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Hiroto Mizutani[2], Takaaki Takahara[3], Osamu Mori[2]

[1]Graduate School of Natural Science and Technology
Okayama University
Okayama, Japan

[2]Advanced Technology R&D Center, Mitsubishi Electric Corporation,
Amagasaki, Japan

[3]Living Environment Systems Laboratory, Mitsubishi Electric Corporation,
Shizuoka, Japan

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[1]Okayama University
3-1-1, Tsushima-naka, Kita-ku,
Okayama, Japan

[2]Advanced Technology R&D Center
Mitsubishi Electric Corporation
8-1-1, Tsukagushi-Honmachi,
Amagasaki, Japan

[3]Living Environment Systems Laboratory
Mitsubishi Electric Corporation
3-18-1, Oshika, Suruga-ku,
Shizuoka, Japan

Corresponding E-Mail: p9nf00b3@s.okayama-u.ac.jp

Keywords

«Transformer», «Current distribution», «Copper loss», «Extremum co-energy principle».

Abstract

The windings of high-frequency high-current transformers are required to reduce the proximity effect loss. Therefore, the Litz wire in parallel connection of interleaved winding layers is usually used as the winding of transformers. However, this can cause unbalanced AC current distribution, hindering effective reduction of the copper loss. This paper solves this problem by optimizing the distance between the winding layers based on the analytical principle called the extremum co-energy principle. The transformers used in the experiment to verify this method consists of three parallel-connected primary winding and two parallel-connected secondary winding, PQ core, thin polypropylene sheets for adjusting the distance between the winding layers. As a result, the copper loss can be recused by homogenizing the AC current distribution, and the effectiveness of this method has been clarified by experiments.

Introduction

In the isolated DC-DC power converters, the copper loss of the high-frequency transformers is one of the major causes of the power loss. For reducing the copper loss, the Litz wire is usually used to achieve the low copper loss in high frequency [1]-[4]. Furthermore, the interleaved winding layer structure is effective and commonly utilized for practical design because this structure is known to mitigate the proximity effect, which causes the eddy current inside the wire to increase the copper loss.

The interleaved winding layer structure has been commonly made with the series-connected winding layers, as the conventional low-frequency power transformers tend to have a great number of turns, which naturally requires the series-connection of the winding layers. However, recent high-frequency design can have the primary and secondary windings with a small number of turns. In this design, many transformers have parallel-connected winding layers because the multiple winding layers are commonly utilized to expand the cross-sectional area for AC current rather than to implement a large number of turns. Consequently, a number of recent transformers are designed to have a parallel connection of interleaved winding layers.

However, the AC current does not necessarily flow uniformly among the parallel-connected winding layers, unlike the DC current, which flows uniformly according to the DC resistance [5]-[11]. The reason is that the parasitic magnetic coupling among the winding layers, as well as the leakage inductance of the winding layers, [5], [8], [10]-[13] affects the AC current distribution of the parallel-connected winding layers. The unbalanced AC current distribution tends to increase in the copper loss, which hinders the effective reduction of the copper loss by the interleaved winding layer structure.

The solution to this problem may lie in the optimization of the winding layer disposition because the proximity effect is known to be significantly affected by the winding layer disposition [12], [14], [15]. The purpose of this paper is to propose a method to derive the optimum winding layer disposition to homogenize the AC current distribution in the parallel-connection of the interleaved winding layers of a high-frequency transformer. Particularly, this paper focuses on the distance between the winding layers and analytically derives the optimal distance to achieve homogeneous AC current distribution.

This paper adopts a recently proposed analytical method [16]-[19] based on the analytical principle called the extremum co-energy principle [20], [21], which is briefly reviewed in the next section. Certainly, a number of preceding studies have analyzed the proximity effect and resulting the AC current distribution by the FEM simulation [8], [14], [15]. However, the FEM simulation requires detailed geometrical data of the magnetic cores and windings,. Therefore, total recalculation is indispensable in every time the design has changed. As an alternative approach, [7], [10], [11] rather adopted a sophisticated approach utilizing the equivalent circuit model, although the model construction, as well as the circuit calculation, is somewhat complicated. The extremum co-energy principle directly utilizes the analytical solution of the magnetic field inside the transformer, which can be straightforwardly formulated by the Dowell's approximation [22]-[26], as shown later.

The extremum co-energy principle was first proposed in [16] as a simple method for analyzing the AC current distribution of the transformers with parallel-connected winding. [17] and [19] proposed a new copper loss analysis method of the transformers with parallel-connected winding by applying the extremum co-energy principle proposed in [16] to a famous copper loss analysis model called Dowell model. [17] focused on the transformers which carry only AC current, whereas [19] focused on the transformers that carry both DC and AC current. [18] proposed a method to derive the optimum winding turn allocation among winding layers to homogenize the AC current distribution in the parallel connection of the interleaved winding layers according to the extremum co-energy principle. This paper proposes a method to derive the optimum "distance between the winding layers" unlike "winding turn allocation among winding layers [18]" to homogenize the AC current distribution in the parallel-connection of the interleaved winding layers according to the extremum co-energy principle.

Review of the Extremum co-energy principle

According to the extremum co-energy principle[16], AC current in a magnetic device is distributed so that the magnetic co-energy of the device must take the extremum. This section briefly explains this reason by the transformer with parallel-connected n primary windings, P_1, P_2, …, P_n, and parallel-connected k secondary windings, S_1, S_2, …, S_k, as depicted in Fig. 1. For simplifying the discussion, we assume that there is no DC current flowing the windings. The extremum co-energy principle can be utilized for high-frequency AC current, for which the reactance is much larger than the resistance. Hence, this section neglects the resistance of the wire to simplify the calculation.

Let i_j and ψ_j be the AC current and AC flux linkage of winding j, respectively. Then, the total magnetic co-energy of the transformer E_{co} can be expressed as follows, if $\mathbf{i}$ and $\boldsymbol{\psi}$ are defined as $\mathbf{i} \equiv [i_{p1}, i_{p2}, \ldots, i_{sk}]^t$ and $\boldsymbol{\psi} \equiv [\psi_{p1}, \psi_{p2}, \ldots, \psi_{sk}]^t$:

$$E_{co}(\mathbf{i}) = \int_0^{\mathbf{i}} \mathbf{\Psi}(\mathbf{i}) \cdot d\mathbf{i}, \tag{1}$$

Now, we consider an arbitrary infinitesimal virtual change $\delta\mathbf{i} \equiv [\delta i_{p1}, \delta i_{p2}, \ldots, \delta i_{sk}]^t$ in the AC current vector $\mathbf{i}$, where δi_{p1}, δi_{p2}, …, δi_{pn} are the AC current change in the primary windings and δi_{s1}, δi_{s2}, …, δi_{sk} are that of the secondary windings. Because the total primary current is determined by the circuit operation outside the transformer, we impose the requirement that this virtual change does not affect the total primary and secondary current, i.e. $\delta i_{p1}+\delta i_{p2}+\ldots+\delta i_{pn}=0$ and $\delta i_{s1}+\delta i_{s2}+\ldots+\delta i_{sk}=0$. Then, the change in the magnetic co-energy δE_{co} is obtained as follows, noting that the parallel-connected windings must have the same AC flux linkage according to Faraday's law and therefore $\psi_{p1}=\psi_{p2}= \ldots=\psi_{pn}$ and $\psi_{s1}=\psi_{s2}=\ldots=\psi_{sk}$.

$$\begin{aligned}\delta E_{co} &= \boldsymbol{\Psi}(\mathbf{i})\cdot\delta\mathbf{i} = \psi_{p1}\delta i_{p1} + \psi_{p2}\delta i_{p2} + \cdots + \psi_{pn}\delta i_{pn} + \psi_{s1}\delta i_{s1} + \psi_{s2}\delta i_{s2} + \cdots + \psi_{sk}\delta i_{sk} \\ &= \psi_{p1}\left(\delta i_{p1} + \delta i_{p2} + \cdots + \delta i_{pn}\right) + \psi_{s1}\left(\delta i_{s1} + \delta i_{s2} + \cdots + \delta i_{sk}\right) = 0.\end{aligned} \tag{2}$$

Equation (2) indicates that the AC current of parallel-connected windings is distributed to achieve the extremum of the magnetic co-energy.

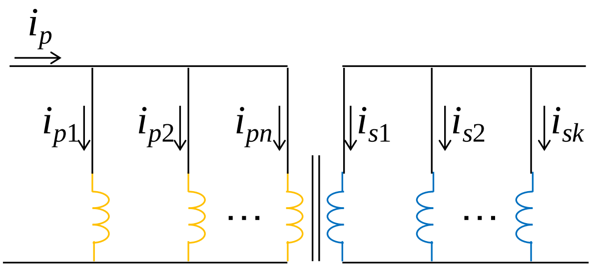

Fig. 1: Equivalent circuit of a transformer

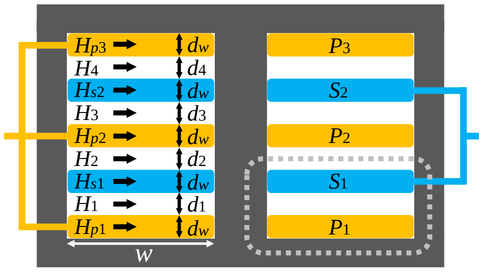

Fig. 2: Analyzed transformer structure

Homogenization of AC Current Distribution

This section analytically calculates the optimum distance between the winding layers according to the extremum co-energy principle so that the AC current distribution is homogenized. As an example, we consider the transformer structure, whose cross-sectional view is shown in Fig. 2. The windings P_1-P_3 are the parallel-connected primary winding layers, whereas the windings S_1 and S_2 are the parallel-connected secondary winding layers. The parallel-connected winding layers are assumed to have the same number of turns. In this paper, we assume that the magnetic core is lossless and has a permeability much larger than the air.

First, we formulate the magnetic co-energy of this transformer. Because the permeability of the core is large, the magnetic co-energy stored in the magnetic core is ignorable. (Note that the co-energy per unit volume is $B^2/2\mu$, where μ is the permeability and B is the magnetic flux density.) Additionally, vast open space outside the transformer provides a large cross-sectional area for the leakage flux path and therefore has a low reluctance. Hence, the open space outside the transformer has little magnetic co-energy and can be ignorable. Thus, the magnetic co-energy of the transformer is mainly contributed by the wire and the narrow space between the winding layers.

The magnetic field inside the space between the winding layers may have local inhomogeneity. However, for simplifying the calculation, we approximate that the uniform magnetic field throughout this space. This approximation is known as Dowell's approximation and widely utilized in the preceding studies [22]-[26]. According to this approximation, the magnetic field between the winding layers is easily formulated by Ampere's law. For example, the magnetic field H_2 of the space between winding layers S_1 and P_2 can be formulated as follows by applying Ampere's law along the dashed line in Fig. 2:

$$H_2 = (N_p i_{p1} + N_s i_{s1})/w, \tag{3}$$

where N_p and N_s are the numbers of turns of the primary and secondary windings, respectively, w is the width of the window space as shown in Fig. 2. Similarly, magnetic field H_1 in the space between P_1 and S_1, magnetic field H_3 in the space between P_2 and S_2, and magnetic field H_4 in the space between S_2 and P_3 are obtained as

$$H_1 = N_p i_{p1}/w, \quad H_3 = (N_p i_{p1} + N_s i_{s1} + N_p i_{p2})/w, \quad H_4 = (N_p i_{p1} + N_s i_{s1} + N_p i_{p2} + N_s i_{s2})/w. \tag{4}$$

Litz wire is not easily affected by the skin effect unlike the solid wire and the foil. Therefore, the current density inside the winding can be approximated as uniform the magnetic field inside the winding is distributed linearly as depicted in Fig. 3. Hence, when calculating the magnetic co-energy of the transformer, the magnetic field inside the winding cannot be ignored. Then, the magnetic fields are functions of x in Fig. 3, and defined as

$$H_{p1}(x)=\frac{H_1}{d_w}\cdot x, H_{s1}(x)=\frac{H_2-H_1}{d_w}\cdot x+H_1, H_{p2}(x)=\frac{H_3-H_2}{d_w}\cdot x+H_2, H_{s2}(x)=\frac{H_4-H_3}{d_w}\cdot x+H_3, H_{p3}(x)=\frac{-H_4}{d_w}\cdot x, \quad (5)$$

where d_w the width of winding layers.

For calculating the magnetic co-energy inside the winding, the integrated average magnetic fields inside the winding are defined as

$$H_{p1}=\sqrt{\frac{1}{d_w}\cdot\int_0^{d_w}\left(\frac{H_1}{d_w}\cdot x\right)^2dx}=\sqrt{\frac{1}{3}H_1^2}, H_{s1}=\sqrt{\frac{1}{d_w}\cdot\int_0^{d_w}\left(\frac{H_2-H_1}{d_w}\cdot x+H_1\right)^2dx}=\sqrt{\frac{1}{3}\left(H_1^2+H_1H_2+H_2^2\right)},$$
$$H_{p2}=\sqrt{\frac{1}{d_w}\cdot\int_0^{d_w}\left(\frac{H_3-H_2}{d_w}\cdot x+H_2\right)^2dx}=\sqrt{\frac{1}{3}\left(H_2^2+H_2H_3+H_3^2\right)}, H_{s2}=\sqrt{\frac{1}{d_w}\cdot\int_0^{d_w}\left(\frac{H_4-H_3}{d_w}\cdot x+H_3\right)^2dx}=\sqrt{\frac{1}{3}\left(H_3^2+H_3H_4+H_4^2\right)}, \quad (6)$$
$$H_{p3}=\sqrt{\frac{1}{d_w}\cdot\int_0^{d_w}\left(\frac{-H_4}{d_w}\cdot x\right)^2dx}=\sqrt{\frac{1}{3}H_4^2}.$$

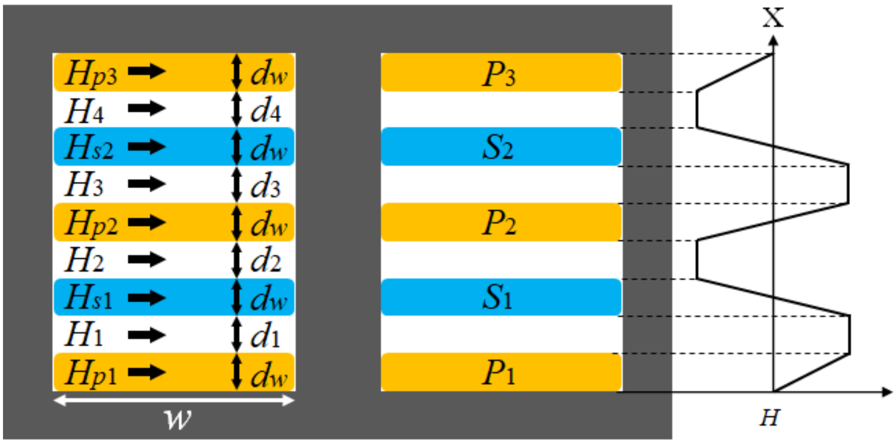

Fig. 3: Magnetic field distribution of the original transformer composed of Litz wire
($d_1 : d_2 : d_3 : d_4 = 1 : 1 : 1 : 1$)

Because the magnetic co-energy per unit volume is $B^2/2\mu$ and $\mu H^2/2$, the total magnetic co-energy E_{co} can be obtained as

$$E_{co}(i_{p1},i_{s1},i_{p2},i_{s2})=\frac{1}{2}\mu_0\left(H_{p1}^2Sd_w+H_1^2Sd_1+H_{s1}^2Sd_w+H_2^2Sd_2+H_{p2}^2Sd_w+H_3^2Sd_3+H_{s2}^2Sd_w+H_4^2Sd_4+H_{p3}^2Sd_w\right), \quad (7)$$

where μ_0 is the permeability of the air, and S is the top surface area of the winding layers.

Next, the AC current distribution in parallel-connected winding layers is determined according to the extremum co-energy principle. The total primary current i_p, defined as $i_p \equiv i_{p1} + i_{p2} + i_{p3}$, is given by the circuit operation outside the transformer. Besides, the total secondary current i_s, defined as $i_s \equiv i_{s1} + i_{s2}$, is required to cancel the magnetomotive force of the primary winding layers, according to the operating principle of the transformer. Hence, $N_p i_p = -N_s i_s = -N_s(i_{s1} + i_{s2})$ is imposed to the secondary current. Therefore, the extremum of the total magnetic co-energy should be searched under the constraint of $i_p = i_{p1} + i_{p2} + i_{p3}$ and $N_p i_p = -N_s(i_{s1} + i_{s2})$. For this purpose, we utilized the Lagrangian multiplier method, in which the modified function E_{co}' is introduced as

$$E'_{co}=\frac{1}{2}\mu_0\left(H_{p1}{}^2Sd_1+H_1{}^2Sd_1+H_{s1}{}^2Sd_1+H_2{}^2Sd_2+H_{p2}{}^2Sd_1+H_3{}^2Sd_3+H_{s2}{}^2Sd_1+H_4{}^2Sd_4+H_{p3}{}^2Sd_1\right)$$
$$-\lambda_p\left(i_{p1}+i_{p2}+i_{p3}-i_p\right)-\lambda_s\left(N_pi_p+N_si_{s1}+N_si_{s2}\right), \tag{8}$$

where λ_p and λ_s are the Lagrangian multipliers.

The solution of the AC current in the winding layers can be obtained by solving $\partial E_{co}'/\partial i_{p1}=0$, $\partial E_{co}'/\partial i_{p2}=0$, $\partial E_{co}'/\partial i_{p3}=0$, $\partial E_{co}'/\partial i_{s1}=0$, $\partial E_{co}'/\partial i_{s2}=0$, $\partial E_{co}'/\partial\lambda_p=0$ and $\partial E_{co}'/\partial\lambda_s=0$. Consequently, we have

$$\begin{aligned}
i_{p1}&=\frac{38d_w{}^3+\left[45d_2+60(d_3+d_4)\right]d_w{}^2+\left[(72d_2+90d_3)d_4+72d_2d_3\right]d_w+108d_2d_3d_4}{171d_w{}^3+\left[192(d_1+d_4)+165(d_2+d_3)\right]d_w{}^2+\left\{\left[180(d_1+d_3)+144d_2\right]d_4+144(d_1+d_2)d_3+180d_1d_2\right\}d_w+108\left\{\left[(d_1+d_2)d_3+d_1d_2\right]d_4+d_1d_2d_3\right\}}i_p,\\
i_{p2}&=\frac{95d_w{}^3+\left[132(d_1+d_4)+60(d_2+d_3)\right]d_w{}^2+\left[(180d_1+72d_2+90d_3)d_4+72d_1d_3+90d_1d_2\right]d_w+108(d_2+d_3)d_1d_4}{171d_w{}^3+\left[192(d_1+d_4)+165(d_2+d_3)\right]d_w{}^2+\left\{\left[180(d_1+d_3)+144d_2\right]d_4+144(d_1+d_2)d_3+180d_1d_2\right\}d_w+108\left\{\left[(d_1+d_2)d_3+d_1d_2\right]d_4+d_1d_2d_3\right\}}i_p,\\
i_{p3}&=\frac{38d_w{}^3+\left[60(d_1+d_2)+45d_3\right]d_w{}^2+\left[72(d_1+d_2)d_3+90d_1d_2\right]d_w+108d_1d_2d_3}{171d_w{}^3+\left[192(d_1+d_4)+165(d_2+d_3)\right]d_w{}^2+\left\{\left[180(d_1+d_3)+144d_2\right]d_4+144(d_1+d_2)d_3+180d_1d_2\right\}d_w+108\left\{\left[(d_1+d_2)d_3+d_1d_2\right]d_4+d_1d_2d_3\right\}}i_p,\\
i_{s1}&=-\frac{N_p}{N_s}\frac{57d_w{}^3+(40d_1+30d_2+80d_3+88d_4)d_w{}^2+\left[(60d_1+48d_2+120d_3)d_4+48(d_1+d_2)d_3\right]d_w+72(d_1+d_2)d_3d_4}{114d_w{}^3+\left[128(d_1+d_4)+110(d_2+d_3)\right]d_w{}^2+\left\{\left[120(d_1+d_3)+96d_2\right]d_4+96(d_1+d_2)d_3+120d_1d_2\right\}d_w+72\left\{\left[(d_1+d_2)d_3+d_1d_2\right]d_4+d_1d_2d_3\right\}}i_p,\\
i_{s2}&=-\frac{N_p}{N_s}\frac{57d_w{}^3+(88d_1+80d_2+30d_3+40d_4)d_w{}^2+\left[120d_1d_2+48(d_1+d_2)d_3+(60d_1+48d_2)d_4\right]d_w+72(d_3+d_4)d_1d_2}{114d_w{}^3+\left[128(d_1+d_4)+110(d_2+d_3)\right]d_w{}^2+\left\{\left[120(d_1+d_3)+96d_2\right]d_4+96(d_1+d_2)d_3+120d_1d_2\right\}d_w+72\left\{\left[(d_1+d_2)d_3+d_1d_2\right]d_4+d_1d_2d_3\right\}}i_p.
\end{aligned} \tag{9}$$

As an example, in the case in which all the distance between the winding layers are almost the same, i.e. $d_1=d_2=d_3=d_4$ as shown in Fig. 3, the AC current distribution is not uniform; and therefore, the copper loss tends to increase compared to the uniform AC current distribution. In fact, the AC current distribution of the original transformer, i.e. $d_1=d_2=d_3=d_4$ is calculated according to equation (9) as

$$i_{p1}:i_{p2}:i_{p3}=3:7:3,\ i_{s1}:i_{s2}=1:1. \tag{10}$$

Equation (9) can also determine the distance between the winding layers that makes the homogeneous AC current distribution, i.e. $i_{p1}=i_{p2}=i_{p3}$ and $i_{s1}=i_{s2}$. The necessary ratio of the distance was calculated as

$$d_1:d_2:d_3:d_4=d_1:2d_1+d_w:2d_1+d_w:d_1. \tag{11}$$

As can be seen in equation (9), the AC current distribution is not dependent on the load impedance. Therefore, the necessary ratio of the distance for the uniform AC current distribution, i.e. equation (11), is effective regardless of the load condition.

This method is effective when the current density inside the Litz wire can effectively be homogenized. However, the copper loss of the proposed transformer structure ($d_1:d_2:d_3:d_4=d_1:2d_1+d_w:2d_1+d_w:d_1$) may be larger than the copper loss of the original transformer structure ($d_1:d_2:d_3:d_4=1:1:1:1$) at extremely high frequencies, which the proximity effect loss is dominant. The proximity effect loss is proportional to the square of the magnetic field [1]. As shown the proposed transformer structure ($d_1:d_2:d_3:d_4=d_1:2d_1+d_w:2d_1+d_w:d_1$) in Fig. 4, this structure has a large magnetic field strength in the winding layer. Therefore, the proximity effect loss of the proposed transformer structure is 153.8 % larger than the proximity effect loss of the original transformer structure according to the calculation of the square of the magnetic field. On the other hand, the total loss of the DC resistance and the skin effect loss (i.e. the copper loss excluding the proximity effect loss) of the proposed transformer structure is 7.0 % smaller than the original transformer structure one. Consequently, when the proposed transformer structure is be used at extremely high frequencies, it should be designed using sufficiently high quality Litz wire.

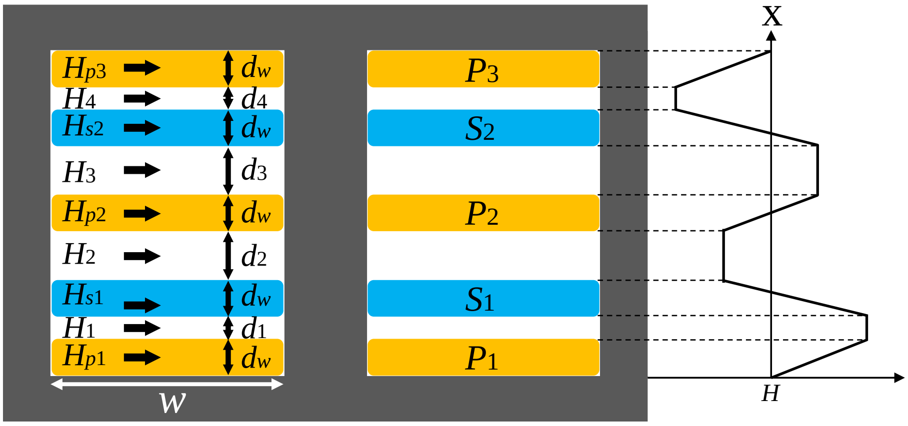

Fig. 4: Magnetic field distribution of the adjusted transformer composed of Litz wire when the AC current distribution is homogenized. (d_1: d_2: d_3: d_4= d_1: $2d_1$+ d_w: $2d_1$+ d_w: d_1)

Also, the proposed method can be applied to a transformer composed of the solid wire or foil as well as the Litz wire. In the case of the solid wire or foil, note the skin effect that appears remarkably compared to the Litz wire, the skin depth in high frequency is extremely small. Therefore, the magnetic co-energy inside the winding cannot be ignored because the magnetic field inside the solid wire or foil is small due to the skin effect. Hence, the total magnetic co-energy E_{co} of a transformer composed of the solid wire or foil is generated only between the winding layers, the total magnetic co-energy E_{co} can be obtained as

$$E_{co}(i_{p1},i_{s1},i_{p2},i_{s2}) = \frac{1}{2}\mu_0\left(H_1{}^2Sd_1 + H_2{}^2Sd_2 + H_3{}^2Sd_3 + H_4{}^2Sd_4\right). \qquad (12)$$

Consequently, in the case of a transformer composed of the solid wire or foil, the proposed method can be applied in the same as the Litz wire.

This method for the homogenization of AC current distribution is based on the premise that the Dowell model can apply to the transformers. This Dowell model can apply to transformers, in which the magnetic field between the winding layers is almost uniform. Therefore, a shell-type transformer used in this paper as shown in Fig.2 can be applied the Dowell model and this proposed method, because the magnetic path through the air is short, and the magnetic field between the winding layers is almost uniform. On the other hand, the magnetic path through the air of a core-type transformer is longer than a shell-type one. However, it may be applied the Dowell model. Because if a core-type transformer in which both the primary and secondary winding wrap around the one core can almost cancel the magnetic field around each winding, and the magnetic field between the winding layers is almost uniform. And conversely, a core-type transformer in which each primary and secondary winding should wrap around another core for the insulation of the primary and secondary winding cannot be applied to this proposed method because it cannot be applied the Dowell model.

Experiment

The experiment was carried out to validate the effect of optimizing the distance between the winding layers. For this purpose, we constructed the experimental transformer by the PQ core and the parallel connection of the interleaved winding layers, as shown in Fig. 5. The experimental transformer has three parallel winding layers in the primary-side and has two parallel winding layers in the secondary-side, respectively. The total of five winding layers is arranged as shown in Fig. 2. Each primary and secondary winding layer is formed by the same alpha winding coil made of Litz wire. Fig. 6 shows the photograph of the winding layer in this experimental transformer. The designed power rating of the transformer in this paper is 1.5 kW. The specifications of the experimental transformer are shown in Table I.

Table I: Specifications of the experimental transformer

Core	Ferroxcube, 3C97
Primary and secondary winding	Litz wire 84/φ0.1
Number of turns	16 T
Height of alpha winding coil	3 mm

We measured AC current of the primary winding layers, i.e. i_{p1}, i_{p2}, and i_{p3}, under the constant total primary AC current (100 kHz, 1 Arms) by the experimental set-up as shown in Fig. 7. Then, we compared the estimated copper loss among 9 conditions of d_2 and d_3 under the premise of $d_1 = d_4 = 1$ mm, $d_2 = d_3$. These tested 9 conditions were $d_2 = 1$ mm to 9 mm. The space between the winding layers was adjusted by changing the number of thin polypropylene sheets inserted between the winding layers.

Primary copper loss P_p and secondary copper loss P_s can be expressed as

$$P_p = R(i_{p1}^2 + i_{p2}^2 + i_{p3}^2), \quad P_s = R(i_{s1}^2 + i_{s2}^2), \tag{13}$$

where R is the resistance of a winding layer. According to equation (9), P_p is expected to be dependent on these 9 conditions of the distance ratio, whereas P_s is expected to be constant regardless of these 9 conditions. Therefore, we compared the factor $i_{p1}^2 + i_{p2}^2 + i_{p3}^2$ among the 9 conditions of the distance ratio.

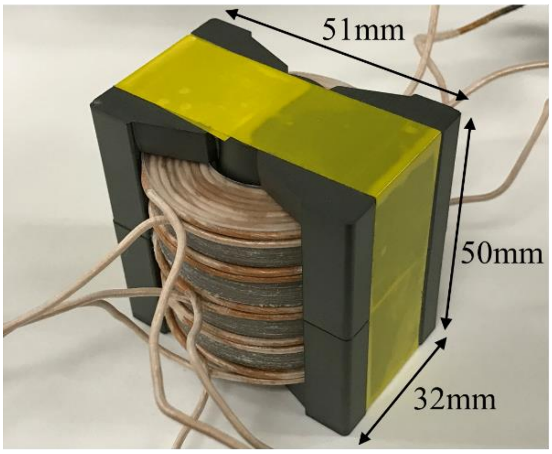

Fig. 5: Experimental transformer

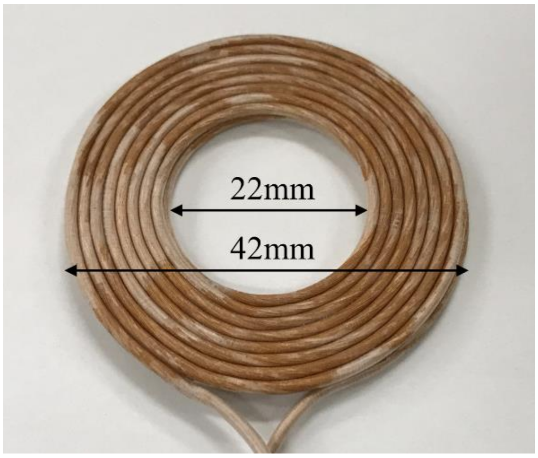

Fig. 6: Alpha winding coil used as a winding layer

Fig. 8 shows the comparison results of these 9 conditions of the distance ratio. The orange dots show the experimental results and the blue dots show the analytically calculated results according to equation (9). The horizontal axis shows d_2. (d_1 and d_3 and d_4 are omitted because of $d_1 = d_4 =$ 1 mm and $d_2 = d_3$ for all conditions of the distance.)

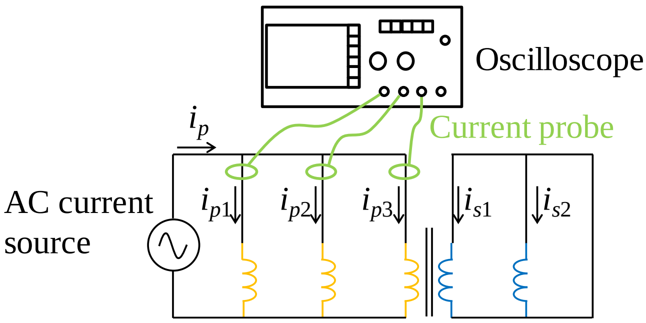

Fig. 7: Measurement system for the AC current distribution

As can be seen in Fig. 8, the experimental results agreed well with the calculated results within 2.6 %, indicating the effectiveness of the extremum co-energy principle for predicting the AC current distribution in the parallel-connected winding layers. The experimental results showed that the estimated copper loss is minimum at the condition of $d_2 = 5$ mm ($d_1 : d_2 : d_3 : d_4 = 1 : 5 : 5 : 1$), which was predicted to be an ideal structure by the theory. The experimental result suggests that the distance ratio can reduce the primary copper loss by 13.7 % compared to the original condition, i.e. $d_2 = 1$ mm ($d_1 : d_2 : d_3 : d_4 = 1 : 1 : 1 : 1$).

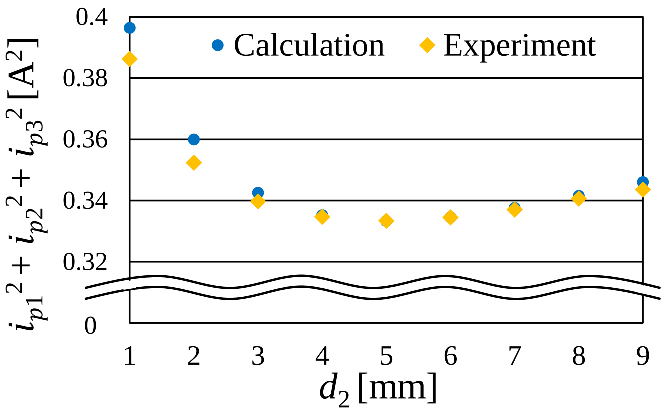

Fig. 8: Experimental and calculation results of factor $i_{p1}^2+i_{p2}^2+i_{p3}^2$ compared among 9 conditions of the distance

Let to focus on $d_2 = 1$ mm, which is the original transformer condition, and $d_2 = 5$ mm, in which AC current distribution is homogenized. The respective AC current distributions are shown in Table II. According to the results, the primary current distribution can be made homogenize by adjusting to the optimum distance between the winding layers. It is implied that the proposed method can homogenize the AC current distribution in the parallel connection of the interleaved winding layers. On the other hand, it was confirmed that the secondary current distribution kept homogenized as expected even if the distance between the winding layers was changed.

Table II: Measurement result of the AC current distribution

d_2[mm]	i_{p1}[Arms]	i_{p2}[Arms]	i_{p3}[Arms]	i_{s1}[Arms]	i_{s2}[Arms]
1	0.241	0.521	0.238	0.501	0.499
5	0.336	0.332	0.332	0.502	0.498

However, in the case of the estimation of the copper losses by measuring the AC current distribution, the skin effect loss and the proximity effect loss cannot be included in the copper loss. Therefore, the primary conversion AC resistances of respective conditions are measured with the secondary side short-circuited condition. The AC resistances were measured by LCR meter (ZM2376; NF co. ltd) from 10 kHz to 1 MHz. Focus on the original transformer structure ($d_2 = 1$ mm), and the adjusted transformer structure ($d_2 = 5$ mm). Fig. 9 shows the respective measurement results from 10 kHz to 100 kHz. Also, Fig. 10 shows the respective measurement results from 100 kHz to 1 MHz.

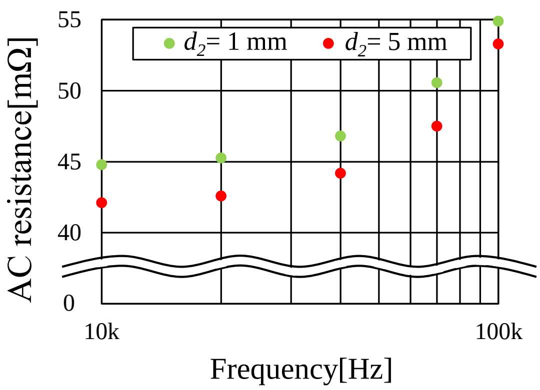

Fig. 9: AC resistance (f = 10 kHz ~ 100 kHz)

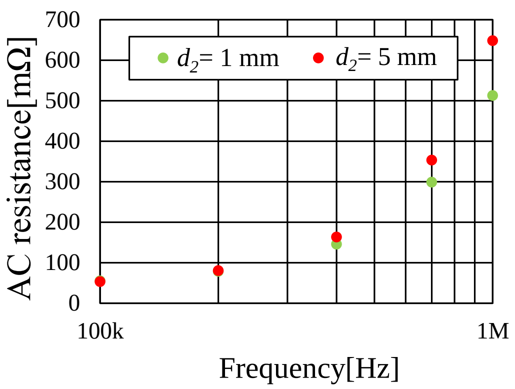

Fig. 10: AC resistance (f = 100 kHz ~ 1 MHz)

In the case of estimation of the AC resistance by the AC current distribution without the skin effect and proximity effect, the AC resistance of the adjusted transformer structure (d_2 = 5 mm) is theoretically expected as 7.0 % lower than the AC resistance of the original transformer structure (d_2 = 1 mm). At 100 kHz as shown in Fig. 9, the adjusted transformer structure (d_2 = 5 mm) has a smaller AC resistance 2.9% compared to the original transformer structure (d_2 = 1 mm). Because the effect of reducing the copper loss by the uniform current distribution and the effect of increasing the copper loss by the proximity effect cancel each other, the copper loss at 100 kHz cannot be decreased theoretically. At a frequency range from 10 kHz to 70 kHz, the adjusted transformer structure (d_2 = 5 mm) has a smaller AC resistance 5.6% to 6.1 % compared to the original transformer structure (d_2 = 1 mm). In this frequency range where the proximity effect does not occur so much, the copper loss can be suppressed almost as theoretically, and thus the validity of the proposed method was successfully revealed. However, at high frequency range from 200 kHz to 1 MHz, the adjusted transformer structure (d_2 = 5 mm) conversely has a larger AC resistance 2.7 % to 26.3 % compared to the original transformer structure (d_2 = 1 mm). Because the increase of the AC resistance by the proximity effect at high frequency is more than the reduction of the AC resistance by homogenizing the AC current distribution.

Therefore, the AC current distribution can be homogenized by adjusting the distance between winding layers, however, the magnetic field distribution also changes, and the proximity effect loss may increase at high frequency. Consequently, the proposed method in this paper can reduce the copper loss of the transformer by controlling the AC current distribution and magnetic field distribution according to the switching frequency.

Conclusion

The Parallel-connection of the interleaved winding layers is recently becoming used in high-frequency power transformer. However, the parallel connection of the winding layers can easily result in the unbalanced AC current distribution, which hinders the effective reduction of the copper loss. For achieving the homogeneous AC current distribution in the parallel-connected winding layers, this paper proposed optimization of the distance between the winding layers. This paper presented the technique to derive the optimum distance between the winding layers according to the recently proposed analysis method called as the extremum co-energy principle. As a result of the experiment, the AC current distribution can be homogenized by adjusting to the optimum distance between the winding layers. However, the magnetic field distribution also changes, and the proximity effect loss may increase at high frequency compared to the original transformer. Therefore, the proposed method in this paper can reduce the copper loss of the transformer by controlling the AC current distribution and magnetic field distribution according to the switching frequency. Consequently, the optimization of the distance between the winding layers for reducing the copper loss is successfully revealed effectiveness.

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