Design and Analysis of Noise–Reduction Transformer Based on Equivalent Circuit

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***Abstract* — The present paper deals with the analysis of noise-reduction transformer that has a filter function for conductive noise transmission. A simple structured prototype transformer utilizing C-cores is prepared. To determine an optimum design for the noise-reduction transformer, noise attenuation of this transformer is discussed based on the equivalent circuit analysis. The analysis gives a quantitative relation between the circuit parameters and the noise attenuation. High performance noise-reduction transformer that has noise attenuation of -80 dB for a power supply unit of digital devices is developed.**

***Index Terms* — Transformer, Conductive noise, Noise attenuation, EMI, EMC.**

I. INTRODUCTION

AMBIENT electric noise or electromagnetic interference causes malfunction of electric, electronic and information equipments including digital devices [1]. Conductive noise, *e.g.* electric surge noise and lightning stroke, is eliminated by noise filtering elements or surge absorbers [2]. Since most of the conductive noise transmits through the power grid, it is effective if the power supply unit has a suitable noise filter to prevent the conductive noise transmission. Several types of noise-reduction transformers that are used exclusively for noise elimination have been turned into commercial products [3]. For designing such transformers, not only noise attenuation characteristics but performance as a power transformer should be considered. Few papers, however, have reported the optimum design and the noise attenuation mechanism with quantitative analysis.

In this paper, we prepare a simple structured prototype transformer that utilizes C-cores. To determine a method for the optimum design of the noise-reduction transformer, noise attenuation of this transformer is quantitatively discussed based on the equivalent circuit analysis. Then a high performance noise-reduction transformer for a power supply unit of digital devices such as personal computers and electronic switching systems for telephone exchange is presented.

II. NOISE ATTENUATION MECHANISM OF TRANSFORMER

A. Structure of Prototype Transformer

For the equivalent circuit analysis, we prepare simple structured prototype transformer (PTT) that has no electromagnetic shields and filtering elements for conductive noise elimination. Fig. 1(a) shows dimensions of silicon steel C-cores used in the PTT, and Fig. 1(b) illustrates a schematic diagram of the PTT. The rating of the PTT is 50 VA, and the input and the output voltages are 100 V.

Fig. 2 gives frequency characteristics of apparent relative permeability of the C-cores used in the PTT and that of silicon steel EI-Cores used in the conventional power transformer. At low frequencies, the permeability of the C-cores is higher than that of the EI-cores, and the permeability decreases with frequency increasing. At high frequencies, the permeability of both cores is approximately equal. Frequency characteristics of distributed capacitance between the primary and secondary windings were measured. In this experiment, each terminal of windings is shorted and shorted terminals are connected to an impedance analyzer. The distributed capacitance of the PTT is 20 pF, which is one-seventh of the typical conventional power transformer.

To prevent the conductive noise transmission, the noise-reduction transformer requires some features [4]. If C-cores are used, it is easy to construct a suitable structure preventing the noise transmission.

B. Equivalent Circuit of the Transformer

Conductive noise includes various frequency spectra. Therefore, frequency characteristics of noise attenuation are discussed based on the equivalent circuit analysis.

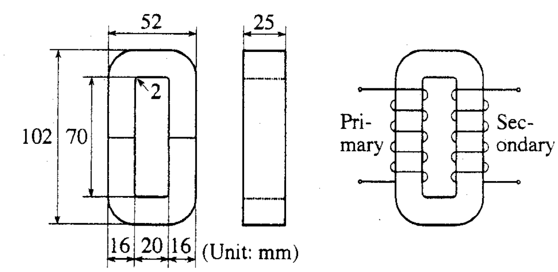

Fig. 1(a). Dimensions of a magnetic core. Fig. 1(b). Schematic diagram.

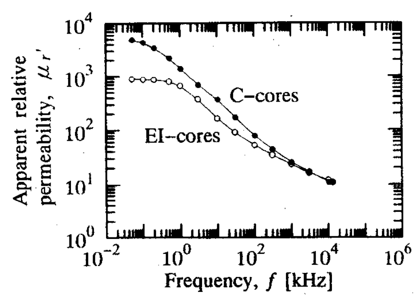

Fig. 2. Frequency characteristics of apparent relative permeability.

Manuscript received October 13, 1997.
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Fig. 3 is a normal mode equivalent circuit of the PTT. In the figure, r_1 and r_2 are winding resistances, L_1 and L_2 are leakage inductances, R_f represents equivalent iron loss resistance of the core, and L_f is the exciting inductance of the core. C_w is the distributed capacitance between the primary and the secondary windings. C_1 and C_2 are stray capacitances of each winding, respectively.

Noise attenuation α is defined as a ratio of the input voltage V_1 to the output V_2 in dB. By using four terminal network A, B, C and D, the input and the output relation at no-load is given by $V_1 = A\ V_2$. Thus noise attenuation is

$$\alpha = 20\log_{10} |V_2/V_1| \quad [\text{dB}], \tag{1}$$

$$\alpha = 20\log_{10} |1/A| \quad [\text{dB}]. \tag{2}$$

Table I lists the circuit constants of the PTT. In order to estimate the stray capacitance, both resonance frequency and frequency characteristics of self-inductance of the primary and secondary windings without the magnetic core were measured. Based on the results, the stray capacitance of each winding can be obtained. Although the most of circuit parameters in Fig. 3 are frequency dependent, frequency characteristics of the circuit parameters have not been considered in the analysis. Fig. 4 shows normal mode noise attenuation characteristics of the PTT. In the figure, black circle is experimental result. In the experiment, a sinusoidal voltage is applied to the primary, and output voltage is measured. As shown in Fig. 4, both noise attenuation characteristics keep the initial attenuation of 0 dB at frequency range lower than 30 kHz. After 30 kHz, the noise attenuation sharply increases. Over 300 kHz, experimental result has many resonance points. Calculated result has no resonance points because the effect of line impedance is neglected in the calculation. The main reason for the errors between calculation and measurement results is that the frequency characteristics of circuit parameters are ignored in the analysis.

C. Analysis of Noise Attenuation

Because various filters can be made by combination of any circuit element, it is important to clarify the influence of the noise attenuation mechanism on variety of circuit parameters. Circuit parameters are depend on both structure and rating of the transformer, the parameters, however, are dependent variables in the calculation.

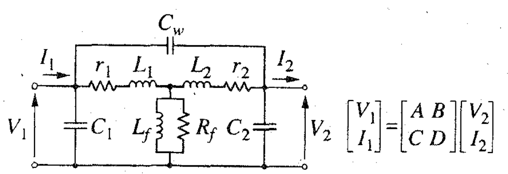

Fig. 3. Normal mode equivalent circuit.

TABLE I
PARAMETERS OF THE EQUIVALENT CIRCUIT.
(FREQUENCY IS 50 Hz.)

r_1 [Ω]	r_2 [Ω]	L_1 [mH]	L_2 [mH]	R_f [kΩ]	L_f [H]	C_1 [pF]	C_2 [pF]	C_w [pF]
7.93	7.80	40.4	39.8	13.9	10.3	358	358	20.0

Fig. 5(a) is the calculation result of frequency characteristics of the PTT with various primary winding resistances. Fig. 5(b) is frequency characteristics with various exciting inductances. At low frequencies, the noise attenuation increases with either the winding resistance increasing or the exciting inductance decreasing. These circuit elements make a kind of high pass filter, and the filter prevents commercial voltage transmission. In case of the PTT, the winding resistance must be smaller than 20 Ω, and the exciting inductance must be more than 3 H.

Fig. 6 is frequency characteristics with various equivalent iron loss resistances. This reveals that when the equivalent iron loss resistance exceeds 10 kΩ, maximal attenuation tends to increase, and noise amplification occurs.

Fig. 7 shows noise attenuation characteristics with various secondary leakage inductances. As the leakage inductance is decreasing, maximal attenuation is increasing and cutoff frequency shifts to high frequency range. When the inductance is less than 10 mH, no noise amplification could

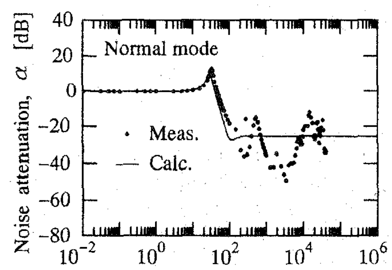

Fig. 4. Normal mode noise attenuation characteristics of the PTT.

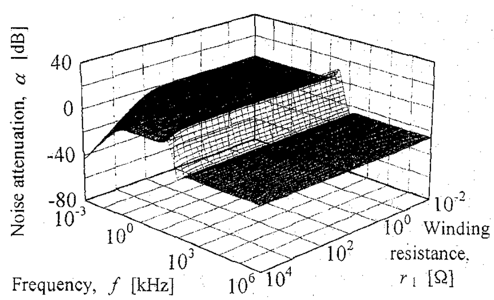

Fig. 5(a). Calculations of frequency characteristics of the PTT with various primary winding resistances.

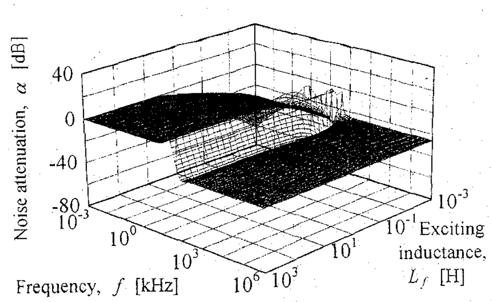

Fig. 5(b). Calculations of frequency characteristics of the PTT with various exciting inductances.

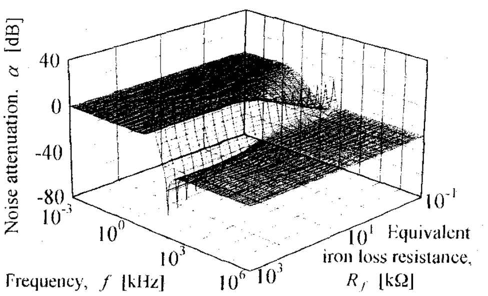

Fig. 6. Calculations of frequency characteristics of the PTT with various equivalent iron loss resistances.

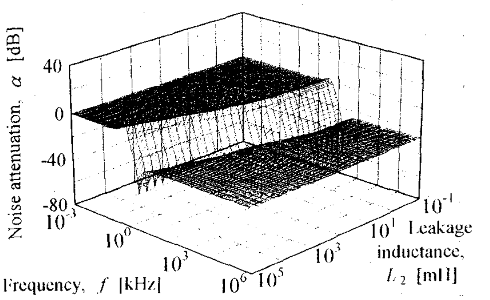

Fig. 7. Calculations of frequency characteristics of the PTT with various secondary leakage inductances.

be found. The leakage inductance and the stray capacitance of the secondary winding make a kind of low pass filter, and it will be able to eliminate the high frequency noise. In order to get good noise attenuation characteristics, the leakage inductance should be low and filtering capacitance should be connected parallel to secondary winding.

III. High Performance Noise-Reduction Transformer

We proposed a noise-reduction transformer (NRT) for a power supply unit of digital devices. Fig. 8(a) shows the magnetic core dimensions, and illustrates a schematic diagram. C-cores that consist of silicon steel sheets were used. The silicon steel sheets contain grain oriented 3 % silicon, and thickness of a piece of sheet is 0.3 mm. Fig. 8(b) shows an appearance of the NRT. The structural features of the NRT are: (1) Primary and secondary windings are separated to reduce the distributed capacitance, and to decrease the magnetic coupling without core; (2) Grounded aluminum plate is inserted into each winding for electromagnetic shield; (3) Filtering capacitance of 0.033 μF is connected to the secondary winding. The input and the output voltages are 100 V, and the maximum output power is 30 VA. The voltage regulation at resistive load is 9 %, the efficiency is over 90 %, and input power factor is 98 %.

Fig. 9 shows noise attenuation characteristics of the NRT. Network analyzer with line impedance stabilizing network was used in measurements to isolate the line impedance from affecting measurement results. This figure reveals that normal mode noise attenuation sharply increases after 1 kHz, and maximal noise attenuation is -80 dB. Common mode noise attenuation exceeds -80 dB over a wide frequency range. The NRT is an efficient noise attenuator.

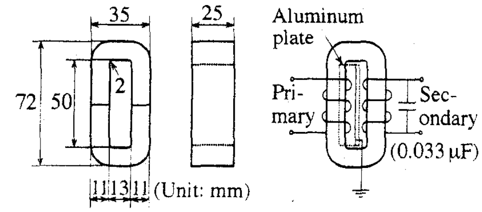

Fig. 8(a). Magnetic core dimensions and schematic diagram.

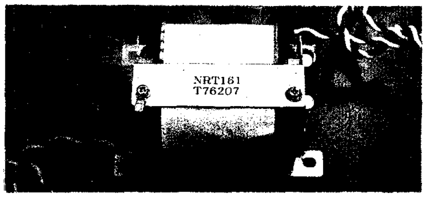

Fig. 8(b). Appearance of the NRT.

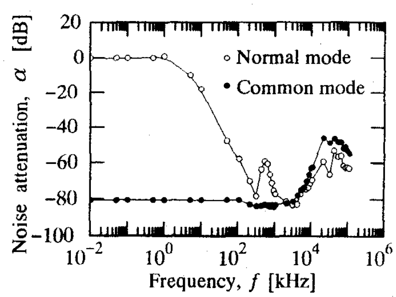

Fig. 9. Noise attenuation characteristics of the NRT.

IV. Conclusions

The equivalent circuit analysis and high performance NRT have been presented. The analysis gives a quantitative relation between the circuit parameters and the noise attenuation. It is possible to design noise-reduction transformers which have total high performance through a suitable combination of the circuit parameter. The NRT has excellent noise attenuation characteristics, and it has good potential in practical application. As a feature work, we will determine an optimum design of various ratings and uses noise-reduction transformers with considering common mode noise attenuation characteristics.

Acknowledgment

The authors gratefully thank Taiyo Electronics Co. Ltd. Development of the NRT is the joint research with Taiyo Electronics Co. Ltd.

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