Electromagnetic Field Analysis Of Film Transformer

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Abstract—**In this paper, we investigate a thin film transformer for small electronic devices. This transformer is composed of the lamination of thin film conductors. Both the primary and secondary coils of the film transformer are arranged coaxially on one layer and multiply laminated. The operation principle of the transformer is based on the skin effect and the mutual effect between the coils at high frequency. Using the integral equation method, we evaluate the electromagnetic field and calculate the lumped circuit parameters, (e.g. inductance and resistance, etc.). A fairly good agreement is obtained comparing with experimental values. Thus, the applied method is quite useful for design and investigation of the thin film transformer.**

I. Introduction

To design and construct compact electric power supplies, it is essential to reduce the size of their magnetic devices, e.g. reactors and transformers. One of the ways is to employ high frequency excitation [1-3]. In this case, a serious problem is that the performance of the device is dominated by the frequency characteristics of the core magnetic materials. Another solution for this problem is to exploit a thin and light weight high frequency transformer which we call a film transformer.

The film transformer is composed of a lamination of thin film conductors. Each film is constructed by chemical etching processes. Both the primary and secondary coils of our film transformer are arranged coaxially on the one layer and multiply laminated. The operating principle is based on the skin effect and mutual effect between coils at high frequency similar to that of our coreless transformer [4]. To design and improve the film transformer characteristics, it is essential to analyze its electromagnetic phenomena and parameters.

In this paper, an integral equation method is applied to analyze this film transformer. The magnetic field of the transformer can be modeled with the axisymmetric assumption. Applying the numerical methods, e.g. the finite element method (FEM) and boundary element method (BEM) to this problem leads to results with good accuracy. Particularly, some calculation methods for voltage source problems that consider the current distributions in conductors are very useful tools for designing of magnetic devices [5-7]. In the present, we applied a method to obtain current distributions in the thin film conductors of the transformer. This method uses Fredholm integral equation of the second kind for the electric field intensity. To demonstrate the advantages of the method, using a vector potential expression, we calculate the magnetic field, impedance and ratio of transformation of the thin film transformer for various frequencies under different secondary circuit conditions. The results obtained show good agreement with experimental results. Thus, the applied method is quite useful for design and investigation of the thin film transformer.

II. Film transformer

The shape and geometry of the thin film transformer are shown in Figs. 1 and 2.

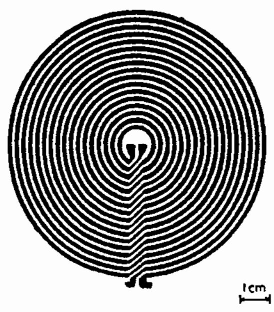

Fig. 1 Thin film transformer

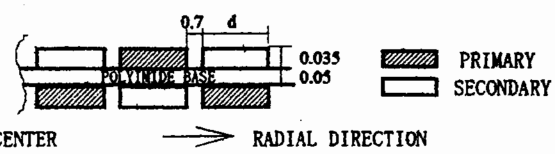

Fig. 2. The sizes of the turns, d=1.7mm (unit in mm).

This transformer is composed of two-layer primary and secondary coils. Connections between layers of separate coils are serial. Figure 2 shows the sizes of the separate turns and the distances between them. This transformer may be composed of two, four or more layers.

III. Method of Analysis

1) Integral equation for axisymmetrical electromagnetic field. If we consider a conductor with axisymmetric electromagnetic field, then the vector potential $\mathbf{A}$ and the current density $\sigma\mathbf{E}$ have only components directed tangent to the current contour. According to Faraday's law, we have

$$u = iR + \frac{d\Phi}{dt}, \quad (1)$$

where R is the resistance of the conductor, i is the current and Φ is the interlinkage magnetic flux.

Using conventional loop analysis, the conductor is composed of single current loop with current Δi. The magnetic flux can be calculated from the magnetic vector potential $\Phi = \oint_L \mathbf{A}d\mathbf{l}$. Also, ΔiR can be expressed in terms of the electric field intensity $\Delta \dot{i}R = \oint_L \mathbf{E}d\mathbf{l}$, where L refers to the current path in each loop.

Denoting ρ_Q as a loop radius, equation (1) can be rewritten in a form

$$\dot{u} = 2\pi\rho_Q \dot{E}(Q) + j\omega 2\pi\rho_Q \dot{A}(Q), \quad (2)$$

where $\cdot$ refers to the vector quantities.

The vector potential $\mathbf{A}$ at the point Q of the axisymmetric electromagnetic field is defined by the expression :

$$\dot{A}(Q) = \frac{\mu_0}{2\pi}\int_S \sigma(M)\dot{E}(M)\sqrt{\frac{\rho_M}{\rho_Q}} f(k) dS_M, \quad (3)$$

where S, Q and M are the cross-sectional area of the conductor, a observation point and a point of current integration, respectively. The function *f(k)* is

$$f(k) = \left(\frac{2}{k} - k\right)K(k) - \frac{2}{k}E(k), \quad (4)$$

where *K(k)* and *E(k)* are the complete elliptic integrals of the first and second kind with module k defined by the expression

$$k^2 = \frac{4\rho_Q \rho_M}{(\rho_Q + \rho_M)^2 + (z_Q - z_M)^2}. \quad (5)$$

Substituting Eqs.(3)-(5) into Eq.(2) yields the Fredholm integral equation of the second kind for the electric field intensity

$$\dot{E}(Q) + j\omega\frac{\mu_0}{2\pi}\int_S \sigma(M)\dot{E}(M)\sqrt{\frac{\rho_M}{\rho_Q}} f(k) dS_M = \frac{\dot{u}}{2\pi\rho_Q}. \quad (6)$$

This integral equation has a kernel with a weak logarithmic singularity. Solving Eq.(6), it is possible to determine the current distribution in the conductor due to the axisymmetric electromagnetic field. If the current distribution is known, then the different electromagnetic field characteristics are easily evaluated by means of the vector potential expression (3). For example, the impedance of the loop having a radius ρ, cross-section S and current I can be calculated from the electric field and vector potential distributions using the expression

$$\dot{Z} = \frac{2\pi}{\dot{I}S}\left(\int_S \rho(\dot{E} + j\omega\dot{A})dS\right). \quad (7)$$

The inductance can be determined directly from

$$L = \frac{2\pi}{\dot{I}S}\int_S \rho\dot{A}\, dS. \quad (8)$$

2) *The system of integral equation.* If an electromagnetic system is composed of *n* parallel coaxial conductors and each conductor is fed by a voltage u_i, then a system of integral equations is as follows

$$\dot{E}_i(Q) + j\lambda\sum_{l=1}^{n}\int_{S_l} \sigma_l(M)\dot{E}_l(M)\sqrt{\frac{\rho_M}{\rho_Q}} f(k) dS_l = \frac{\dot{u}_i}{2\pi\rho_Q}$$

$$i=1,\dots,n, \quad (9)$$

where $\lambda = \frac{\omega\mu_0}{2\pi}$ is the characteristic parameter of the integral equations.

Thus, the electromagnetic field calculation of such electromagnetic systems is reduced to a set of Fredholm integral equations of the second kind while the system is driven by constant voltage. Discretization of this system yields a set of linear simultaneous equations with complex variables. Using HP735 EWS, we solved the simultaneous equation iteratively. A few minuts were required for the 680 unknown complex variables with double precision.

IV. Results and Discussion

The method and computer program, presented above, are applied to analyze the thin film transformer.

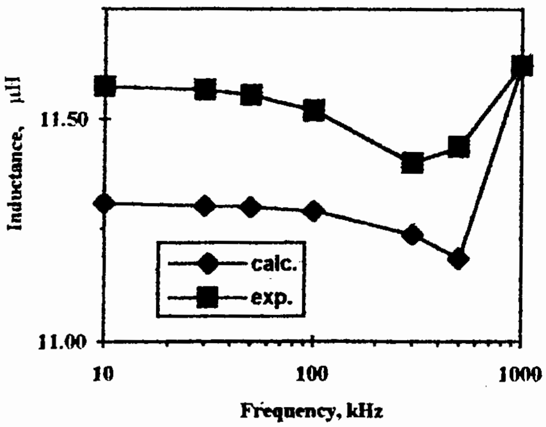

Fig. 3. Coil Inductance vs. Frequency.
(two layer film transformer)

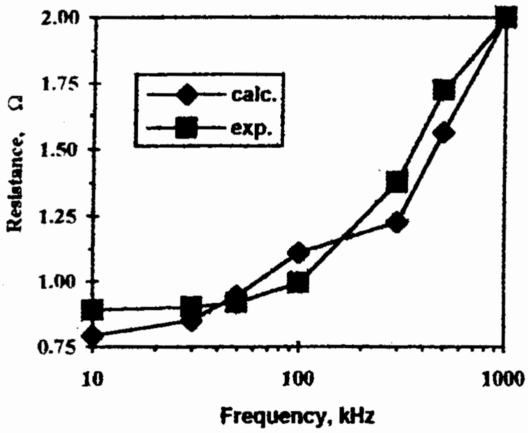

Fig. 4. Coil Resistance vs. Frequency.
(two layer film transformer)

Figures 3 and 4 show the computed results of the inductance and the resistance together with experimental ones for the various frequencies. By considering the results in Figs. 3 and 4, it is obvious that the coil's inductance decreases and the resistance increases due to the skin effect when the exciting frequency is raised. The change of the inductance is approximately 0.15 μH and the change for resistance is 1.1Ω. The results obtained from calculations coincide well with experiments. The difference between them is always less than 3.5% for the inductance and 10% for the resistance.

Figure 5 shows the computed ratio of transformation together with the experimental one. Clearly, when the frequency is increased, the induced voltage in the secondary coil simultaneously increases. After 50kHz, the ratio of transformation exceeds 90%. Again the tendency of the calculated values agree well with the measured values.

Figure 6 shows the efficiency as a function of the frequency using two different values of the pure resistive load (1.4Ω and 21.9Ω). The calculated values at low resistive load (1.4Ω) were somewhat lower than the experimented values, because we neglected the skin effect of the connecting wires from the transformer to the load. The efficiency exceeds 80% when the value of load resistance is relatively large (21.9Ω). This fact demonstrates the usefulness of the thin film transformer for constructing of the compact power supplies.

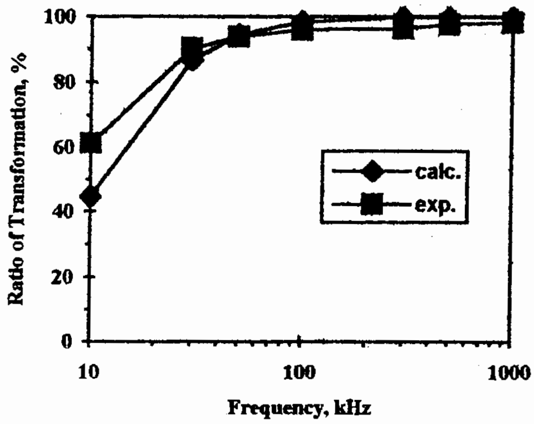

Fig. 5. Ratio of Transformation vs. Frequency.
(Two layer film transformer)

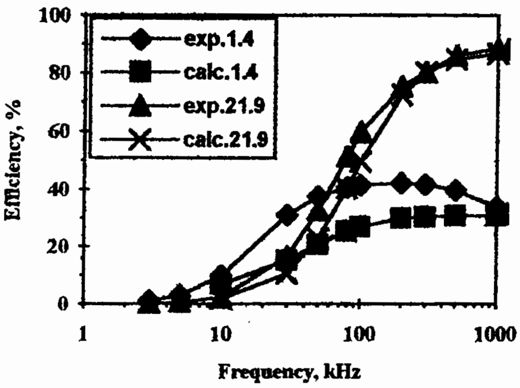

Fig. 6. Efficiency vs. Frequency.
(two layer film transformer)

Figure 7 shows the magnetic field distributions under the secondary open circuited conditions. The applied frequency is 1MHz. It observes the edge effect which changes significantly the magnetic field distribution in the conductors. This increase the inductance at high frequency as shown in Fig. 3.

The edge effect of the films which appears at high frequency can be controlled by changing the sizes of the conductors. Figure 8 shows magnetic field distribution at 1MHz of the two layer film transformer, where the size *d* of the cross section of the conductors proportionally increases from the center to outer (d=1.7mm; 1.9mm, 2.1mm, 2.3mm, 2.5mm, 2.7mm, 2.9mm, 3.1mm, respectively).

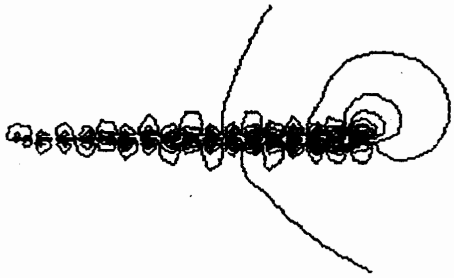

Fig. 7 Magnetic field distribution of the film transformer. (d=1.7mm, frequency-1MHz)

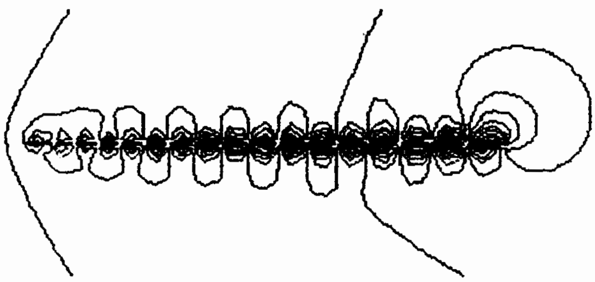

Fig. 8 Magnetic field distribution of the film transformer. (d=1.7;1.9;2.1;2.3;2.5;2.7; 2.9; 3.1mm; frequency-1MHz)

V. Conclusion

A method of analysis and computer program has been applied to investigate the characteristics of thin transformer. The tendency of the calculated results has correlated well with experimental results. Thus, it has been shown that the applied method for film transformer analysis can be successively used to design such electromagnetic system composed of coaxial parallel conductors with a high-frequency voltage supply.

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