A spice model of orthogonal-core transformers

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A SPICE model of orthogonal-core transformers

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This paper deals with a numerical model of orthogonal-core transformers for use in SPICE. The model was devised on the basis of the magnetic circuit of the orthogonal-core with the saturation and hysteresis effects. Using the numerical model, the behavior of the dc-ac converter constructed with the orthogonal-core transformers and square-wave transistor choppers was analyzed. The calculated values and measured ones show a good agreement. The method presented here is suitable for the circuit analysis and design optimization of the dc-ac converter taking account of nonlinear characteristics of the orthognal-cores and semiconductor devices used in the converter.

I. INTRODUCTION

The authors have proposed earlier, a dc-ac converter equipped with orthogonal-core transformers for connecting a solor cell array to the utility grid.[1]

For circuit analysis and design optimization, it is necessary to predict circuit behavior considering the nonlinear characteristics of the orthogonal-core transformers and semiconductor devices used in the converter.

One method of analysis is the utilization of SPICE, which is general-purpose circuit simulation program. But a suitable model for orthogonal-core transformers has not been reported. This paper deals with a numerical model of the orthogonal-core transformers for use in SPICE.

II. MAGNETIC CIRCUIT OF ORTHOGONAL-CORE

Figure 1 shows the orthogonal-core transformer. The primary and secondary windings are N_1 and N_2. The primary and secondary currents are i_1 and i_2. The dashed curves ϕ_1 and ϕ_2 illustrate the primary and secondary fluxes.

Figure 2 shows a magnetic circuit of the orthogonal-core. In this circuit, the reluctances express the saturation and the inductances the hysteresis. Therefore, each current can be divided into the current due to the saturation and the current due to the hysteresis.

Now, let the former and latter currents be i_{1m} and i_{1g} in the primary and i_{2m} and i_{2g} in the secondary. That is, $i_1 = i_{1m} + i_{1g}$ and $i_2 = i_{2m} + i_{2g}$. From the magnetic circuit, these currents are given by

$$N_1 i_{1m} = 2[F(\phi_a) + F(\phi_b)],$$
$$N_2 i_{2m} = 2[F(\phi_a) - F(\phi_b)],$$

$$N_1 i_{1g} = 2\left[F'\left(\frac{d\phi_a}{dt}\right) + F'\left(\frac{d\phi_b}{dt}\right)\right],$$
$$N_2 i_{2g} = 2\left[F'\left(\frac{d\phi_a}{dt}\right) - F'\left(\frac{d\phi_b}{dt}\right)\right], \quad (1)$$

where

$$\phi_a = (\phi_1 + \phi_2)/2 \text{ and } \phi_b = (\phi_1 - \phi_2)/2. \quad (2)$$

Considering the nonlinearity of the reluctances and inductances, we assume their characteristics as:

$$F(\phi) = a_1\phi + a_3\phi^3 + a_5\phi^5,$$
$$F'\left(\frac{d\phi}{dt}\right) = b_1\left(\frac{d\phi}{dt}\right) + b_3\left(\frac{d\phi}{dt}\right)^3 + b_5\left(\frac{d\phi}{dt}\right)^5, \quad (3)$$

where a_1, a_3, a_5, b_1, b_3, and b_5 are constants.

From Eqs. (1)–(3), we can obtain the currents i_{1m}, i_{2m}, i_{1g} and i_{2g}. The characteristics of the orthogonal-core are that the saturation currents i_{1m} and i_{2m} are determined by the relative values of the primary and secondary fluxes and that the hysteresis currents i_{1g} and i_{2g} depend on both the primary and secondary excitation voltages.

III. SPICE MODEL OF ORTHOGONAL-CORE TRANSFORMER

In SPICE analysis, magnetic saturation and hysteresis are simulated by using nonlinear current-controlled and voltage-controlled current sources, respectively.[2] For this

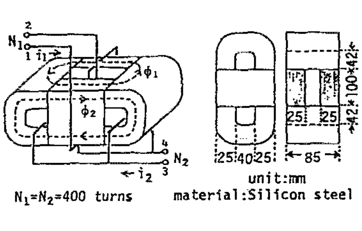

FIG. 1. Schematic diagram of the orthogonal-core transformer.

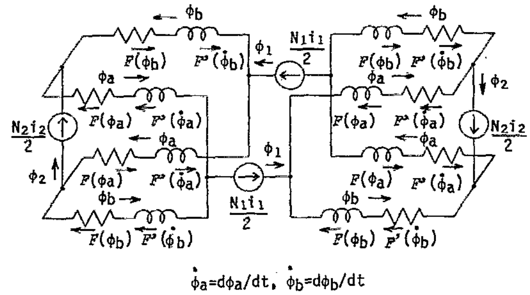

FIG. 2. Magnetic circuit of the orthogonal core.

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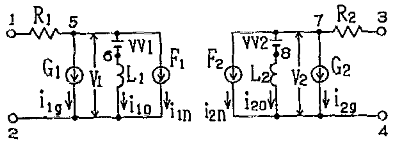

FIG. 3. Numerical model of orthogonal-core transformer for SPICE.

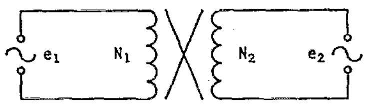

FIG. 4. Experimental circuit for obtaining the constants.

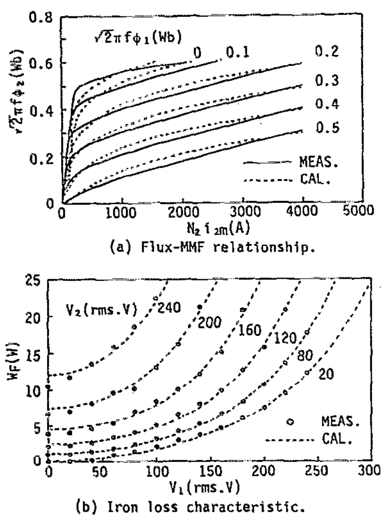

FIG. 5. Measured characteristics of the orthogonal core used in this paper.

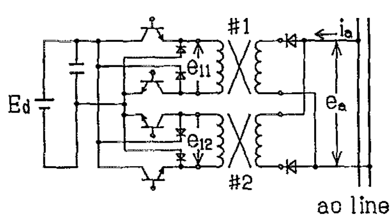

FIG. 6. Circuit configuration of the orthogonal-core-type dc-ac converter.

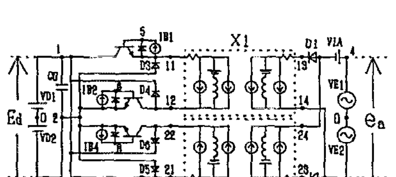

FIG. 7. SPICE implementation of the dc-ac converter.

```
SPICE PROGRAM
VD1 1 0 DC 50
VD2 0 2 DC 50
C0 1 2 4700UF
XT1 1 5 11 TR
XT2 12 6 2 TR
XT3 1 7 21 TR
XT4 22 8 2 TR
.SUBCKT TR 1 2 3
Q 1 2 3 QMOD
D 3 2 DMOD
.ENDS TR
D3 2 11 DMOD
D4 12 1 DMOD
D5 2 21 DMOD
D6 22 1 DMOD
IB1 11 5 PULSE(1 -1 0 0.2M
+ 0.2M 9.8M 20M)
IB2 2 6 PULSE(1 -1 0 0.2M
+ 0.2M 9.8M 20M)
IB3 21 7 PULSE(-1 1 0 0.2M
+ 0.2M 9.8M 20M)
IB4 2 8 PULSE(-1 1 0 0.2M
+ 0.2M 9.8M 20M)
VE1 4 0 SIN(0 70.5 50 5M)
VE2 0 14 SIN(0 70.5 50 5M)
VIA 4 24 0
D1 24 13 DMOD
D2 14 23 DMOD
X1 11 12 13 14 OCORE
X2 21 22 23 24 OCORE

.SUBCKT OCORE 1 2 3 4
R1 1 5 0.68
R2 3 7 0.68
L1 6 2 0.6667H IC=0
L2 8 4 0.6667H IC=0
VV1 5 6 0
VV2 7 8 0
F1 5 2 POLY(2) VV1 VV2 0 0 0 0
+ 0 0 -1.2037 0 -3.6111 0 0 0 0
+ 0 0 0.65506 0 6.5506 0 3.2753
F2 7 4 POLY(2) VV2 VV1 0 0 0 0
+ 0 0 -1.2037 0 -3.6111 0 0 0 0
+ 0 0 0.65506 0 6.5506 0 3.2753
G1 5 2 POLY(2) 5 2 7 4 0 0.000174
+ 0 0 0 0 -2.58E-10 0 -7.75E-10 0
+ 0 0 0 0 0 6.32E-15 0 6.32E-14 0
+ 3.16E-14
G2 7 4 POLY(2) 7 4 5 2 0 0.000174
+ 0 0 0 0 -2.58E-10 0 -7.75E-10 0
+ 0 0 0 0 0 6.32E-15 0 6.32E-14 0
+ 3.16E-14
.ENDS OCORE
.MODEL QMOD NPN(TF=200NS)
.MODEL DMOD D(IS=1E-6)
.OPTIONS LIMPTS=2000 ITL5=0
+ VNTOL=100MV ABSTOL=10MA
.TRAN 0.1MS 100MS 0 0.1MS UIC
.PRINT TRAN V(11,12) V(21,22)
+ V(4,14) I(VIA)
.END
```

FIG. 8. SPICE program of the dc-ac converter.

reason, we subdivide the saturation currents as: $i_{1m}=i_{10}+1_{1n}$, and $i_{2m}=i_{20}+i_{2n}$, where i_{10} and i_{20} are currents proportional to each side flux. From the calculations mentioned above, i_{10} and i_{20} are obtained as:

$$i_{10}=2a_1\phi_1/N_1, \quad i_{20}=2a_1\phi_2/N_2. \tag{4}$$

Using i_{10} and i_{20}, we rewrite the fluxes ϕ_1 and ϕ_2 in the equations of the currents i_{1n} and i_{2n}. Then these currents can be expressed as follows:

$$i_{1n}=A_{11}\,i_{10}^3+A_{12}\,i_{10}\,i_{20}^2+A_{13}\,i_{10}^5 + A_{14}\,i_{10}^3\,i_{20}^2+A_{15}\,i_{10}\,i_{20}^4, \tag{5}$$

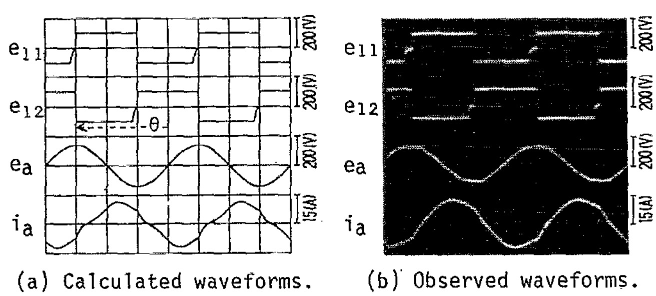

FIG. 9. Comparison between the calculated and observed wave forms.

TABLE I. Coefficients in Eqs. (5)–(8).

j	A_{1j}	A_{2j}	B_{1j}	B_{2j}
0	···	···	$2b_1/N_l^2$	$2b_1/N_2^2$
1	$a_3N_1^2/16a_1^3$	$a_3N_2^2/16a_1^3$	$b_3/2N_1^4$	$b_3/2N_2^4$
2	$3a_3N_2^2/16a_1^3$	$3a_3N_1^2/16a_1^3$	$3b_3/2N_1^2N_2^2$	$3b_3/2N_2^2N_1^2$
3	$a_5N_1^4/256a_1^5$	$a_5N_2^4/256a_1^5$	$b_5/8N_1^6$	$b_5/8N_2^6$
4	$5a_5N_1^2N_2^2/128a_1^5$	$5a_5N_2^2N_1^2/128a_1^5$	$5b_5/4N_1^4N_2^2$	$5b_5/4N_2^4N_1^2$
5	$5a_5N_2^4/256a_1^5$	$5a_5N_1^4/256a_1^5$	$5b_5/8N_1^2N_2^4$	$5b_5/8N_2^2N_1^4$

$$i_{2n}=A_{21}\, i_{20}^3 + A_{22}\, i_{20}\, i_{10}^2 + A_{23}\, i_{20}^5 + A_{24}\, i_{20}^3\, i_{10}^2 + A_{25}\, i_{20}\, i_{10}^4. \qquad (6)$$

Furthermore, let the excitation voltages $N_1(d\phi_1/dt)$ and $N_2(d\phi_2/dt)$ be v_1 and v_2, respectively. Then the hysteresis currents i_{1g} and i_{2g} are expressed as:

$$i_{1g}=B_{10}v_1 + B_{11}v_1^3 + B_{12}v_1v_2^2 + B_{13}v_1^5 + B_{14}v_1^3v_2^2 + B_{15}v_1v_2^4, \qquad (7)$$

$$i_{2g}=B_{20}v_2 + B_{21}v_2^3 + B_{22}v_2v_1^2 + B_{23}v_2^5 + B_{24}v_2^3v_1^2 + B_{25}v_2v_1^4. \qquad (8)$$

The coefficients in the equations are listed in Table I.

Accordingly, the SPICE model is presented as shown in Fig. 3. In the figure, L_1 and L_2 are linear inductances given by $L_1 = N_1^2/2a_1$ and $L_2 = N_2^2/2a_1$, F_1 and F_2 are nonlinear current-controlled current sources based on Eqs. (5) and (6), G_1 and G_2 are nonlinear voltage-controlled current sources based on Eqs. (7) and (8). R_1 and R_2 are the primary and secondary winding resistances, and $VV1$ and $VV2$ are zero-valued voltage sources for the purpose of measuring current.

IV. ANALYSIS OF dc-ac CONVERTER

On the SPICE analysis, it is necessary to provide the constants a_1, a_3, a_5, b_1, b_3 and b_5 in Table I. In this paper, we determine the coefficients experimentally by the simple circuit shown in Fig. 4. In the figure, e_1 and e_2 are sinusoidal voltages with the same frequency and are in phase with each other. From the flux-MMF relationship[3] measured in the circuit, we can determine the constants a_1, a_3 and a_5. The constants b_1, b_3 and b_5 can be determined by the measured iron loss characteristic.

Figures 5(a) and 5(b) show the flux-MMF relationship and iron loss characteristic. In the figures, the dashed curves show the calculated values when the constants are: $a_1 = 1.20 \times 10^5$ A/Wb, $a_3 = -2.08\times10^{11}$ A/Wb^3, $a_5 = 1.63\times10^{17}$ A/Wb^5, $b_1 = 13.9$ A/V, $b_3 = -13.2$ A/V^3, and $b_5 = 207$ A/V^5.

Based on the above results, we analyze the orthogonal-core-type dc-ac converter shown in Fig. 6. The primary sides of the orthogonal-core transformers No. 1 and No. 2, which have the same construction, are excited by square-wave transistor choppers. The power is transferred from the dc source to the ac line by adjusting the phase angle θ of the output voltages e_{11} and e_{12} of the transistor choppers.[1]

Figure 7 shows a SPICE implementation of the dc-ac converter. The subcircuits $X1$ and $X2$ are the orthogonal-core transformers shown in Fig. 3. For convenience of calculation, each voltage source is divided into two sources.

Figure 8 shows the SPICE program at $E_d = 100$ V, $E_a = 100$ V, and $\theta = 270°$. Figure 9 shows the calculated and observed wave forms in steady state. In the figures, e_a and i_a are the voltage and current of the ac system. This reveals that the calculated values agree well with the measured ones.

V. CONCLUSION

We proposed a numerical model of the orthogonal-core transformer for use in SPICE and calculated the voltage and current of the orthogonal-core-type dc-ac converter. The calculated results agree well with the measured ones. The analytical method presented here is useful for the circuit analysis and design optimization of other power converters equipped with orthogonal-core transformers.

[1] O. Ichinokura, M. Maeda, H. Takahashi, and K. Murakami, IEEE Trans. Magn. **MAG-24**, 1969 (1988).

[2] D. Pei and P. O. Lauritzen, IEEE Trans. Power Electron. **PE-1**, 101 (1986).

[3] O. Ichinokura and K. Murakami, IEEE Trans. Magn. **MAG-21**, 1750(1985).