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Analysis and Performance Evaluation of Noise-Reduction Transformer

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Abstract**—**The present paper deals with the analysis and development of noise-reduction transformer that has a filter function for conductive noise transmission. Two types of prototype noise-reduction transformers with two different output voltages are proposed. To determine an optimum design for the noise-reduction transformer, noise attenuation characteristics are discussed based on the experiments and the equivalent circuit analysis. The analysis gives a relation between the circuit parameters and the noise attenuation. High performance step-down noise-reduction transformer for direct power supply to electronics equipment is developed. The input voltage of the transformer is 100 V and the output voltage is 5 V. Frequency characteristics of noise attenuation are discussed, and prevention of pulse noise transmission is demonstrated. Normal mode noise attenuation of this transformer is –80 dB, and common mode exceeds –90 dB. The step-down noise-reduction transformer eliminates pulse noise efficiently.

Keywords**—**conductive noise, EMC, EMI, noise attenuation, transformer.

I. Introduction

ELECTROMAGNETIC interference or ambient electric noise causes malfunction of electric, electronic and information equipment including digital devices. Therefore, electromagnetic compatibility has been gaining broad interest and many aspects of this field have been widely researched [1]–[3].

Conductive noise, e.g., electric surge noise or lightning stroke, is eliminated by noise filtering elements and surge absorbers [4], [5]. 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. For example, the parametric transformer [6], [7] and the constant voltage transformer [8] are useful for the noise filter. In recent, several types of noise-reduction transformers [9]–[12] that are used exclusively for noise elimination have been turned into commercial products.

Most of the noise-reduction transformers normally have input voltage of commercial power of ranging from 100 V to 240 V, and the secondary voltage of the transformers is equal to the primary voltage. However, many electronics equipment especially digital circuits operate under low voltage such as 5 V or 3 V. For designing the noise-reduction transformers, not only noise attenuation characteristics but performance as a power transformer should be considered. Few papers have reported the optimum design and the noise attenuation mechanism with quantitative analysis.

In this paper, we propose two types of prototype noise-reduction transformers with a rating of 50 VA. In order to determine a method for the optimum design of the noise-reduction transformers, the noise attenuation mechanism and characteristics of these transformers are quantitatively discussed based on the experiments and the equivalent circuit analysis. Then a high performance step-down noise-reduction transformer for a power supply unit of digital devices is presented.

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II. Structure and Basic Characteristics

A. Structure of the Transformer

To prevent the conductive noise transmission, the noise-reduction transformer requires such features: (1) Apparent relative permeability of the magnetic core should be low at high frequency range; (2) Magnetic coupling between primary and secondary windings without main flux should be low; (3) Distributed capacitance between primary and secondary windings must be low.

We prepared two types of prototype noise-reduction transformer with two different output voltages. Fig. 1(a) shows the magnetic core dimensions used in the prototype noise-reduction transformers. We used C-cores that consists of silicon steel sheets. The silicon steel sheets contain grain oriented 3 % silicon, and thickness of a piece of sheet is 0.3 mm. Fig. 1(b) illustrates a schematic diagram of the prototype noise-reduction transformer. As shown in this figure, primary and secondary windings are separated to reduce distributed capacitance, and to decrease the magnetic coupling without core. The ratings of two samples are 50 VA. The input voltage for sample #1 and #2 are 100 V. The output voltage for #1 is 100 V, and for #2 5 V. The number of primary windings for both samples are 800 turns. The number of secondary winding for #1 is 800 turns, and #2 40 turns. Fig. 2 shows load characteristics. Table I lists the voltage regulation ε at resistive load, efficiency η and input power factor PF_1 for resistive loads.

B. Frequency Characteristics of Noise Attenuation

Conductive noise includes various frequency spectra. Therefore, frequency characteristics of noise attenuation are measured. In this experiment, output voltage is measured with loaded pure resistive load 50 Ω, and a sinusoidal voltage, ranging from 10 Hz to 50 MHz, is applied to the primary. The noise attenuation α [dB] is defined as:

$$\alpha = 20\log_{10}\left|\frac{V_2}{V_1}\right| \text{ [dB]}, \qquad (1)$$

where V_1 is the input voltage and V_2 is the output voltage.

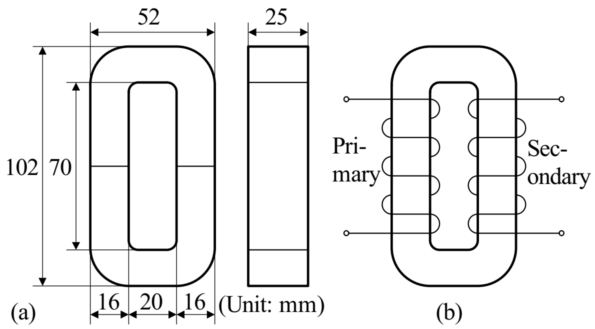


Fig. 1(a) Dimensions of magnetic core. Fig. 1(b) Schematic diagram.

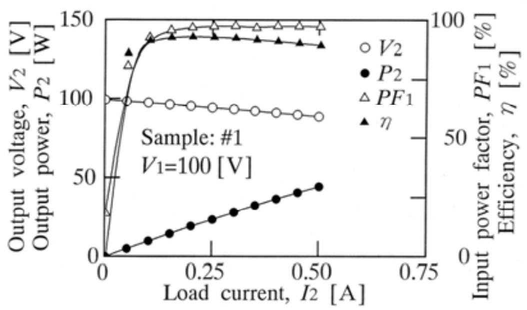


Fig. 2(a) Load characteristics of sample #1.

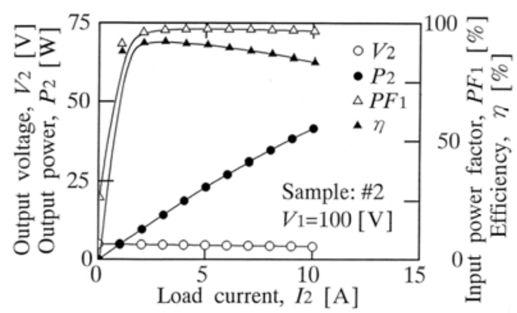


Fig. 2(b) Load characteristics of sample #2.

TABLE I
PERFORMANCE OF THE LOAD CHARACTERISTICS AT RESISTIVE LOAD.
(POWER FACTOR OF THE LOAD IS 1.0.)

	Voltage regulation ε [%]	Efficiency η [%]	Input power factor PF_1 [%]
#1	11.9	89.2	97.2
#2	19.7	83.5	97.6

Fig. 3 shows the measurement method. In case of the common mode, the terminals of each winding are short circuited, and a sinusoidal voltage is applied between the short circuited terminal and the ground.

Fig. 4(a) is the normal mode noise attenuation characteristics of the prototype noise-reduction transformer, and Fig. 4(b) is the common mode noise attenuation characteristics. As shown in Fig. 4(a), noise attenuation for sample #1 has a peak point at 30 kHz and increases sharply above this frequency. Over 300 kHz, there are many resonance points. Sample #2 keeps the initial attenuation of –26 dB lower than 1 MHz. Fig. 4(b) indicates that common mode noise attenuation decreases gradually, and it becomes constant until 10 MHz.

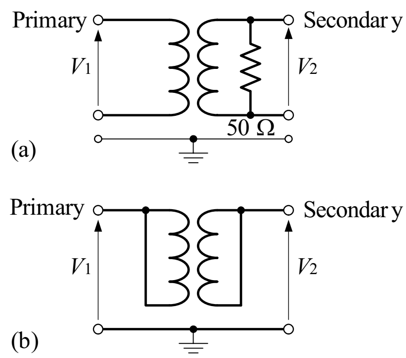


Fig. 3 Measurement method of noise attenuation.
(a) Normal mode. (b) Common mode.

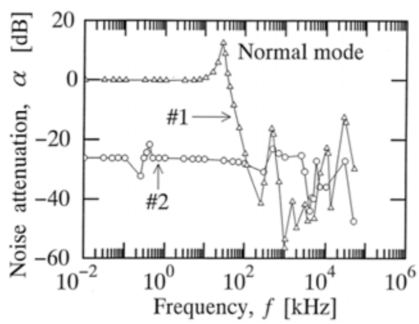


Fig. 4(a) Frequency characteristics of normal mode noise attenuation.

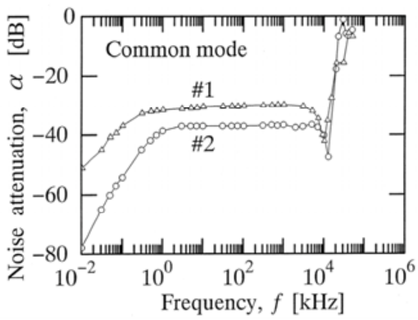


Fig. 4(b) Frequency characteristics of common mode noise attenuation.

Fig. 5 shows frequency characteristics of distributed capacitance between the primary and secondary windings, and equivalent circuit of the distributed capacitance. In this experiment, each terminal of windings is shorted and shorted terminals are connected to an impedance analyzer. This figure shows that distributed capacitance of sample #1 is larger than sample #2. It means that sample #1 transmits common mode noise more easily compared to sample #2.

III. Equivalent Circuit Analysis

A. Equivalent Circuit of the Transformer

Frequency characteristics of noise attenuation are discussed based on the equivalent circuit analysis. Fig. 6(a) is a normal mode equivalent circuit of the prototype transformer, and Fig. 6(b) is four terminal network of the transformer. In the figure, I_1 is input current and I_2 is output current. 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. By using four terminal network A, B, C, and D, the input and the output relation is given by

$$V_1 = AV_2 + BI_2 . \qquad (2)$$

Noise attenuation can be obtained as follows:

$$\alpha = -20\log_{10}\left| A + \frac{B}{Z} \right| \text{ [dB]} . \qquad (3)$$

Here Z is load impedance. The parameters of A and B are given by

$$\begin{cases} A = \dfrac{K_1 + j\omega\left(C_2 + C_w\right)K_2}{1 + j\omega C_w K_2} \\ B = \dfrac{K_2}{1 + j\omega C_w K_2} \end{cases} ,$$

$$\text{where } \begin{cases} K_1 = 1 + \dfrac{R_1 + j\omega L_1}{R_f} - j\dfrac{R_1 - j\omega L_1}{\omega L_f} \\ K_2 = \left(R_1 + R_2\right) + j\omega\left(L_1 + K_1 L_2\right) \end{cases} . \qquad (4)$$

Table II lists the circuit constants of the prototype noise-reduction transformers. 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 of the equivalent circuit are frequency dependent, frequency characteristics of the circuit parameters have not been considered in the analysis.

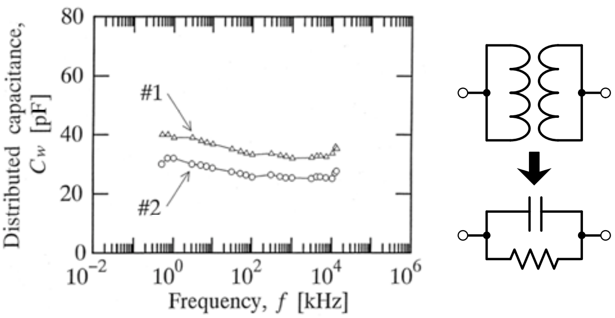


Fig. 5 Frequency characteristics of distributed capacitance between the primary and secondary windings.

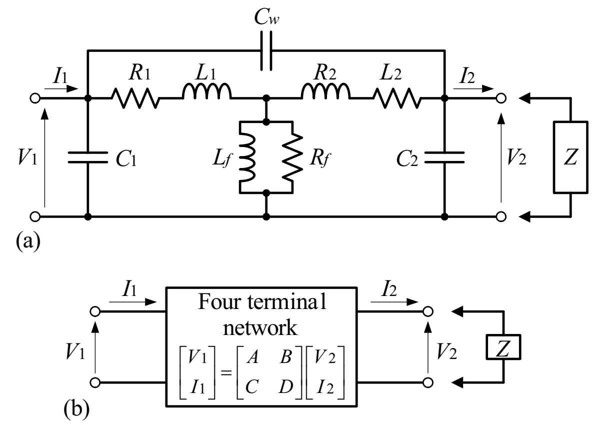


Fig. 6 Equivalent circuit of the transformer.
(a) Normal mode equivalent circuit. (b) Four terminal network.

TABLE II
Parameters of the Equivalent Circuit.
(Frequency is 50 Hz.)

		#1	#2 *
Winding resistances	R_1 [Ω]	7.9	3.5
	R_2 [Ω]	7.8	26
Leakage inductances	L_1 [mH]	40	9.8
	L_2 [mH]	40	73
Equivalent iron loss resistance	R_f [Ω]	14	13
Exciting inductance	L_f [mH]	10	10
Stray capacitances	C_1 [pF]	360	270
	C_2 [pF]	360	0.14
Distributed capacitance	C_w [pF]	40	30

* The circuit parameters of R_2, L_2 and C_2 are transferred to the primary side using the impedance reflection technique.

B. Calculations of the Noise Attenuation

Fig. 7 is a comparison of measured and calculated noise attenuation of sample #1. As shown in this figure, 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.

IV. Step-Down Noise-Reduction Transformer

A. Performance of the Transformer

Many electronics equipment especially digital circuits operate under low voltages such as 5 V or 3 V. It is effective that the transformers of the power supply units have a suitable performance efficiency to reduce the conductive noise transmission. We propose a step-down noise-reduction transformer for a power supply unit of digital devices.

Normal mode noise is eliminated by the filter constructed with leakage inductance and stray capacitance. If the filter capacitance connected parallel to the secondary, it thought that we can get more noise attenuation. Normal mode noise attenuation characteristics with various filter capacitances C_f are calculated based on the equivalent circuit. Fig. 8(a) is calculated results of normal mode noise attenuation. This reveals that noise attenuation increases when filter capacitance is increased. Fig. 8(b) is the measured frequency characteristics of the noise attenuation. The experiment shows that the maximal noise attenuation is not proportional to the capacitance. Higher than 1 MHz, the noise attenuation diminishes right down to the initial level.

Fig. 9 is the noise attenuation characteristics of the step-down noise-reduction transformer. Filtering capacitance of 0.1 μF is connected to the secondary winding. This figure reveals that when the filter capacitance is connected, maximal normal mode noise attenuation is –80 dB at 1 MHz and the common mode exceeds –90 dB over a wide frequency range.

B. Prevention of Pulse Noise Transmission

Fig. 10 shows the shame of measurement system for pulse noise prevention, and one example of full-wave bridge rectification circuit used in a power supply unit for electronics circuits. Pulse voltage of pulse width is 1 μs is superimposed on the sinusoidal supply voltage with r.m.s. value of 100 V and frequency of 50 Hz, and is applied to the primary winding of the step-down noise-reduction transformer.

Fig. 11 is one example of the observed waveforms when the pulse voltage is set up to 300 V. There are several reasons for the pulse waveform distortion as shown in Fig. 11(a). One is the saturation effect on the core, and another reason is effect of charging and discharging for the filtering capacitances. The saturation effect, however, is less than filtering capacitance effect, because the pulse width of 1 μs is very short period as compared to fundamental wave cycle of 20 ms. These figures indicate that the step-down transformer eliminates pulse noise efficiently.

Fig. 12 shows measured results of the noise attenuation versus the load current. In this figure, vertical axis α is calculated by (1), by substitute V_{1p} into V_1, and V_{2pD} into V_2. The

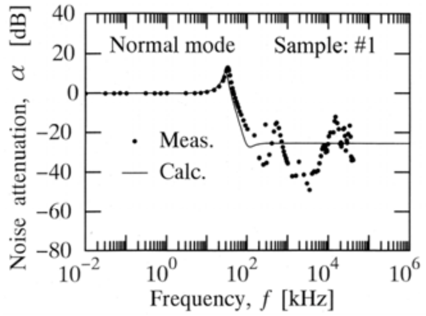
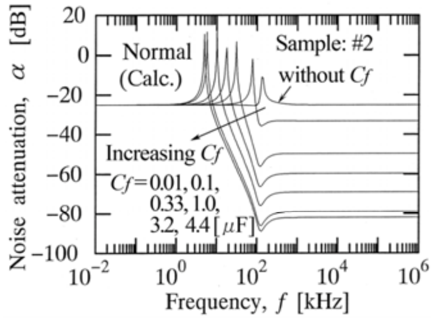
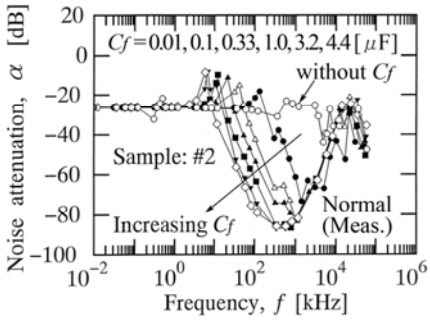


Fig. 7 Normal mode noise attenuation characteristics.



(a) Calculations.



(b) Measurements.

Fig. 8 Normal mode noise attenuation characteristics with various flittering capacitances.

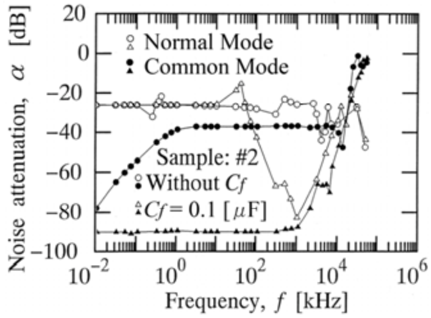


Fig. 9 Measured results of normal mode and common mode noise attenuation characteristics.

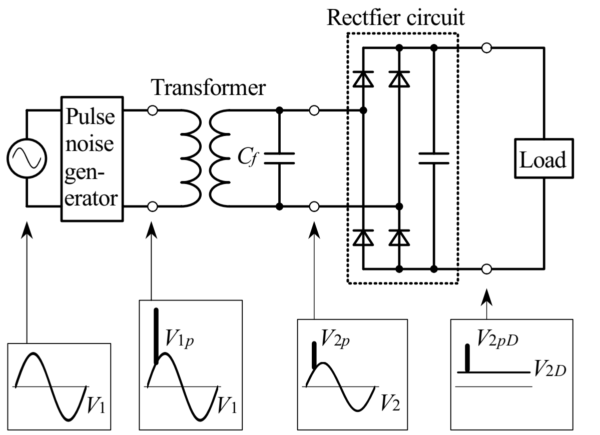
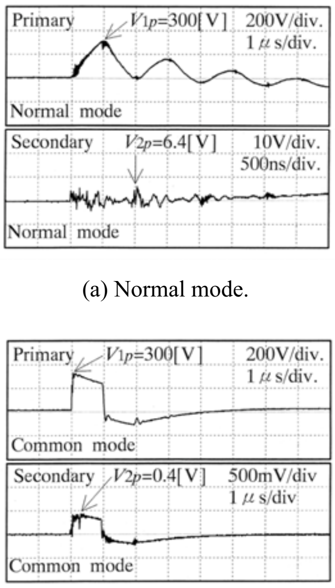


Fig. 10 Shame of measurement system for pulse noise prevention.



(a) Normal mode.

(b) Common mode.

Fig. 11 Observed waveforms.

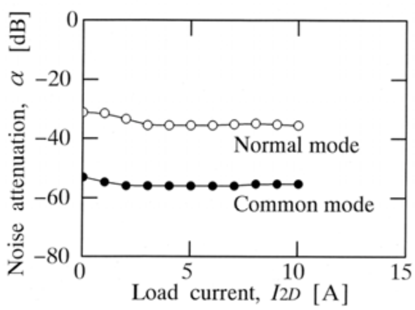


Fig. 12 Measurement results of noise attenuation characteristics due to load current.

experiments reveal that maximal normal mode noise attenuation is about –32 dB, and common mode is –52 dB. Although the noise attenuation slightly increases with the load current increasing, the noise attenuation is almost constant after 3 A. The step-down noise-reduction transformer is an efficient noise attenuator.

V. Conclusion

The equivalent circuit analysis and high performance step-down noise-reduction transformer have been presented. The equivalent circuit is useful for calculating the noise attenuation. The analysis gives a relation between the circuit parameters and the noise attenuation. It is also effective in estimating the value of optimum circuit parameters to get the maximal noise attenuation with the frequency dependency of the circuit parameters considered. The maximal normal mode noise attenuation of the step-down noise-reduction transformer is –80 dB, and common mode noise attenuation exceeds –90 dB over a wide frequency range. The step-down noise-reduction transformer eliminates pulse noise efficiently. The transformer has excellent noise attenuation characteristics, and it has good potential in practical application.

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