A New Type High Frequency Transformer

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Abstract - In order to realize small power supplies, we propose here a new type coreless high frequency transformer. This new transformer is composed of simple twisted coils and its operating principle is based on the skin effect of current carrying conductors. Simple analytical and experimental works suggest that twisted coils have versatile possibilities as a high frequency transformer.

I. INTRODUCTION

In order to design small and compact electric power supplies, it is essential to reduce the size of the magnetic devices, e.g. reactor and transformer. One way to reduce the size of a magnetic device is to employ high frequency excitation [1-3]. In such a high frequency exciting condition, a serious problem is that the major performance of the devices is dominated by the frequency characteristics of the core magnetic materials. To overcome this difficulty, new magnetic materials, such as amorphous and rapid quenching magnetic materials, have been exploited and utilized [4-6]. Nevertheless, it is difficult to avoid an essential increase of iron loss in accordance with the rise of operating frequency. Another solution is to exploit a coreless transformer.

In the present paper, we propose a new type coreless high frequency transformer. This new transformer is composed of simple twisted coils and its operating principle is based on the skin effect of the current carrying conductors. Simple analytical and experimental works suggest that twisted coils have versatile characteristics and could likely realize a highly efficient transformer at a limited high frequency operating range.

II. A CORELESS TRANSFORMER

A. Basic theory

Figure 1(a) shows a typical conventional transformer which utilizes the magnetic flux linking the loop conductors. Our new transformer directly utilizes the magnetic flux enclosing the current carrying conductors as shown in Fig. 1(b).

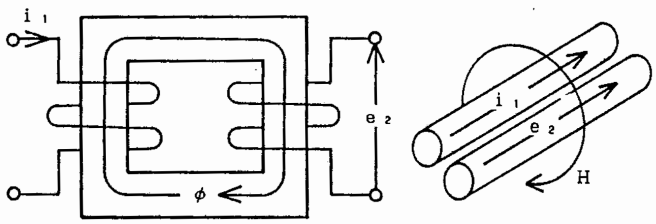
A DC resistance R_{D1} of the primary coil is given by

$$R_{D1}=\rho l_1/(\pi a^2), \quad (1)$$

where ρ, l_1 and a are the resistivity, length and radius of the primary coil, respectively. Denoting I_0 as a zeroth order first kind modified Bessel function, the AC resistance R_{A1} and internal leakage inductance L_{i1} are related with the DC resistance R_{D1} as

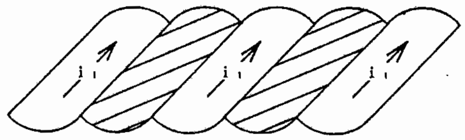
$$(1/R_{D1})(R_{A1}+j\omega L_{i1})=(\kappa_1 a/2)[I_0(\kappa_1 a)/I_0'(\kappa_1 a)], \quad (2)$$

where $\omega=2\pi f$, f=frequency, $j=\sqrt{-1}$, μ_0=permeability of air and $\kappa_1=a\sqrt{\omega\mu_0\pi/2\rho}$ [7]. By means of (2), R_{A1} and L_{i1} are given by

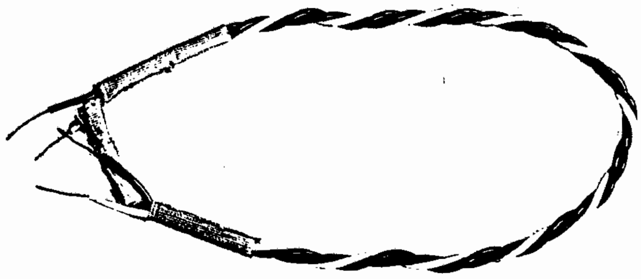


(a) Conventional core type transformer. (b) New type transformer.

Figure 1. Principle of transformer operation.



(a) Schematic diagram of the twisted coils.



(b) A practical example of the twisted coils.

Figure 2. Structure of the new type transformer using the twisted coils.

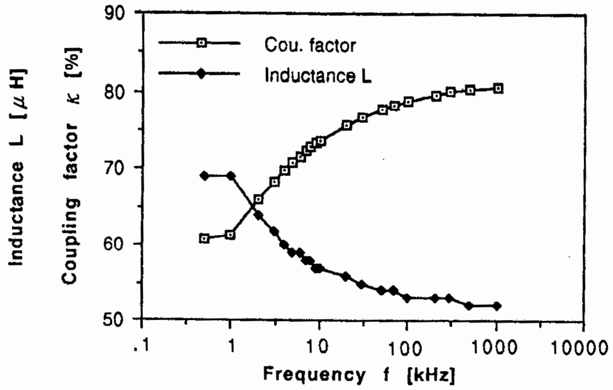


Figure 3. Frequency characteristics of the self inductance L ($=L_1=L_2$) and coupling factor κ. l_1=3[m], l_2=3[m], l_{1e}=2.7[m], l_{2e}=2.7[m], a=0.0004[m], b=0.0004[m] and material : copper wire.

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$\kappa_1 < 1$

$$R_{A1} \sim R_{D1}[1+(1/3)\kappa_1^4], \quad (3)$$

$$L_{i1} \sim (\mu_0 l_1/2)[1-(1/6)\kappa_1^4], \quad (4)$$

$\kappa_1 \geqq 1$

$$R_{A1} \sim R_{D1}[(1/4)+\kappa_1+(1/64)(1/\kappa_1^3)], \quad (5)$$

$$L_{i1} \sim (\mu_0 l_1/2)[(1/\kappa_1)-(1/64)(1/\kappa_1^3)]. \quad (6)$$

The secondary AC resistance R_{A2} and internal leakage inductance L_{i2} can be obtained in much the same way as those of primary ones.

At high frequency, the currents in the conductors may be forced into a symmetrical distribution with respect to each of the coil axes by the skin effect. Assuming this condition, the mutual inductance M, primary self inductance L_1 and secondary self inductance L_2 are given by

$l_{1e} \leqq l_{2e}$

$$M=(\mu_0/2\pi)l_{2e}\{\log[2l_{1e}/(a+b)]-1\}, \quad (7)$$

$l_{1e} > l_{2e}$

$$M=(\mu_0/2\pi)l_{1e}\{\log[2l_{2e}/(a+b)]-1\}, \quad (8)$$

$$L_1=L_{i1}+(\mu_0/2\pi)l_1\{\log[2l_1/a]-1\}, \quad (9)$$

$$L_2=L_{i2}+(\mu_0/2\pi)l_2\{\log[2l_2/b]-1\}, \quad (10)$$

where l_{1e}, l_{2e}, l_2 and b are the effective length of the primary coil, the effective length of the secondary coil, the length of secondary coil and the radius of the secondary coil, respectively.

A practical structure of the new transformer is composed of the twisted coils as shown in Fig.2.

B. Frequency characteristics

The coupling factor κ between the primary and secondary coils is defined by

$$\kappa = M/\sqrt{L_1 L_2}. \quad (12)$$

In order to realize a highly efficient transformer, as large as possible coupling factor κ is reasonable. Figure 3 shows the theoretical frequency characteristics of the coupling factor κ and self inductance $L(=L_1=L_2)$. When the operating frequency f is increased, the internal leakage inductances L_{i1} and L_{i2} become small due to the skin effect. Thereby, the self inductance L in Fig.3 becomes small at high frequency, and this improves the coupling factor κ. Thus, it is possible to expect a large coupling factor κ at the higher frequency range.

Further, at no load and high frequency conditions, this coupling factor κ coincides with the transformer ratio c defined by

$$c = \text{induced voltage/impressed voltage}. \quad (13)$$

Figure 4 shows the frequency characteristics of the coupling factor κ and the transformer ratio c. It must be noted in Fig.4 that the experimental values in the low frequency region are smaller than the theoretical ones because the currents are not symmetrically distributed with respect to each of their coil axes by the proximate effect. However, at high frequency, the skin effect forces the symmetrical current distribution, thereby, fairly good agreement can be observed at high frequency region in Fig.4. Furthermore, a resonance frequency can be observed on the experimental curve in Fig.4. This resonance may be caused by the capacitive effect between the coils. Our theoretical model did not take into account the capacitive effect so that a smooth curve appeared in Fig.4.

To examine the effects of coil diameter size, we constructed three different types of twisted coils. Types A, B and C are constructed by the coils having 0.8, 0.4 and 0.2 mm diameters, respectively. As shown in Fig.5, a significant skin effect occurs for the conductor having a large diameter (Type A) so that the transformer ratio c rises with frequency

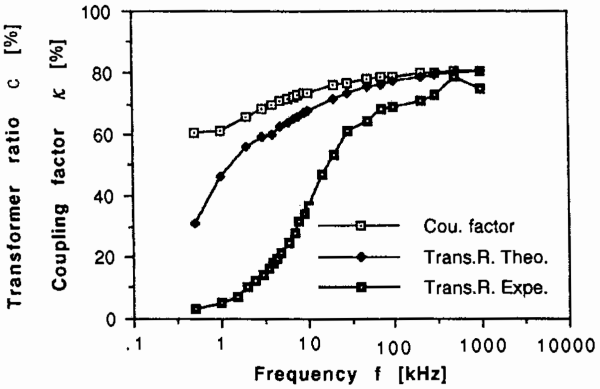
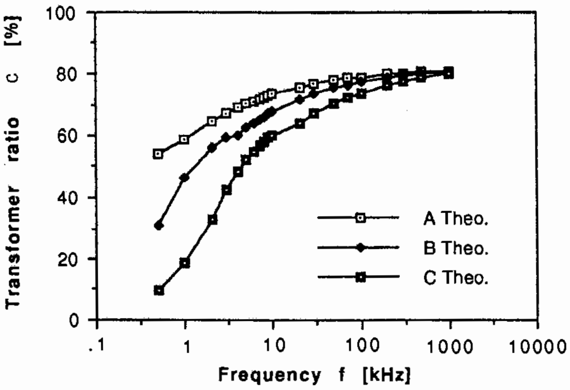
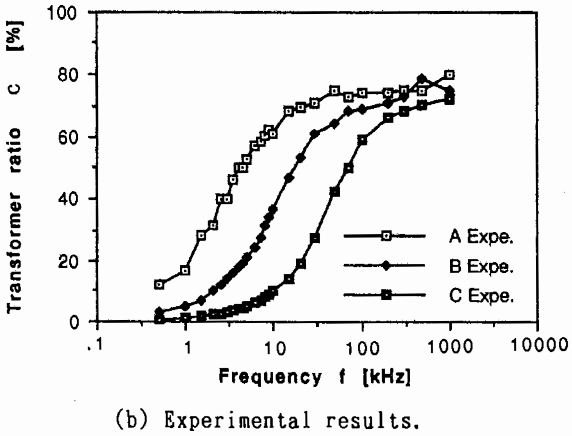


Figure 4. Frequency characteristics of the coupling factor κ and transformer ratio c. l_1=3[m], l_2=3[m], l_{1e}=2.7[m], l_{2e}=2.7[m], a=0.0004[m], b=0.0004[m] and material: copper wire.



(a) Theoretical results.



(b) Experimental results.

Figure 5. Effect of the coil diameter size. l_1=3[m], l_2=3[m], l_{1e}=2.7[m], l_{2e}=2.7[m], Type A: a=b=0.0008[m], Type B : a=b=0.0004[m], Type C: a=b=0.0002[m].

faster than the other types. On the other hand, the transformer ratio c of the twisted coils using the small diameter size rises slowly with frequency, but its theoretical upper limit is large. Also, Fig.5 shows that the theoretical model is valid only at the high frequency region.

The step up and down of the transformer ratio c can be carried out by changing the coil lengths l_{1e} and l_{2e} in (7) or (8). Figure 6 shows an example of the twice step up transformer. On the experimental curve in Fig.6, resonance frequencies are observed that are caused by the capacitive effects between the coils. Further, Fig.6 reveals that the theoretical values agree with the experimental ones in the high frequency region.

Finally, we examined the efficiency of the transformer theoretically. The efficiency ε of the transformer is defined by

$$\varepsilon = \text{output power/total input power.} \tag{14}$$

Figure 7 shows the typical frequency characteristics of the efficiency ε. The results in Fig.7 suggest that it is possibile to realize highly efficient coreless high frequency transformers even though the load and operating frequency conditions are limited. Also, Fig.7 shows that the optimum operating frequency depends on the load resistance R, and it moves to a higher frequency in accordance with the larger load resistance R.

Thus, a versatile new transformer using twisted coils can be realized with the coreless highly efficient transformer.

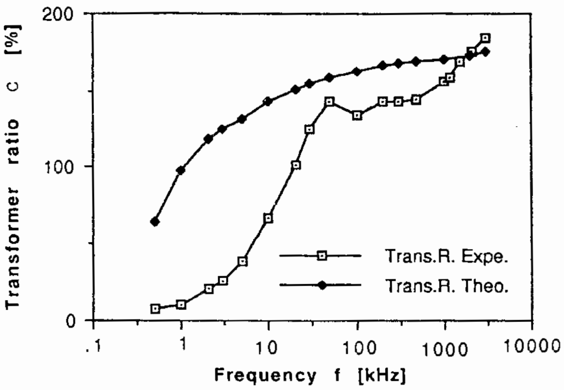


Figure 6. An example of the twice step up transformer. l_1=3.0[m], l_2=6.0[m], l_{1e}=2.7[m], l_{2e}=5.7[m], a=0.0004[m] and b=0.0004[m].

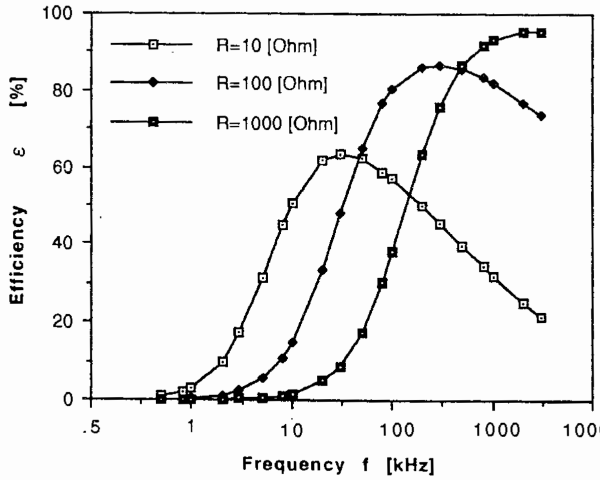


Figure 7. Typical theoretical frequency characteristics of the efficiency ε. l_1=4.0[m], l_2=4.0[m], l_{1e}=3.9[m], l_{2e}=3.9[m], a=b=0.0004[m]. Pure resistance load R.

III. CONCLUSION

As shown above, we have proposed a new type of coreless high frequency transformer that utilizes the flux enclosing the current carrying conductors. Approximate analysis based on the symmetrical current distributions in each of the coil axes has been applied to this new transformer. As a result, it has been clarified that the simple analytical model can be used to estimate a rough performance of the transformer. Several theoretical and experimental works have suggested that a versatile new type of transformer can be realized with a highly efficient coreless high frequency transformer.

REFERENCES

[1] K.Harada and T.Nabeshima,"Application of magnetic amplifier to high-frequency DC-to-DC converter," Proc. IEEE Vol.76, pp.353-361, April 1988.

[2] F.C.Lee, "High-frequency quasi-resonant converter technology, Proc. IEEE Vol. 76, pp.377-390 April 1988.

[3] S. Hayano, A. Miyazaki and Y.Saito, "Frequency characteristics of the complex permeability and its application to the FEM solutions of hysteretic fields," Journal of Applied Physics, Vol.69, No.8, IIA, pp.4838-4840, April 1991.

[4] K.Arai, H. Tsutsumitake and K.Ohmori, "Grain growth of rapid quenching high silicon-iron alloys," IEEE Trans. Magn., Vol. MAG-20, No.5, pp. 1463-1465, Sep. 1984

[5] R. V. Major, T. M. Jasko and K. J.Cruickshank, "Development of amorphous Fe-B based alloys for choke and inductor applications," IEEE Trans. Magn., Vol.MAG-20, No.5, pp.1415-1416, Sep. 1984.

[6] T.Sano, A.Morita, A.Matsukawa, " A new power ferrite for high frequency switching power supplies," Proceedings of the Third Annual High Frequency Power Conversion Conference, San Diego, CA, May 1-5, 1988.

[7] P. Silvester, Modern Electromagnetic Fields (Prentice-Hall,INC.,Englewood Cliffs, N.J. 1968).