Examination of Two-Dimensional Magnetic Properties in a 5-Leg-Different-Volume-V-Connection-Transformer Core

Shinya Urata*, Hiroyasu Shimoji*, Takashi Todaka* and Masato Enokizono*

Abstract - The Different-volume-V-connection transformer is known as an electric power source that can supply 3-phase electric power and single-phase electric power at the same time. Usually, we use two single-phase transformers that have different volumes. In this paper, we propose the use of a 3-phase 5-leg transformer with the different-volume-V-connection. And, we examine the magnetic properties of the 5-leg core model with the different-volume-V-connection. The magnetic properties of cores with the different-volume-V-connection are compared with those with the delta-connection. In order to express the magnetic anisotropy of the core materials and to calculate the iron loss directly, the two-dimensional vector magnetic property is considered with the E&SS modeling in the simulation.

Keywords: Transformer, Different-volume-V-connection, Delta-connection, FEM, Two-dimensional magnetic properties, E&SS modeling, and Iron loss.

1. Introduction

THE different-volume-V-connection transformer is usually constructed with two single-phase transformers that have different volumes. The characteristic of this connection is known as an electric power source that can supply 3-phase electric power and single-phase electric power at the same time. However, we need large space to install the conventional different-volume-V-connection transformer, because it is constructed with two single-phase transformers. In order to solve this problem, we propose the use of a 5-leg core with the different-volume-V-connection. Fig. 1 shows the 3-phase 5-leg transformer core model. Fig. 2 show the relationship among the exciting vectors of each coil (U, V and W). (a) is for the delta-connection, (b) is for the different-volume-V-connection. In order to get the exciting condition shown in Fig. 2(b) by using the 5-leg core, we have combined the two coil-units. The one is the single U-coil and the other is the V and W-coils in parallel. In this paper, we have evaluated the magnetic properties of 5-leg core with different-volume-V-connection, and compared with those with delta connection. In order to evaluate the magnetic properties of cores, we have carried out the numerical magnetic field analysis considering the two-dimensional vector magnetic properties. The two-dimensional vector magnetic properties make possible to express not only arbitrary magnetic fields (alternating magnetic field in any directions and rotating magnetic field) but also iron loss by using the vector relationship between $\boldsymbol{B}$ and $\boldsymbol{H}$ [1-4]. In order to consider the two-dimensional vector magnetic properties in the analysis, we have used the FEM considering E&SS modeling [5-7].

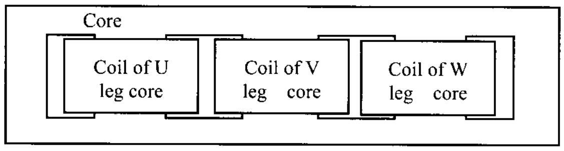
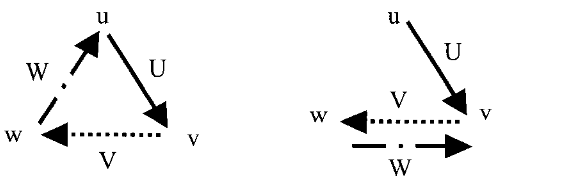
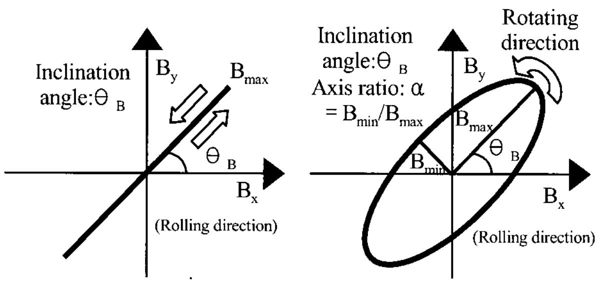


Fig. 1 5-leg transformer core model



(a) Delta-connection. (b) Different-volume-V-connection.

Fig. 2 Relationship among the excitation vectors



(a) Alternating flux condition (b) Rotating flux condition

Fig. 3 Representation of alternating and rotating flux

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2. Definitions Of The Conditions

Fig. 3 shows the definition of the alternating magnetic flux condition (a) and the rotating magnetic flux condition (b). The two-dimensional vector magnetic properties are defined by three parameters. These are the maximum magnetic flux density B_{max}, the inclination angle θ_B and the axis ratio α. θ_B is defined as the angle between the rolling direction (magnetization easy axis) and the direction of the maximum flux density vector. α is the ratio of the minimum flux density to the maximum flux density. The precise circular rotating flux means that α is one, and the alternating flux condition means α is zero. The non-linear magnetic properties used in the analyses are obtained by the measurements of the two-dimensional vector magnetic properties [1-4].

3. Magnetic Property Analysis with E&SS Modeling

3.1 E&SS Modeling

The magnetic material with a magnetic anisotropy has strong non-linearity as a function of the B_{max}, θ_B, and α particularly. The E&SS modeling is expressed as follows [5-7].

$$H_x = \nu_{xr}\left(B_{\max},\theta_B,\alpha,\tau\right)B_x(\tau) + \nu_{xi}\left(B_{\max},\theta_B,\alpha,\tau\right)\int_0^\tau B_x(\tau)d\tau, \quad (1)$$

$$H_y = \nu_{yr}\left(B_{\max},\theta_B,\alpha,\tau\right)B_y(\tau) + \nu_{yi}\left(B_{\max},\theta_B,\alpha,\tau\right)\int_0^\tau B_y(\tau)d\tau, \quad (2)$$

where ν_{xr}, ν_{yr} are the magnetic reluctivity coefficients, and ν_{xi}, ν_{yi} are the magnetic hysteresis coefficients. The magnetic reluctivity coefficients and the magnetic hysteresis coefficients are altered in time, during one period. The variable τ is in a range from zero to 2π. We assume that flux density waveforms are sinusoidal, and the waveforms can be expressed as follows.

$$B_x = R_{Bx}\cos\tau - I_{Bx}\sin\tau, \quad (3)$$

$$B_y = R_{By}\cos\tau - I_{By}\sin\tau, \quad (4)$$

where R_{Bx}, R_{By}, I_{Bx} and I_{By} are coefficients. The distorted magnetic field strength waveforms can be expressed as the following equation in the Fourier series.

$$H_x = \sum_{n=1}^{N}\left(R_{(2n-1)Hx}\cos(2n-1)\tau - I_{(2n-1)Hx}\sin(2n-1)\tau\right), \quad (5)$$

$$H_y = \sum_{n=1}^{N}\left(R_{(2n-1)Hy}\cos(2n-1)\tau - I_{(2n-1)Hy}\sin(2n-1)\tau\right), \quad (6)$$

where $R_{(2n-1)Hx}$, $R_{(2n-1)Hy}$, $I_{(2n-1)Hx}$ and $I_{(2n-1)Hy}$ are coefficients. As a result, the magnetic reluctivity coefficient and the magnetic hysteresis coefficient are given by followings equations.

$$\nu_{xr} = \frac{\sum_{n=1}^{N} R_{(2n-1)H_x}\cos(2n-1)\tau}{\cos\tau}\left(\frac{R_{B_x}}{R_{B_x}^2 + I_{B_x}^2}\right) + \frac{\sum_{n=1}^{N} I_{(2n-1)H_x}\sin(2n-1)\tau}{\sin\tau}\left(\frac{I_{B_x}}{R_{B_x}^2 + I_{B_x}^2}\right), \quad (7)$$

$$\nu_{xi} = \frac{\sum_{n=1}^{N} R_{(2n-1)H_x}\cos(2n-1)\tau}{\cos\tau}\left(\frac{I_{B_x}}{R_{B_x}^2 + I_{B_x}^2}\right) - \frac{\sum_{n=1}^{N} I_{(2n-1)H_x}\sin(2n-1)\tau}{\sin\tau}\left(\frac{R_{B_x}}{R_{B_x}^2 + I_{B_x}^2}\right). \quad (8)$$

In the same way, ν_{yr} and ν_{yi} can be obtained.

3.2 Governing Equation of Magnetic Field

From the Maxwell's equations and the constitutive relation, the governing equation in the two-dimensional magnetic field can be written as follows.

$$\frac{\partial}{\partial x}\left(a_4\frac{\partial A_z}{\partial x} - a_3\frac{\partial A_z}{\partial y} + b_4\int\frac{\partial A_z}{\partial x}d\tau - b_3\int\frac{\partial A_z}{\partial y}d\tau\right) + \frac{\partial}{\partial y}\left(a_1\frac{\partial A_z}{\partial y} - a_2\frac{\partial A_z}{\partial x} + b_1\int\frac{\partial A_z}{\partial y}d\tau - b_2\int\frac{\partial A_z}{\partial x}d\tau\right) = -J_{0z}, \quad (9)$$

$$\begin{cases} a_1 = \cos^2(\phi)\nu_{xr} + \sin^2(\phi)\nu_{yr} \\ a_2 = a_3 = \sin(\phi)\cos(\phi)\nu_{xr} - \sin(\phi)\cos(\phi)\nu_{yr}, \\ a_4 = \sin^2(\phi)\nu_{xr} + \cos^2(\phi)\nu_{yr} \end{cases} \quad (10)$$

$$\begin{cases} b_1 = \cos^2(\phi)\nu_{xi} + \sin^2(\phi)\nu_{yi} \\ b_2 = b_3 = \sin(\phi)\cos(\phi)\nu_{xi} - \sin(\phi)\cos(\phi)\nu_{yi}, \\ b_4 = \sin^2(\phi)\nu_{xi} + \cos^2(\phi)\nu_{yi} \end{cases} \quad (11)$$

where J_{0z} is the exciting current density, A_z is the magnetic vector potential and ϕ is the inclination angle between the x-axis and the rolling direction.

3.3 Terminal voltage method

Because electric devices are usually excited with a constant terminal voltage, in this paper we have applied the terminal voltage method to the finite element analysis instead of giving current density values. The current density J_{0z} is written by

$$J_{oz} = \frac{NI_o}{S_w}, \tag{12}$$

where I_0 is the line current, S_w is the cross-sectional area of the exciting coil and N is the number of turns. In order to treat the current value as an unknown variable, the electrical circuit equation given by the Kirchhoff's second law is used in the system equations.

$$\frac{d\Phi}{dt} + \left(R_c + R_o\right)I_o + L_o\frac{dI_o}{dt} = V_o, \tag{13}$$

where Φ is the number of interlinkage flux of the coil, V_0 is the terminal voltage of the external circuit, R_0 is the resistance of the external circuit, R_C is the resistance of the winding coil, and L_0 is the inductance of the external circuit.

3.4 Magnetic Power Loss

In this method, the iron loss can be calculated directly from the magnetic flux density vector ***B*** and the magnetic field strength vector ***H*** by using the following equations:

$$P_t = \frac{1}{\rho T}\int_0^T\left(H_x\frac{dB_x}{dt} + H_y\frac{dB_y}{dt}\right)dt \quad \text{[W/kg]}, \tag{14}$$

where ρ is the material density and T is the period of the exciting waveform.

4. Condition Of The 5-Leg-Core Model

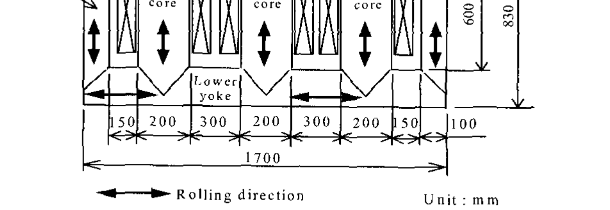


Fig. 4 Condition of the 5-leg-core-model

Fig. 4 shows the 5-leg-core-model used in the numerical magnetic field analysis. The core material is assumed to be the grain-oriented electrical steel sheet named as 35G155. 35G155 is the grade mane of the electrical steel sheet defined by JIS. The rolling direction (θ_B = 0, 180 degrees) of the core is also indicated with arrows in Fig. 4. Fig. 5 shows the example of the two-dimensional magnetic properties of 35G155 when B_{max} is 0.6 T and the frequency is 50 Hz. It can be confirmed that the iron loss increases as α approaches to 0.8 and θ_B approaches to 90 degrees

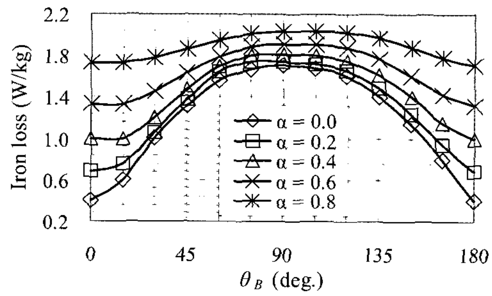
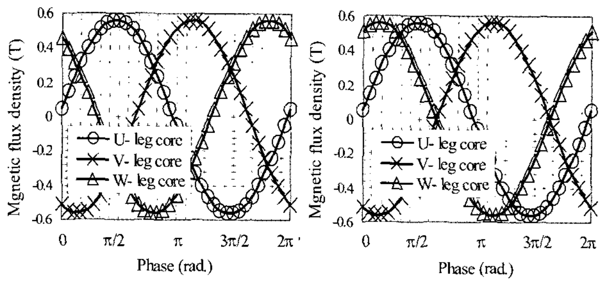


Fig. 5 Iron loss of 35G155 as a function of θ_B and α. [B_{max} is 0.6 T, frequency is 50 Hz]

5. Results Of The Calculation

Fig. 6 shows the average magnetic flux density waveforms of each leg (U-, V-, and W-leg core). Fig. 7 show the magnetic flux lines distribution for each connection when the phase value is 3π/2. Fig. 8 show θ_B distribution. Fig. 9 show the α distribution. Fig. 10 show the maximum flux density distribution. Fig. 11 show the maximum field strength distribution. Fig. 12 show the iron loss distribution. (a) is for the delta-connection, (b) is for different-volume- V-connection. Table I shows the comparison of the total iron loss for each connection.



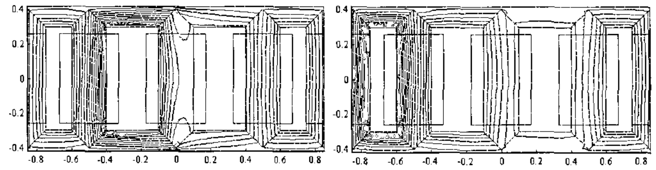
(a) Delta-Connection (b) Different-volume-V-connection

Fig. 6 Average magnetic flux density waveform of each leg.

As shown in Fig. 7, the direction of the magnetic flux is quickly changed at the jointed parts to be in the parallel direction for the rolling direction of each subdivided core. This is due to the strong magnetic anisotropy of the grain-oriented electrical steel sheet. As shown in Fig. 8, θ_B are almost zero or 180 degrees, that is to say, the magnetic flux density vectors are almost parallel to the rolling direction. As shown in Fig. 9, we can confirm that the elliptic rotating fluxes, whose α are about 0.3, existed around the apex of the triangular jointed parts. However, α became smaller as the distance from there is larger. When we compare α in each leg in case of each connection, we can confirm that the largest α is confirmed in the V-leg in case of the delta connection. This is why thee-phase rotating flux is generated there. In other legs, we can only confirm two-phase rotating flux. It is known that thee-phase rotating flux becomes the precise circular more easily than two-phase. As shown in Fig. 10(a), in case of delta-connection, the magnetic flux density of cores around the coil windows, which locate between U and V leg core and between V and W leg core, are larger. This is because of magnetic path length. When we use the electrical steel sheet that has a strong anisotropy and high permeability, as like grain-oriented electrical steel sheet: 35G155, we can confirm this phenomenon. As shown in Fig. 10(b), in case of different- volume-V-connection, we can confirm that the flux density in left outer leg core is particularly larger than that in other regions. This is why the flux can not be counteracting by the fluxes flowed from other leg core. This is a particular difference between these two connections in magnetic flux density distribution. As shown in Fig. 11, around the joints, the magnetic field strength became larger because of rotating magnetic flux, in other word, size of α. Particularly this tendency can be observed around the jointed part of the V-leg core in the delta-connection shown in Fig. 11(a). As shown in Fig. 12, we can confirm that the iron loss is larger in the area where the rotating flux generates or the magnitude of flux density is large. We can confirm that the iron loss depending on the rotating flux around the joints in case of the delta-connection is larger than that in case of the different-volume-V-connection. And, we can confirm that the iron loss in the outer left core of different-volume-V-connection is larger than that of the delta-connection, because of the magnitude of flux density. As shown in Table I, the total iron loss difference of the different-volume-V-connection to the delta-connection is only 2.2 %. We can conclude that the 5-leg core with different-volume-V-connection has almost same total iron loss as that with delta-connection. Furthermore, we can confirm no fatal abnormal loss. We can use the 5-leg core with deltaconnection as that with different-volume-V-connection.

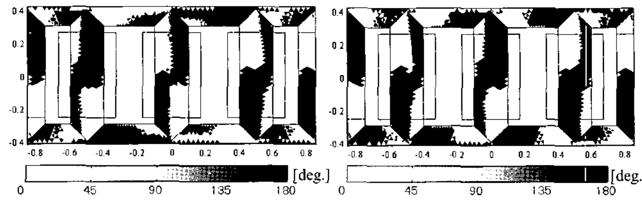
Table 1 Comparison of Total Iron Loss

Connection	Maximum of average flux density in each leg cores (U, V, W). [T]	Total iron loss. [W/kg]
Delta-connection	0.56	0.135
Different-value-V-connection	0.56	0.138



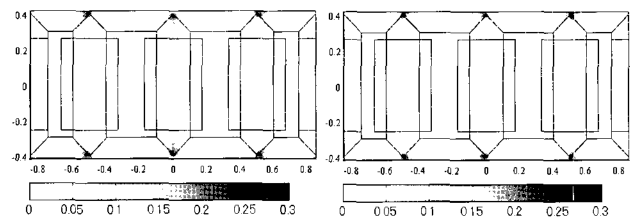
(a) Delta-Connection (b) Different-volume-V-connection

Fig. 7 Flux lines distribution when phase value is $3\pi/2$



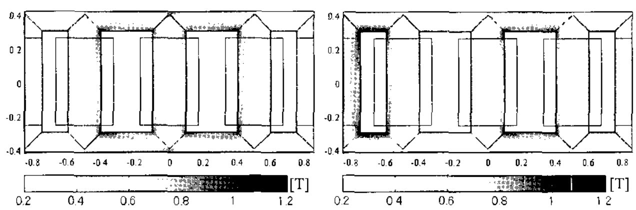
(a) Delta-Connection (b) Different-volume-V-connection

Fig. 8 θ_B distribution



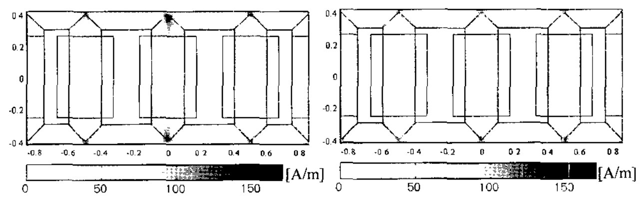
(a) Delta-Connection (b) Different-volume-V-connection

Fig. 9 α distribution



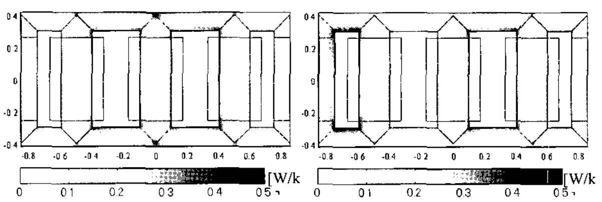
(a) Delta-Connection (b) Different-volume-V-connection

Fig. 10 Maximum flux density distribution



(a) Delta-Connection (b) Different-volume-V-connection

Fig. 11 Maximum magnetic field strength distribution



(a) Delta-Connection (b) Different-volume-V-connection

Fig. 12 Iron loss distribution

6. Conclusion

The difference of the iron loss between the 5-leg core with delta-connection and that with different-volume-V-connection was only 2.2 %. Also the fatal abnormal loss was not observed in the calculated results. Thus, We can use the 5-leg core with delta-connection as that with different-volume- V-connection by just changing the electrical connection.

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