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REALIZATION OF A CORELESS TRANSFORMER AND ITS APPLICATION TO A DC/DC CONVERTER

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In order to realize a compact size power supply, previously we have proposed a new type of coreless high frequency transformer whose operating principle is based on the skin effect in the current carrying conductors. In the present paper, the new transformer is applied to a fly back type DC/DC converter. As a result, over 80 % efficiency has been obtained. Thus, we have succeeded in realizing an ultimate compact and light weight DC power supply using the coreless transformer.

K e y w o r d s: high frequency transformer, DC power supply, DC/DC converter

1 INTRODUCTION

In order to realize the ultimate compact and light weight DC power supplies, it is essential to reduce the size of magnetic devices, e.g. reactors and transformers. One of the ways how to reduce the size of magnetic devices is to employ high frequency excitation [1]–[3]. However under such a high frequency exciting condition, we are confronted with a serious problem that the major performance of devices is limited by the frequency characteristics of core magnetic materials. To overcome this difficulty, new magnetic materials, such as amorphous and rapidly quenched magnetic materials, have been exploited and utilized [4]–[6]. Nevertheless it is difficult to avoid an essential increase of iron loss with the rise of operating frequency.

Another way to avoid the losses is to exploit a coreless transformer. Previously we had proposed a new coreless transformer. This new transformer is composed of simple twisted coils and its operating principle is based on the skin effect in the current carrying conductors [7]. In the present paper, this new transformer is now applied to a fly back type DC/DC converter. As a result, over 80 % efficiency has been obtained. Thus, we have succeeded in realizing an ultimate compact and light weight DC power supply using the coreless transformer.

2 A CORELESS TRANSFORMER

2.1 Basic equations

Figure 1(a) shows a typical conventional transformer which utilizes the magnetic flux linking the loop conductors, but the new transformer directly utilizes the magnetic flux enclosing the current carrying conductors as

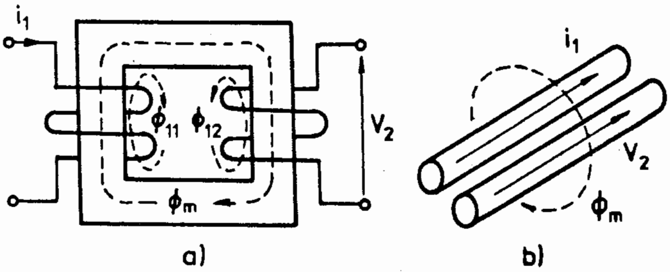

Fig. 1. Principle of transformer operation. (a) Conventional core type transformer and (b) new type transformer

shown in Fig 1(b). The DC resistance R_{D1} of the primary coil is given by

$$R_{D1} = \frac{\varrho l_1}{\pi a^2}, \qquad (1)$$

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

$$\frac{1}{R_{D1}}(R_{A1} + \mathrm{j}\omega L_{i1}) = \varkappa_1 \frac{a}{2} \frac{I_0(\varkappa_1 a)}{I_0'(\varkappa_1 a)}$$

where $\omega = 2\pi f$, and f – is frequency, $\mathrm{j} = \sqrt{-1}$, μ_0 – is permeability of air and $\varkappa_1 = a\sqrt{\omega\mu_0\pi/1\varrho}$, [7].

By means of (2) R_{A1} and L_{i1} are approximately given as

$$\varkappa_1 < 1, \qquad R_{A1} \sim R_{D1}\big(1 + \frac{1}{3}\varkappa_1^4\big) \qquad (3)$$

$$l_{I1} \sim \frac{1}{2}\mu_0 l_1 \big(1 - \frac{1}{6}\varkappa_1^4\big) \qquad (4)$$

$$\varkappa_1 \geq 1, \qquad R_{A1} \sim R_{D1}\big(\frac{1}{4} + \varkappa + \frac{1}{64}\varkappa_1^{-3}\big) \qquad (5)$$

$$l_{I1} \sim \frac{1}{2}\mu_0 l_1 \big(\varkappa_1^{-1} - \frac{1}{64}\varkappa_1^{-3}\big) \qquad (6)$$

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

At high frequencies, the currents in conductors may be forced to be distributed symmetrically 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

$$l_{1e} \leq l_{2e}, \qquad M = \frac{\mu_0}{2\pi} l_{2e} \left(\log \frac{2 l_{1e}}{a+b} - 1 \right), \tag{7}$$

$$l_{1e} > l_{2e}, \qquad M = \frac{\mu_0}{2\pi} l_{1e} \left(\log \frac{2 l_{2e}}{a+b} - 1 \right), \tag{8}$$

$$L_1 = L_{i1} + \frac{\mu_0}{2\pi} l_1 \left(\log \frac{2 l_1}{a} - 1 \right), \tag{9}$$

$$L_2 = L_{i2} + \frac{\mu_0}{2\pi} l_2 \left(\log \frac{2 l_2}{a} - 1 \right), \tag{10}$$

where l_{1e}, l_{2e}, l_2 and b are the effective length of primary coil, effective length of secondary coil, and radius of secondary coil, respectively. Figure 2(a) shows a practically constructed transformer having 14 mm thickness. As shown in Fig. 2(b), the primary and secondary coils of the transformer are twisted with each other to make the most of the skin effect phenomenon for the transformer coupling.

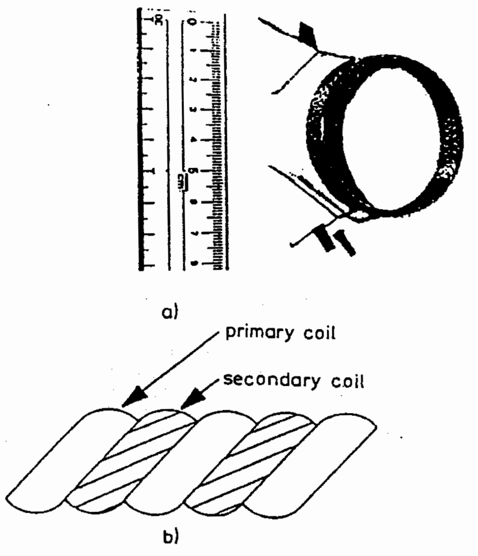

Fig. 2. Construction of the new transformer using the twisted coils. (a) A practically constructed coreless transformer $a = b = 0.0002$ m, $l_1 = l_2 = -3$ m, $R_{D1} = R_{D2} = 0.4\ \Omega$ at 25 deg, diameter = 0.053 m, thickness = 0.014 m, weight = 7;g, material: copper wire; and (b) schematic diagram of the twisted coils.

2.2 Frequency characteristics

The coupling factor $\varkappa$ between the primary and secondary coils is defined by

$$\varkappa = M / \sqrt{L_1 L_2}. \tag{11}$$

So as to realize a highly efficient transformer, the coupling factor $\varkappa$ should be as large as possible. Further, at no load and high frequency conditions, this coupling factor $\varkappa$ coincides with the transformer ratio c defined by

$$c = \frac{\text{induced secondary voltage}}{\text{impressed primary voltage}}. \tag{12}$$

Fig. 3 shows the frequency characteristics of the theoretical coupling factor $\varkappa$, transformer ratio c and experimental transformer ratio c'. 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 inductances L_1 and L_2 in (11) become small at the high frequency, and this improves the coupling factor $\varkappa$. Thus, it is possible to expect a large coupling factor $\varkappa$ at the higher frequency range. In Fig. 3, it must be noted that the experimental values of c' 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 the high frequency the skin effect forces the symmetrical current distributions. Further, because of the common magnetic flux (which corresponds to the main magnetic flux of conventional transformers, see Fig. 1(a) and Fig. 2(a))

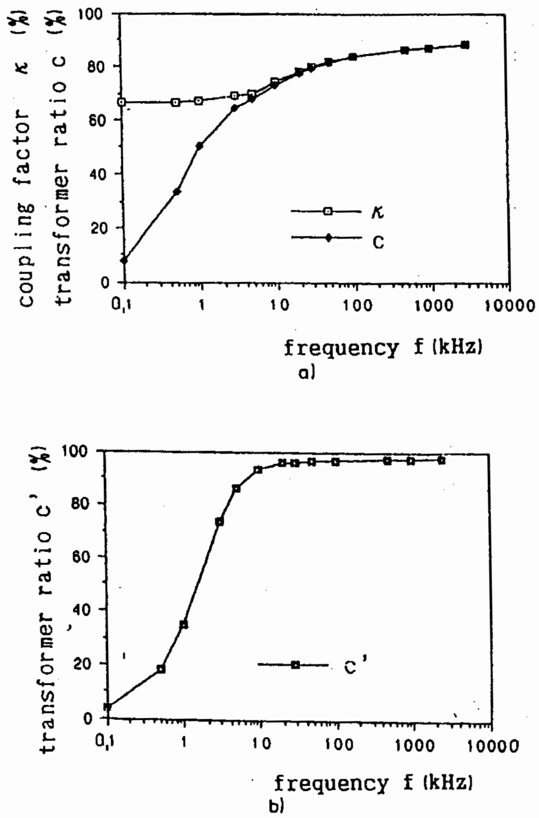

Fig. 3. Frequency characteristics of the theoretical coupling factor $\varkappa$, transformer ratio c, and experimental transformer ratio c'. $l_1 = l_2 = 3$ m, $l_{1e} = l_{2e} = 2.7$ m, $a = b = 0.0002$ m, material: copper wire. (a) Theoretical and (b) experimental.

linking the primary and secondary coils, experimentally higher couplings compared with theoretical ones can be observed at the high frequency region in Fig. 3.

The efficiency ε of the transformer is defined by

$$\varepsilon = \frac{\text{output power}}{\text{total input power}} . \tag{13}$$

Figures 4(a) and 4(b) show the theoretical and experimental frequency characteristics of the efficiency ε, respectively.

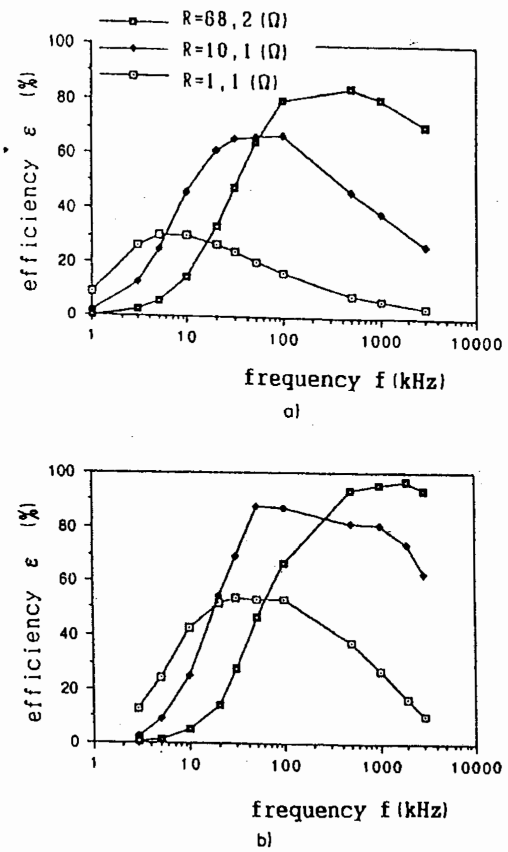

Fig. 4. Frequency characteristics of efficiency ε. $l_1 = l_2 = 3$ m, $l_{1e} = l_{2e} = 2.7$ m, $a = b = 0.0002$ m material: copper wire. (a) Theoretical and (b) experimental.

The results of Fig. 4 show that the optimum operating frequency depends on the load resistance R, and it moves to the higher frequency region with a larger load resistance R. Thus we have succeeded in realizing the highly efficient coreless high frequency transformer even though the load and operating frequency conditions are limited.

3 AN APPLICATION TO A DC/DC CONVERTER

Fly back type DC/DC converter

Figures 5(a) and 5(b) show the circuit diagrams of a fly back type DC/DC converter and of its equivalent circuit neglecting the leakage inductances of the transformer, respectively. One of the merits of this type of DC/DC

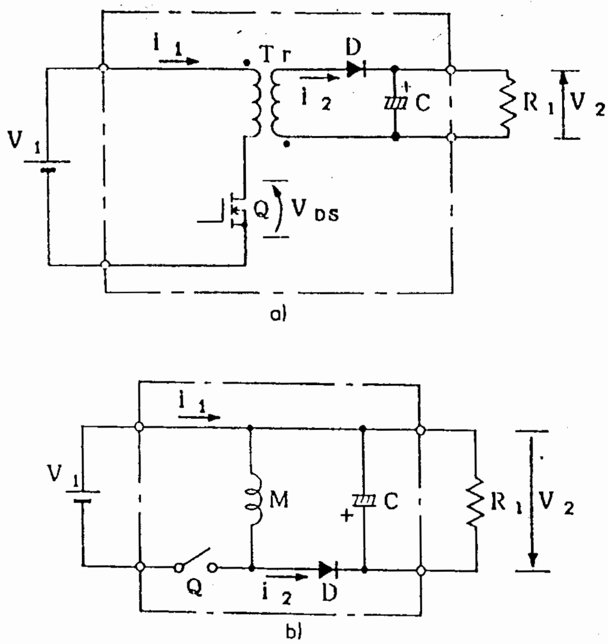

Fig. 5. A fly back type DC/DC converter and its equivalent circuit. (a) Circuit diagram (b) equivalent circuit.

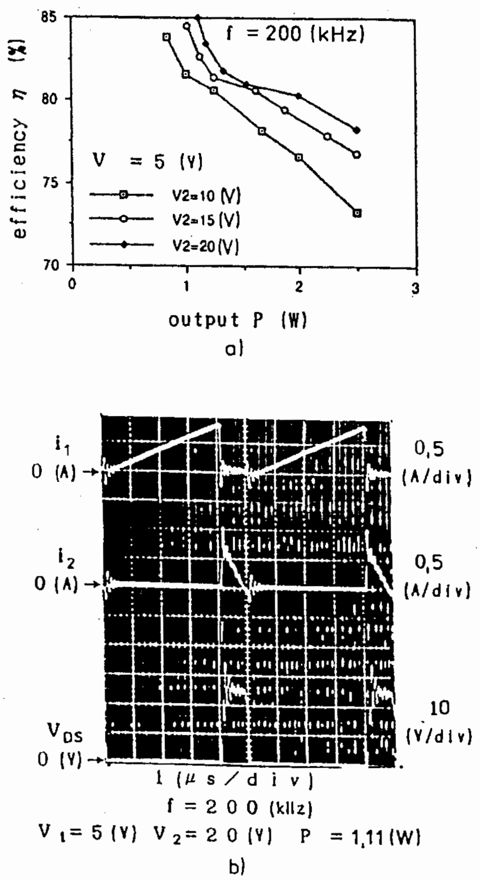

Fig. 6. Efficiency and operating waveforms of the fly back type DC/DC converter utilizing the coreless transformer shown in Fig. 2(a). (a) Efficiency for different load conditions at $f = 200$ kHz, (b) operating waveforms at the maximum efficiency. $V_1 = -5$ V, $V_2 = 20$ V, $P = 0.8$ W and $f = 200$ kHz.

converter is that the number of parts is less than in the previous operating type. The operating principle of this converter is as follows. When the power MOS–FET Q in Fig. 5(a) is on-state, then the magnetic energy is stored in the mutual inductance M in Fig. 5(b) by the primary current i_1. Subsequently this energy is transferred to the secondary circuit by the current i_2 while the power MOS–FET Q is off-state. Thereby, the switching operation of the power MOS–FET Q makes it possible to transfer the primary DC power to the secondary load. Moreover, the mutual inductance being as small as possible is preferable for obtaining a high power transferring from the primary to secondary circuits because the current i_1 fed from the voltage source V_1 becomes large. In this sense, the coreless transformer is suitable for a fly back type DC/DC converter because no magnetic material is used in the transformer.

The efficiency η of this converter is defined by

$$\eta = \frac{V_2^2/R_1}{V_1(f\int_0^{1/f} i_1 \mathrm{d}t)}. \tag{14}$$

Fig. 6 shows the efficiency and operating waveforms of the fly back type DC/DC converter utilizing the coreless transformer shown in Fig. 2(a). The experimental results shown in Fig. 6 demonstrate that over 80 percent efficiency can be obtained by means of our coreless transformer. This means that the ultimate compact size and lightest weight DC power suppliers have been realized by the coreless transformer.

4 CONCLUSION

As shown above, we have succeeded in realizing the new type of coreless high frequency transformer with high efficiency. Further, we have demonstrated that the ultimate compact and lightest weight fly back type DC/DC converter having high power transfer efficiency can be exploited by utilizing the coreless transformer.

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