of the load-specific efficiencies and annual energy losses using the characteristic load curve of the selected application. The results show, that superconducting transformers made from high temperature superconductors (Coated Conductors), could have up to 80 percent less annual energy losses compared to the conventional transformer made from copper wires.

1. Introduction
In recent years, superconducting transformers have been investigated in different projects [1] - [4]. One main reason for the interest in superconducting transformers is the reduction of energy losses compared to conventional technique. The annual energy loss of a transformer in a power system depends on the load curve of the specific application and on the load-dependent efficiency of the transformer. In this paper the annual energy losses of a superconducting and a conventional transformer in a specific location were calculated and compared. A real case application for a power transformer with a characteristic load curve was chosen and a superconducting version of the transformer was conceptually designed. The data and parameters of the normal conducting transformer originate from a manufacturer datasheet. For both transformers, the load-dependent efficiencies and annual energy losses in the chosen application were calculated in as detailed as possible.

2. Transformer Application
In this study an auxiliary transformer supplying several drives in a power plant has been selected as an example. This transformer type has high currents at medium voltages and is therefore an interesting application for superconducting transformers because of the considerable reduction of the conductor
size and the losses. In figure 1, a typical annual load curve for such an auxiliary transformer is shown. This transformer is constantly loaded by 75% for 5000 h per year. The remaining time of the year the transformer is loaded by 0.5% but not switched off. The higher loading during the short start up of the power plant is neglected for the calculation of the annual energy losses and is not shown in the load curve. The load curve in figure 1 is used to calculate the annual energy losses of both transformers.

![Annual load curve of an auxiliary transformer for a power plant. 100% workload corresponds to 63 MVA](image)

**Figure 1.** Annual load curve of an auxiliary transformer for a power plant. 100% workload corresponds to 63 MVA

### 3. Transformer Specification
The general specification of the auxiliary transformer for this study is given in table 1. Further data are summarized in the following sections.

| Table 1. Specification of auxiliary transformer for power plant |
|---------------------------------------------------------------|
| rated power | 63 MVA | voltage pri | 21 kV | current pri | 1000 A | vector group | Dyn5 |
| rated frequency | 50 Hz | voltage sec | 9.09 kV | current sec | 2309 A | |

#### 3.1. Conventional Transformer
The conventional transformer is a 3-Phase oil-immersed transformer with the specifications given in table 2.

| Table 2. Specification of conventional transformer |
|--------------------------------------------------|
| winding voltage | 100.9 V | resistance pri winding | 39.2 mΩ | turns pri/sec | 216/90 |
| leakage impedance | 11.5% | resistance sec winding | 5.6 mΩ | dimensions l/w/h | 3.52 / 1.35 / 2.94 m |
| iron core losses | 24 kW | |

#### 3.2. Superconducting Transformer
The superconducting transformer was conceptually designed and optimized for minimum energy losses. It is a 3-phase transformer with warm iron core and three cryostats for the superconducting windings. The superconductors were YBCO coated conductors (CC) with 4 mm width, cooled with liquid nitrogen at 77 K. In figure 2 a sketch of the transformer is shown and in table 3 the main data are summarized. In the primary winding 50 coated conductors are connected in parallel to carry the rated current. The conductors are separated in two stacks and wound side by side in one layer. In the secondary winding 115 coated conductors are connected in parallel. They are separated in 4 stacks that are also wound side by side in one layer. The height of the windings is 2.97 m.
The coated conductors have a critical current $I_c$ of 100 A in self field at 77 K. The critical current in the stray field of the windings $I_c(B_σ)$ is assumed to be reduced to 40% of the value in self field $I_c$. The safety margin from the critical current of the conductor in the stray field $I_c(B_σ)$ and the maximum of the rated current $I_{r,max}$ is taken as 40% ($I_c(B_σ)/I_{r,max} = 1.4$). A total amount of 150 km superconductor is required for this transformer. The short circuit impedance of the superconducting transformer is lower than for the conventional transformer. This may be accepted because current limiting behavior of the superconducting transformer. In this paper the current limitation is not considered.

**Table 3. Specification of superconducting transformer**

| Description                                      | Value               |
|--------------------------------------------------|---------------------|
| Winding voltage                                  | 85 V                |
| Leakage impedance                                | 2.6 %               |
| Dimensions l/w/h                                 | 0.74/2.21/3.89 m    |
| Magn. stray field $B_σ$ in air gap                | 162 mT              |
| Length of CC per phase pri/sec                    | 27/23 km            |
| $I_c(B_σ)/I_{r,max}$                             | 1.4                 |
| Mass iron core                                   | 14.47 t             |
| Window height                                    | 2.797 m             |
| Iron core material                               | H 085-23, 0.85 W/kg @ 1.7 T, 50 Hz |

### 4. Loss Calculation

#### 4.1. Iron Core Loss

The iron core losses are independent of the load. For the conventional transformer, the core losses are given by the manufacturer and amount to $P_{Fe,NC}$ 24 kW. For the superconducting transformer, the core losses are calculated. The core material has a specific loss of 0.85 W/kg at 1.7 T and 50 Hz. The mass of the iron core is 14.47 t so that the core losses amount to $P_{Fe,SC}$ 12.3 kW. The reason why the iron core of the superconducting transformer has fewer losses than the iron core of the conventional transformer is caused by the different design of both transformers. The superconducting transformer has a lower winding voltage and hence a smaller iron core (smaller cross sectional area).
4.2. Copper Conductor Losses
The resistive copper losses in the windings of the conventional transformer depend on the winding resistances \( R_{\text{pri}} \) and \( R_{\text{sec}} \) and on the currents \( I_{\text{pri}} \) and \( I_{\text{sec}} \).

\[
P_{\text{Cu}} = 3 \left( R_{\text{pri}} \cdot (I_{\text{pri}})^2 + R_{\text{sec}} \cdot (I_{\text{sec}})^2 \right)
\]  

(1)

4.3. Superconductor Losses
Alternating magnetic fields cause losses in YBCO coated conductors (AC-losses). Depending on the origin of the magnetic field, the losses in the superconductors can be self- and external field losses. Self field losses are caused by the magnetic field of the transport current in the superconductor itself, and external field losses are caused by the stray field in the windings.

4.3.1. Self Field Loss
For the calculation of the transport current losses of a single CC, the Norris-equation [5] is used.

\[
P_{\text{self,CC}}(I_t) = \frac{I_c \cdot \mu_0}{\pi} \cdot f \left( 1 - \frac{I_t}{I_c} \right) \cdot \ln \left( 1 - \frac{I_t}{I_c} \right) + \left( 1 + \frac{I_t}{I_c} \right) \cdot \left( 1 + \frac{I_t}{I_c} \right) \cdot \ln \left( 1 + \frac{I_t}{I_c} \right) - \left( 1 + \frac{I_t}{I_c} \right)
\]  

(2)

The transport current \( I_t \) is the maximum of the current in each conductor. For the primary winding \( I_t = I_{\text{pri,max}}/n_{\text{CC,pri}} \) with the number of tapes in the primary winding \( n_{\text{CC,pri}} \) (secondary winding respectively). Stacking of the parallel connected conductors in the windings changes the distribution of the magnetic field within the stacked conductors. Hence, the actual self field losses of the conductors differ from the value calculated with the Norris-equation. It is indicated in Ref. [6] that in a stack of 25 coated conductors, the self field loss of the whole stack is about 50 times higher than the loss of a single conductor apart, carrying the same current as one conductor in the stack. To estimate the influence of the stacking, the self field loss of a single conductor \( P_{\text{self,CC}} \) is calculated. Since the number of conductors in one stack is 25 in the primary and 29 in the secondary winding, the result is increased by the factor of 50 to calculate the losses of the stack \( P_{\text{self,stack}} = 50 \cdot P_{\text{self,CC}} \). The self field loss of one turn is the sum of the losses of all stacks in the turn. The whole self field loss in the transformer \( P_{\text{self}} \) is the sum of the losses in all turns of all windings.

\[
P_{\text{self}} = 3 \left( n_{\text{stack,pri}} \cdot 50 \cdot P_{\text{self,CC}} \left( \frac{I_{\text{pri,max}}}{n_{\text{CC,pri}}} \right) + n_{\text{stack,sec}} \cdot 50 \cdot P_{\text{self,CC}} \left( \frac{I_{\text{sec,max}}}{n_{\text{CC,sec}}} \right) \right)
\]  

(3)

\( n_{\text{stack,pri}} \) and \( n_{\text{stack,sec}} \) are the number of stacks in the primary and the secondary winding respectively.

4.3.2. External Field Loss
Alternating magnetic fields cause external field losses in coated conductors. Due to the strong anisotropy, magnetic field perpendicular to the coated conductor plane leads to higher losses than field parallel to the conductor plane. Therefore the magnetic field in the windings \( B(r,z) \) must be calculated component-by-component to calculate the losses from external fields. Therefore the radial field component \( B_r(r,z) \) (perpendicular to the CC plane) and the longitudinal field component \( B_z(r,z) \) (parallel to the CC plane) has to be calculated for the position of every turn in the windings (see figure 2). Because of the varying load currents, the magnetic field distribution must be calculated for every load condition separately. In our case this was done by solving elliptical integrals [7]. Since the field distributions can also be calculated by FEM simulation, this calculation is no further described. With the calculated magnetic field components \( B_r(r,z) \) and \( B_z(r,z) \), the losses of each turn of the windings was calculated. For the calculation of the specific hysteresis loss in the superconductors caused by magnetic fields perpendicular to the coated conductor plane, the methods of Ref. [8] were used. The loss per meter length is calculated by
Eddy current losses in the normal conducting parts of the coated conductors are calculated by the formula given in [9]:

\[
P_{\text{extern, eddy}}(B_{\text{extern}, r}(r, z)) = \frac{\pi^2}{6 \cdot \rho_s} \cdot \left( f \cdot B_{\text{extern}, r}(r, z) \right)^3 \cdot b^3 \cdot d_S \tag{7}
\]

Due to the shape of the conductors, the eddy current losses caused by longitudinal fields can be neglected. For the calculations of the specific hysteresis loss of superconductors in parallel fields, the relations given in [10] are used. The loss per meter length, caused by the longitudinal field component \( B_z(r, z) \) (parallel to the CC plane), is calculated with the expression:

\[
P_{\text{extern, z}}(B_z(r, z)) = \frac{2 f \cdot t \cdot b \cdot \left( B_z(r, z) \right)^3}{3 \mu_0 \cdot B_p}, \quad B_z(r, z) \leq B_p
\]

\[
\frac{2 f \cdot t \cdot b \cdot \left( 3B_z(r, z) - 2B_p \right)}{3 \mu_0}, \quad B_z(r, z) > B_p
\]

\[
P_{\text{extern}}(B_z(r, z)) = \begin{cases} 
\frac{2 f \cdot t \cdot b \cdot \left( B_z(r, z) \right)^3}{3 \mu_0 \cdot B_p}, & B_z(r, z) \leq B_p \\
\frac{2 f \cdot t \cdot b \cdot \left( 3B_z(r, z) - 2B_p \right)}{3 \mu_0}, & B_z(r, z) > B_p 
\end{cases} \tag{8}
\]

The total external field losses in the windings are the sum of the losses in every turn of the windings.

\[
P_{\text{extern}} = \sum_i \sum_j \left[ \ell \cdot r_i, z_j \left( P_{\text{extern}, r}(B_z(r, z)) + P_{\text{extern}, z}(B_z(r, z)) + P_{\text{extern, eddy}}(B_z(r, z)) \right) \right] \tag{10}
\]

With the length of one turn \( \ell \) and the coordinates of the turns \( r \) and \( z \).

### 4.4. Current Lead Losses

The current leads transfer heat into the cryostat via resistive loss and thermal conductivity. The heat generated by the current leads is calculated with the equation given in [11].

\[
\dot{Q}_{\text{CL}} = \frac{(f)^2 \cdot t \cdot \ell}{A_{\text{CL}}} \cdot \int_0^{q_{\text{CL}}} \rho_{\text{CL}}(x) \cdot dx + A_{\text{CL}} \cdot \lambda_{\text{CL}}(T) \cdot \frac{dT}{dx}. \tag{11}
\]

### 4.5. Cryostat Loss

As already mentioned above, the transformer is designed for warm iron core. This means, the cryostats for the windings have an outer wall and an additional inner wall to the transformer legs. The walls are supposed to be evacuated and to have a warm and a cold cylinder of glass fibre reinforced plastics with multilayer insulation. With such an assembly a heat feed of 2 W/m² at 77 K can be estimated [12]. The surface of each cryostat amounts to 11.6 m² (sum of top, bottom, inner- and outer wall), so that the total heat transfer through the walls is about 23.3 Wth per cryostat.

### 4.6. Cryocooler efficiency

The total loss that is caused by the AC-losses of the superconductors, the current leads and the cryostat itself must be compensated by the cryocooler. Hence the thermal losses are increased by the efficiency of the cryocooler. The maximum thermal losses in the cryostat amount to 1.54 kWth. In this investigation, the efficiency of the cryocooler was assumed to be 0.11 and is included in the following figures.
5. Results of Loss Calculation

5.1. Conventional Transformer
For the conventional transformer, the losses are shown in figure 3. The no-load losses of the transformer are the constant iron core loss of 24 kW. At full load, the total losses amount to 248 kW, whereof 90 % result from the resistive losses in the windings which are a quadratic function of the load and 10 % are caused by the iron core.

![Figure 3. Conventional transformer loss](image)

5.2. Superconducting Transformer
For the superconducting transformer, the components of the losses are shown in figure 4. The no-load losses amount to 15.4 kW whereof 80 % are caused by the iron core, 16 % by the cryostat and 4 % from the heat conduction of the current leads. The cryostat losses are the minor part of the total loss only. At full load, the losses amount to 26.2 kW whereof 47 % are losses in the iron core, 32 % are AC-losses in the superconductors, 18 % are losses in the current leads and 3 % are cryostat losses. The main contribution to the losses is still coming from the iron core.

![Figure 4. Superconducting transformer loss](image)
5.3. Discussion of the results

In figure 5 the losses and the efficiency of both transformers are compared. The total loss and the load dependency of the loss of the superconducting transformer is very low compared to the conventional transformer. At no-load condition the loss of the superconducting transformer is 50 % and at full-load condition only 10 % of the loss of the conventional transformer.

With 99.9 % efficiency at full load condition, the superconducting transformer exceeds the efficiency of the conventional transformer by 0.3 %.

In figure 6 the annual energy loss of both transformers used as auxiliary transformer in a power plant is shown (see section 2). For these calculations the annual load curve shown in figure 1 is used.

The annual energy loss in the application is 839.7 MWh for the conventional and 160.3 MWh for the superconducting transformer. The use of the superconducting transformer would save 679.4 MWh of energy per year. This is a reduction of 81 %.

With 75 % the major fraction of the losses of the conventional transformer is caused by resistive losses in the windings. 25 % are caused by the result from the iron core. The major fraction of the losses of the superconducting transformer is caused by the iron core (67.2 %). In spite of the cooling, only one third of the total losses result from the windings. 17.2 % are caused by the current leads, 12.1 % result from AC-losses of the superconductors and only 3.1 % are caused by the cryostat.

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Figure 5. Loss (left) and efficiency of conventional and superconducting transformer (right)

Figure 6. Partitions of annual energy loss
6. Summary
For this investigation an auxiliary transformer for a power plant with a rating of 63 MVA was chosen. First, a superconducting transformer was conceptually designed for the selected application. The losses of the superconducting and a comparable conventional transformer were calculated and compared. With a real load curve the resulting annual energy loss was calculated. The results show that superconducting transformers can raise the efficiency of power transformers from 99.6% to 99.9%. Depending on the specific application superconducting transformers can save up to 81% of energy loss per year.

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