Study of material characteristics of core and winding to minimize losses on power transformer

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Abstract. Power transformer has an important role in a transmission system. One factor that can reduce efficiency in the transmission system is transmission losses. Efficiency can be increased by reducing losses in the power transformer. The biggest influence determining the losses on the transformer is the material characteristic used by the transformer itself. To get maximum efficiency, it is necessary to optimize the materials on the transformer to get the lowest losses. The study is conducted by measuring core losses and copper losses on the 60 MVA 150/20 kV power transformer with the specified specifications. Furthermore, the transformer materials are changed into several types and the losses calculations are done. The calculation results are compared to get the most effective material. The results show that in the calculation of core losses, the core material type with the lowest core loss value is NK E-core of 0.49 Watt/kg. While in the calculation of copper losses, the winding material type with the lowest loss value is Continuously Transposed Conductor.

1. Introduction
In the distribution of electrical energy from a power plant to a substation, an adequate electrical transmission system is needed in terms of quality and price [1]. One of the things that makes transmission energy-reduced is that there are transmission losses [2]. In the past ten years in Indonesia, with increasing loads, energy loss also has increased. However, the percentage value of transmission losses with total energy is relatively fluctuating [3]. Power transformer is one of the most important parts of an electrical power system to deliver electricity from a power plant to consumers with the functions of stepping-up-and-down the voltage [4][5]. With higher efficiency of power transformer, the energy that can be used by consumers will also be higher. However, the losses on the power transformer can decrease efficiency [6].

In order to minimize the losses, the power transformer can be optimized by changing the type of material, such as copper and core [7]. This research is focused to minimize the core losses and copper losses based on the characteristic of the material. The losses from several types of material will be calculated and compared to get efficient material. With the optimization for losses, it is expected to reduce the transmission losses caused by power transformer.

2. Methodology
This research uses a case study on power transformer design of 60 MVA 150/20 kV. The core losses optimization is carried out by replacing core material that has lower core losses after calculation. The core of the power transformer is manufactured based on customized specifications, applicable standards, and the manufacturer’s practice. Table 1 shows the specification of the core material reference.
### Table 1. Specification of core reference.

| Design                  | Remark       |
|-------------------------|--------------|
| Class of core material  | 23SDR85      |
| Core losses specification | 0.8 W/kg    |
| Core weight             | 34925 kg     |
| Total core losses       | 27.94 kW     |

The copper losses optimization is carried out by analyzing the copper material used on the reference power transformer. After that, the specification of winding material reference is changed to get the highest efficiency. Table 2 shows the specification of winding material on 60 MVA 150/20 kV power transformer.

### Table 2. Specification of winding reference.

| Design                  | Remark       |
|-------------------------|--------------|
| Voltage system          | Low voltage  | High voltage | High voltage |
| Winding number          | 1            | 2            | 3            |
| Voltage (kV)            | 22           | 150          | 150          |
| Current (A)             | 1575         | 231          | 231          |
| Frequency (Hz)          | 50           | 50           | 50           |
| Turns per leg           | 105          | 716          | 716          |
| Winding type            | CTC          | CTC          | PICC         |
| Wire size (mm)          | 47*(6.15*1.2)| 19*(8.6*1.15)| 10.5*5       |
| Insulation thickness (mm)| 0.56        | 0.8          | 2.6          |
| Resistance (Ω)          | 0.00588      | 0.30622      | 0.06662      |
| $h_i/h_w$ (mm)          | 1292/1685    | 1273/1660    | 720/1062     |
| Volume (m$^3$)          | 0.44348      | 1.61422      | 0.25508      |

### 3. Material types for power transformer

The core material commonly used is SiFe and the winding material is copper. This section presents specifications for the various types of SiFe and copper that will be calculated for losses. The types of material to be analyzed are as follows:

#### 3.1. Core material types

The core material is divided based on silicon content in the iron. The effect of the percentage of silicon content on iron can be seen through the graph in figure 1.
Figure 1. Magnetic and electrical parameters as a function of silicon content [8].

Based on figure 1, the good silicon content is 6.5% because it has the highest resistivity and no magnetostriction. The types of core material are as follows:

3.1.1. Conventional grain-oriented SiFe steel.
This type is the base of CRGO (cold rolled grain oriented) by adding silicon to the iron composition. Conventional CRGO usually has 3% silicon content because it is the maximum percentage that can be processed conventionally. Iron with 6.5% silicon content will make the material hard and brittle if processed conventionally [8].

3.1.2. HiB grain-oriented electrical steel.
HiB CRGO steel is a type of CRGO steel with a high level of material permeability. In conventional CRGO steel, there is a tilt angle of 6˚ which is caused by the dispersion of the crystal orientation during the conventional manufacturing process. In the process of making HiB CRGO steel almost the same as conventional CRGO by adding 0.025% aluminum. As a result, a new class of material with more perfect texture is obtained. The tilt angle is on average 2˚ to 3˚. To obtain fewer losses on HiB CRGO steel, domain refinement using a laser beam is needed. With this action, the core losses will be reduced by 5% to 10% [8].

3.1.3. SiFe non-oriented electrical steel
In this material, SiFe is processed through a cold-rolled process without controlling the orientation of the grain, so the flux can be produced maximally in all directions. The silicon content of this type is in the range of 0% - 3% so that in terms of quality, it is not better than CRGO steel. Because of flux is evenly distributed, this type is more suitable for use on dynamic electric machines such as motor and generator and is less suitable for use on transformer [8].

3.1.4. Unconventional iron-based alloys.
The best percentage of silicon for SiFe is 6.5% because it has high resistivity and no magnetostriction, but in conventional CRGO steel, it is only capable of processing as much as 3% silicon content in the material. There are several manufacturing technologies from iron materials to have maximum quality in terms of losses, one of which is chemical vapor deposition. In this technology, a conventional 3% SiFe is chemically polished with a flowing gaseous mixture of SiCl₄ and argon. Fe₃Si forms near the surface of the sheet and the sheet loses Fe as a gaseous FeCl₂. During the diffusion process, a homogeneous FeSi solution is obtained. In this way, it is possible to manufacture grain-oriented 6.5% SiFe. The material class with this technology is named NK E-Core [8].
3.2. Winding material types

The winding material is divided based on the physical structure of the copper. The types of copper material are as follows:

3.2.1. Paper insulated copper conductor (PICC).

PICC is a winding type with a rectangular cross-section and usually consists of one to four sub conductors wrapped in insulation paper.

3.2.2. Continuously transposed conductor (CTC).

CTC is a winding type consisting of ten to fifty sub conductors that are transposed or combined and wrapped in insulation paper. CTC uses continuous transposition technique. In this technique, each sub conductor will change the lane several times from top to bottom or vice versa [9].

![Figure 2. Transposition scheme on CTC with 12 sub conductors [9].](image)

4. Losses calculation

There are two main losses including core losses and copper losses that are impacted by core and winding material on the power transformer.

4.1. Core losses calculation

Core losses are divided into hysteresis loss and eddy current loss. Eddy current loss occurs because of an eddy current flowing in the core. This loss is proportional to the current in the transformer that occurs because of the conductivity of the thick core. Eddy current loss can be formulated with [10]:

\[
W_e = K_e \cdot f \cdot B_m^2
\]

\[
K_e = \frac{4\pi^2 \cdot d^2}{24 \rho \cdot \rho_v}
\]

In the formula, \(W_e\): Eddy current loss (W/kg); \(f\): Frequency (Hz); \(B_m\): Maximum flux density (T); \(d\): Core thickness (m); \(\rho\): Resistivity (Ωm); \(\rho_v\): Density (kg/m³).

Based on equation (1), the ways to minimize eddy current loss are: choose a good core material, reduce the frequency, and reduce core thickness. In reducing the thickness, the laminate is used which is formed in layers of the core. Because the circulation area is smaller so that the eddy current is also lower.

Hysteresis loss occurs in each sinusoidal current cycle. The direction of the flux that follows the intensity of the current makes the core domains follow that cycle. Every half cycle, ideally the flux will turn to zero. However, in the ferromagnetic material, there is still a residual flux. Hysteresis loss is the energy needed to return the residual flux to its original point. Hysteresis loss can be formulated with [11]:

\[
W_h = \int_{B_m}^{B_m} H \cdot dB
\]
\[ W_h = K_h f B_m^2 \]  \hspace{1cm} (3)

\[ K_h = (\pi H_c) / (\rho_f B_m) \]  \hspace{1cm} (4)

In the formula, \( W_h \): Hysteresis loss (W/kg); \( H_c \): Coercive magnetic field when the flux value is equal to zero (A/m).

Based on equation (3), the ways to minimize hysteresis loss are: choose good core material and reduce frequency. The good core material has high permeability so that the value of residual flux is reduced and has a low flux density when saturation occurs.

The formula of total core losses is:

\[ W_{\text{core}} = W_e + W_h \]  \hspace{1cm} (5)

### 4.2. Copper losses calculation

Copper losses are divided into eddy current loss, circulation current loss, and resistive loss. Eddy current loss on copper is different from eddy current loss on the core. Eddy current loss on copper occurs because of leakage flux that induces the winding and causes an eddy current flowing on the copper. Eddy current loss can be formulated with [9]:

\[ P_e = \left( w^2 t^2 B_{gp}^2 V \right) / (72 \rho) \]  \hspace{1cm} (6)

\[ B_{gp}^2 = \left( \sqrt{2} \mu_0 N I / h_w \right) \]  \hspace{1cm} (7)

In the formula, \( P_e \): Eddy current loss (W); \( w \): Angular velocity (rad/s); \( t \): conductor thickness (m); \( B_{gp} \): Flux density peak in the gap (T); \( V \): Volume (m³); \( \mu_0 \): Vacuum permeability (T.m/A); \( N \): Number of turns; \( I \): Current (A); \( h_w \): Length of winding in the axial direction (m).

Based on equation (6), the best way to minimize eddy current loss on winding is to divide the conductor into many sub conductors to decrease the thickness.

Circulating current loss is a new problem because of division into sub conductors. Circulating current is the current that flows between sub conductors. Continuous transposition technique is the best way to minimize circulating current loss because it can limit the flowing current, like Fig. 2. For PICC with \( n \) sub conductors without continuous transposition technique, circulated current loss can be formulated with [9]:

\[ P_{cc} = P_e \left[ 45/(5n^2 - 1) \right] \left[ (t + t_i)/t \right] \left[ 1/n \sum_{1}^{n} \left( s_n - s_{avg} \right)^2 \right] \]  \hspace{1cm} (8)

\[ s_n = n (n - 1) \]  \hspace{1cm} (9)

In the formula, \( P_{cc} \): Circulating current loss (W); \( n \): Number of subconductors; \( t_i \): Insulation paper thickness (m).

Circulating current loss for CTC can be formulated using Kaul’s formula with [9]:

\[ P_{cc} = 13333.33 \left( k D \right)^4 \left[ 1 - 5/n^2 + 4/n^4 \right] P_e \]  \hspace{1cm} (10)

\[ k = 0.000048 \sqrt{\frac{h_c t f}{h_w (t + t_i) \rho}} \]  \hspace{1cm} (11)

\[ D = n (t + t_i) \]  \hspace{1cm} (12)

\[ P_e = F R \]  \hspace{1cm} (13)

In the formula, \( D \): Radial depth of insulated turn (m); \( P_e \): Resistive loss (W); \( h_c \): Total length of copper in the axial direction (m); \( R \): Resistance (Ω).
The formula of total copper losses is:

\[ P_{\text{copper}} = P_c + P_e + P_{cc} \]  (14)

5. Results and discussion

The optimization for core and winding material on power transformer of 60 MVA 150/20 kV is done to minimize the losses.

5.1. Core material optimization

Core losses are calculated from several core material classes to obtain the lowest losses. There are 2 sample classes that are taken from every type of core material, except unconventional iron-based alloys. The rules of naming the electrical steel class follow European standard EN 10107. The types and classes of SiFe can be seen in table 3.

| Material Class | Material Types                        |
|----------------|---------------------------------------|
| M080-23N       | Conventional grain-oriented SiFe steel|
| M097-30N       | Conventional grain-oriented SiFe steel|
| M100-23P       | HiB grain-oriented SiFe steel         |
| M105-30P       | HiB grain-oriented SiFe steel         |
| M235-35A       | SiFe non-oriented electrical steel    |
| M250-50A       | SiFe non-oriented electrical steel    |
| NK E-core      | Unconventional iron-based alloys      |

Specifications of each material are obtained from [8]. Equation (1) and (3) are used to calculate eddy current loss and hysteresis loss. The frequency is 50 Hz and the density is taken for 7650 kg/m³. The maximum flux density and the resistivity are 1.25 T and 70*10⁻⁸ Ωm for NK E-core, and 1.7 T and 48*10⁻⁸ Ωm for others. The losses and other specifications can be seen in table 4.

| Material Class | d (m) | \(H_c\) (A/m) | \(W_e\) (W/kg) | \(W_h\) (W/kg) |
|----------------|-------|---------------|----------------|----------------|
| M080-23N       | 23*10⁻⁵ | 24            | 0.171          | 0.837          |
| M097-30N       | 30*10⁻⁵ | 24            | 0.291          | 0.837          |
| M100-23P       | 23*10⁻⁵ | 21.8          | 0.171          | 0.761          |
| M105-30P       | 30*10⁻⁵ | 21.8          | 0.291          | 0.761          |
| M235-35A       | 35*10⁻⁵ | 98.2          | 0.396          | 3.426          |
| M250-50A       | 50*10⁻⁵ | 982           | 0.808          | 3.426          |
| NK E-core      | 5*10⁻⁵  | 19            | 0.003          | 0.487          |

All material classes in table 4 are compared with core reference in table 1 to determine the smallest core losses. According to table 1, the weight of the reference power transformer is 34925 kg. With the same weight, table 5 shows the total core losses of all materials. Equation (5) is used to calculate core losses.
Table 5. Total core losses.

| Material Class | Core Losses (W/kg) | Total Core Losses (W) |
|----------------|--------------------|-----------------------|
| 23SDR85        | 0.800              | 27940                 |
| M080-23N       | 1.008              | 35228                 |
| M097-30N       | 1.128              | 39418                 |
| M100-23P       | 0.982              | 32546                 |
| M105-30P       | 1.052              | 36737                 |
| M235-35A       | 3.822              | 133527                |
| M250-50A       | 4.234              | 147929                |
| NK E-core      | 0.490              | 17133                 |

Based on table 5, the suitable material used for optimization is NK E-Core, because its core losses are lower than the core material reference by 38.68% more efficient than 23SDR85. This is due to the higher silicon content which causes higher resistivity and lower saturation polarization and results in lower core losses.

5.2. Winding material optimization

The calculation results for copper losses based on table 2 using equation (6), (8), (10), (13), and (14) are shown in table 6.

Table 6. Reference copper losses calculation results.

| Winding Number | $P_c$ (W) | $P_e$ (W) | $P_{cc}$ (W) | $P_{copper}$ (W) |
|----------------|-----------|-----------|--------------|-------------------|
| 1              | 14586     | 1262      | 74152        | 90000             |
| 2              | 16340     | 4350      | 2468         | 23158             |
| 3              | 3555      | 31742     | 0            | 35297             |

Based on table 6, winding number 2 has the lowest copper losses. It uses winding type of CTC with 19 sub conductors and works for high voltage side. Compared to winding number 3 which also works for high voltage side, number 2 has lower losses because number 3 uses winding type of PICC and does not have sub conductor. Although there is no circulating current loss on winding number 3, it still has high eddy current loss because the conductor is very thick. It means that CTC is more efficient than PICC with no sub conductor. Winding number 1 has the highest losses because it works for low voltage side which means the current is very high, even though it uses winding type of CTC. The current has a high impact on resistive loss and CTC is the right choice for low voltage side.

Winding number 3 is chosen as an object of optimization for copper losses. The winding type is changed into three conditions. The new conditions are shown in table 7.

Table 7. New specification of winding number 3.

| Design          | Remark       |
|-----------------|--------------|
| Condition       | 1            | 2            | 3            |
| Winding type    | PICC         | PICC         | CTC          |
| Wire size (mm)  | 10.5*5       | 4*(10.5*1.25)| 4*(10.5*1.25)|
| Insulation thickness (mm) | 2.6 | 0.52 | 0.52 |
Condition 1 is the reference condition that is changed its winding type to PICC with sub conductors as condition 2 and CTC as condition 3. Other specifications are considered the same. Table 8 shows the calculation results of the new conditions.

| Condition | $P_c$ (W) | $P_e$ (W) | $P_{cc}$ (W) | $P_{copper}$ (W) |
|-----------|-----------|-----------|--------------|------------------|
| 1         | 3555      | 31742     | 0            | 35297            |
| 2         | 3555      | 1984      | 47582        | 53121            |
| 3         | 3555      | 1984      | 0.5          | 5539.5           |

According to table 8, CTC is the winding type that has the lowest losses. Its value is very much lower than the others, which is 15.7% of the reference value because circulating current loss and eddy current loss are optimized. The values do not reflect the practice because when changing designs, other specifications will also change. Furthermore, PICC with 4 sub conductors has a greater loss than single PICC. This indicates that circulation current loss has a greater impact than eddy current loss if it is not reduced by continuous transposition.

6. Conclusion
The core and copper losses of 60 MVA 150/20 kVA power transformer can be minimized using more efficient material. Which in this study, the core material class with the lowest core losses is NK E-Core with losses of 17133 W and 38.68% more efficient than the core material reference. The winding material type that is suitable for optimization is CTC because it can minimize eddy current loss and circulating current loss that is better than PICC. CTC is recommended to be used on low voltage side because the current on that side is too high and the copper losses will be much greater if still use PICC. In the high voltage side, either CTC or PICC can be used depending on the economic aspect. Future work will focus on measuring the losses in real practice to validate the results for better optimization.

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