Modeling of Conduction EMI Noise and Technology for Noise Reduction

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1. Introduction

With the recent advances in high-speed power se miconductor devices, the trends toward increased carrier frequencies and smaller-size inverters are advancing. High-frequency switching, however, is associated with the problem of high-frequency leakage current flowing through the stray capacitance of the motor windings to the grounding wire and the problem of EMI (electromagnetic interference). The following three methods are being considered for reducing conduction noise which is a problem in the frequency range of 150 kHz to 30 MHz.

(a) Passive method[1]: Configured from passive components only. The leakage current is suppressed by inserting passive filter in the common-mode current path. This method has the disadvantages, however, of not enabling a reduction in coil size and of requiring a motor neutral point.

(b) Active EMI filter[2]: Injects current having an opposite phase from that of the control current source in order to cancel the leakage current to the power supply. When a long cable is used, this method has the disadvantages of a large leakage current and of requiring large components for grounding.

(c) Active common noise canceller[3]: Superimposes a voltage from the control voltage source that is opposite the common-mode voltage in order to cancel the common-mode voltage. This method has the disadvantages of a large transformer size due to 2-arm modulation. Because the stray capacitance of the heat sink is not considered, the inability to completely prevent noise from entering the power source.

A reduction in size of the conduction EMI filter is difficult to achieve, with the passive method and the active EMI filter method. Fuji Electric's research focused on the active common-mode canceller, and an improved low voltage-type and small size active filter was devised.

Meanwhile, advances in computer technology and simulation technology have enabled realistic modeling of conduction noise and the highly accurate prediction of noise levels[4], [5]. As a result, various analyses and noise suppression methods can be considered within a short time.

This paper describes the modeling of conduction noise, the simulation-based analysis of noise reduction technologies, and experimental results of the noise reduction effect in improved active common-mode canceller.

2. Modeling of Conduction EMI Noise

2.1 Measurement of common-mode leakage current

Figure 1 shows the flow path of common-mode leakage current in the motor drive inverter system. The common-mode leakage current can be categorized as motor leakage current, module leakage current through a copper base, leakage current through a grounding capacitor, and power source (line impedance stabilization network: LISN) leakage current. In this research, a

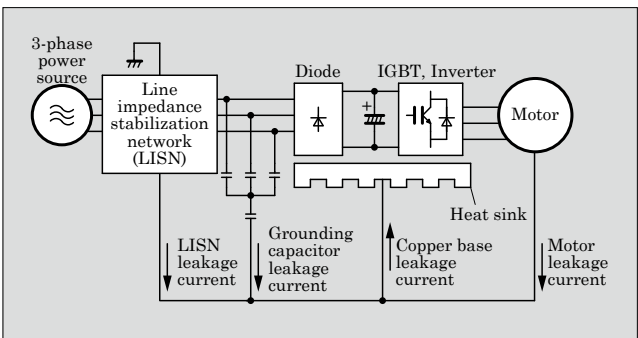Fig.1 Block diagram of measurement circuit for conduction EMI noise

Table 1 Test conditions and test equipment

IGBT module	6MBI75U2A-060
Motor	2.2 kW, 200 V
Cable between IGBT and motor	2 mm^2, 10 m
DC bus voltage	140 V or 280 V
LISN	Kyoritsu Corp. KNW-243C
Spectrum analyzer	Advantest R3261

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15 kW/200 V inverter system was simulated, and the leakage current was measured with a chopper circuit using Fuji Electric's IGBT module 6MBI75U2A-060. A 200 V, 2.2 kW motor was used as the load.

Table 1 lists the test conditions and the test equipment used for measuring the common-mode leakage current. Under the conditions specified in Table 1, the common-mode leakage current waveform was measured for a switching operation, and a high frequency equivalent circuit was derived from the resonant frequency of each current waveform.

2.2 Modeling of motor leakage current

Figure 2 shows actually measured leakage current waveforms for a DC bus voltage of 140 V.

An equivalent circuit for the high-frequency leakage current can be expressed with an LCR series resonant circuit. The equivalent circuit of the leakage current can be considered to be configured as two LCR series resonant circuits connected in parallel as shown in Fig. 3. The L and C values in the resonant circuit can be determined from the natural resonance angular frequency ω_n and the characteristic impedance Z_0 ac-

cording to the following formulas.
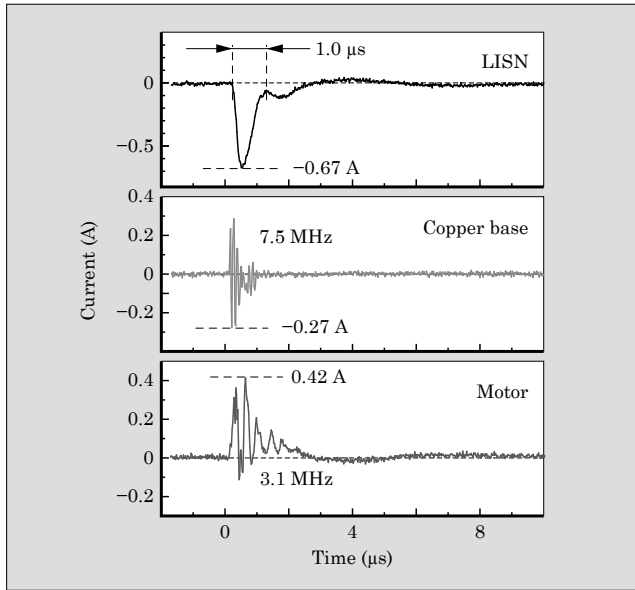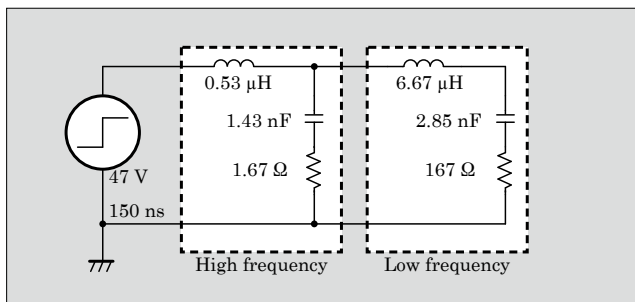
$$L = Z_0/\omega_n, \ C = 1/\omega_n Z_0 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

R is determined from the attenuation of the envelope curve. Because the high-frequency amplitude is greatly affected by the common-mode voltage of the inverter, the measured line inductance of 0.53 µH at 100 kHz is used as the high frequency component inductance.

Figure 4 shows a circuit in which the common-mode leakage current of the motor has been replaced by a 3-phase equivalent circuit[4]. When replacing a single-phase equivalent circuit with a 3-phase equivalent circuit, the low-frequency component inductance and the resistance values are tripled. Also, in consideration of the inductance of the grounding wire, the high-frequency component inductance of the 3-phase equivalent circuit is 3/4 of the single-phase inductance. Moreover, each capacitance is separated into a grounding capacitance C_g and a motor stray capacitance C_m.

2.3 Modeling of the entire circuit

Figure 5 shows a PSIM*[1] simulation circuit that models conduction leakage current. The circuit constants are computed as follows.

(a) Copper base stray capacitance: This is the stray capacitance between semiconductor devices and the copper base, and is 200 pF per device, with the inverter using 6 devices.

(b) Heat sink inductance and resistance value: Computed from an actual measured waveform of the copper base leakage current and from the copper base stray capacitance.

(c) Motor equivalent circuit: The attenuated oscillatory waveform of the measured motor leakage current is separated into a high frequency component and a low frequency component, and circuit constants are computed from a LCR series resonance circuit.

(d) Grounding capacitor: The capacitance used is converted into a single-phase equivalent circuit.

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*1: PSIM is Myway Labs' simulation tool for power electronics circuit.

Fig.2 Measured leakage current waveform (DC bus voltage: 140 V)

Fig.3 Equivalent circuit of motor common-mode leakage current

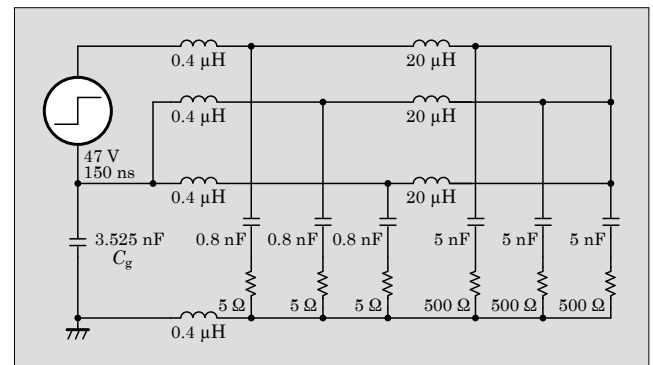Fig.4 3-phase equivalent circuit of motor common-mode leakage current

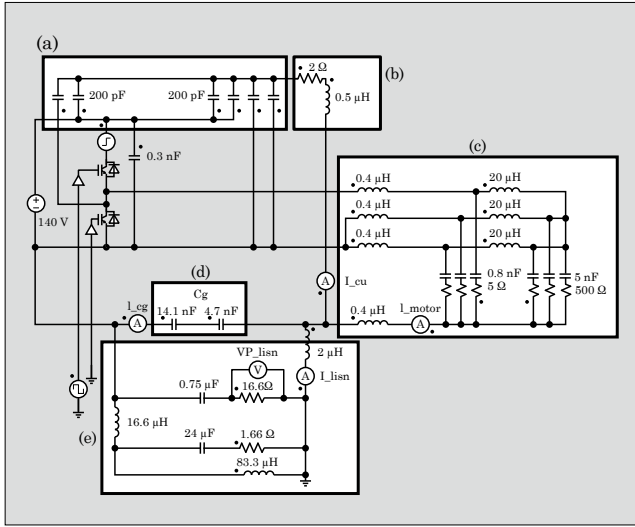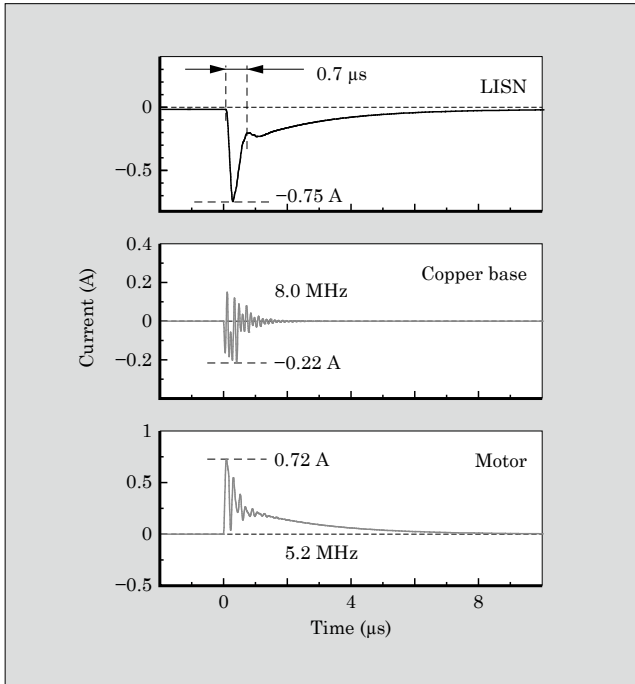Fig.5 PSIM simulation model (chopper circuit)

Fig.6 Simulated leakage current waveform (DC bus voltage: 140 V)

(e) LISN: A 3-phase circuit is converted into a single-phase equivalent circuit.

Figure 6 shows simulated leakage current waveforms obtained using the PSIM simulator with DC bus voltage set to 140 V. The peak value of measured LISN leakage current shown in Fig. 2 was − 0.67 A, and the simulated LISN leakage current had a peak value of − 0.75 A. Moreover, there is close agreement between the measured and simulated values of the frequencies and peak values of copper base leakage current and the motor leakage current. From these results, we conclude that conduction EMI noise can be modeled and that simulation-based analysis is feasible.

Fig.7 ACC circuit configuration
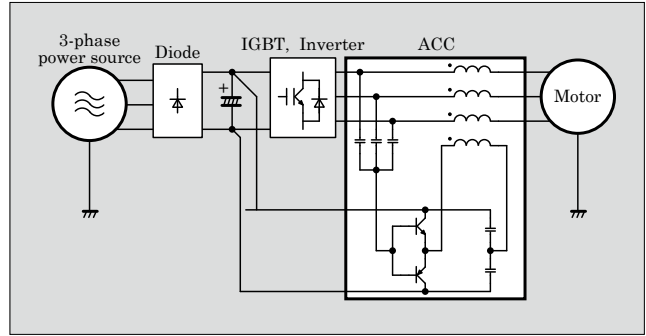
3. Noise Reduction Technology and Effect

3.1 Voltage type active common-mode canceller

The passive filter built into an inverter occupies approximately 30% of the total volume of that inverter. In order to further reduce the volume of the inverter, the filter must be miniaturized. In our research, we propose an improved low-voltage active filter to reduce the size of the EMI filter, so that it may be incorporated into an inverter.

The active common-mode canceller (ACC) shown in Fig. 7 is a method that was proposed by Ogasawara et al[3]. With this method, a voltage, opposite in polarity to and having an amplitude approximately equal that of the common-mode voltage fluctuations generated by switching, is injected between the inverter output and the motor, and cancels the common-mode voltage fluctuations to enable the removal of leakage current generated on the motor side. However, the common-mode voltage between the inverter and the LISN is not cancelled. Therefore leakage current flows to the power source through module copper base and grounding capacitor. This method has a disadvantage that the high voltage transistor is required because the power supply for the compensation voltage source is DC bus of the inverter.

3.2 Low voltage active filter

When one phase of the inverter is switched, the common-mode voltage changes by $1/3$ of the DC bus voltage E_{dc}. Because the stray capacitance of the inverter is extremely small compared to the stray capacitance of the motor, the common-mode equivalent circuit can be considered to be a series circuit of the grounding capacitance C_g and the motor stray capacitance C_m. Thus, the amplitude of the voltage fluctuations generated across the grounding capacitance is $E_d/3$ voltage-divided by C_g and C_m. Limiting the suppression of the LISN leakage current makes it possible to reduce the voltage to be compensated and enables the ACC that generates voltages of opposite polarity to be configured from low-voltage active devices.

Figure 8 shows the proposed low voltage ACC circuit configuration. A common-mode transformer is inserted between the LISN and the inverter. Common-
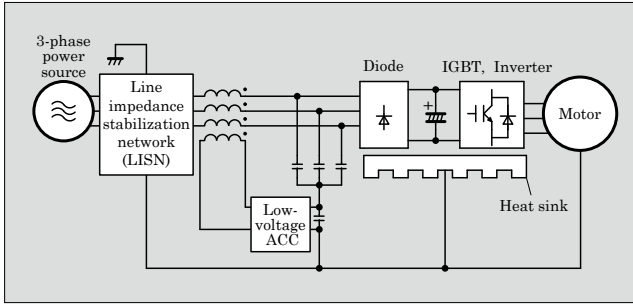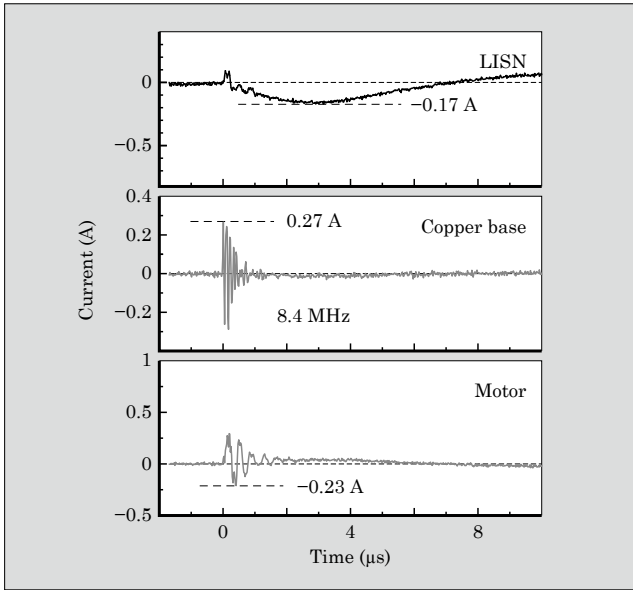
Fig.8 Proposed low-voltage ACC method

Fig.9 Measured waveform of leakage current with ACC (DC bus voltage: 140 V)

Fig.10 Simulated waveform with ACC (DC bus voltage: 140 V)
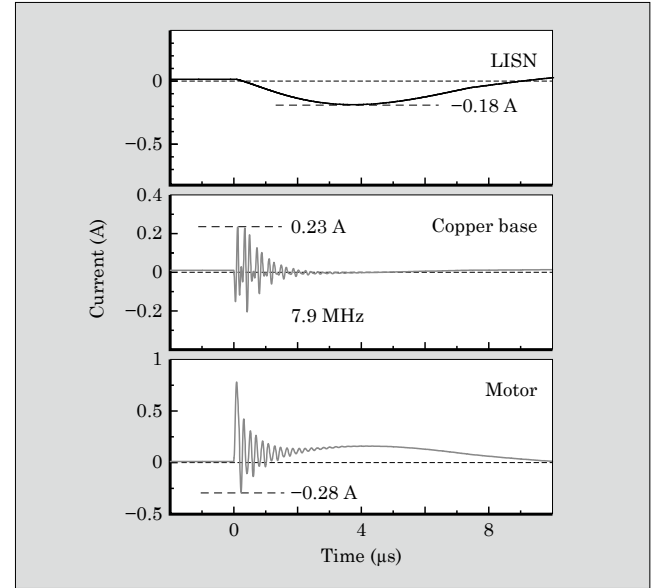
Fig.11 Measured conducted emission noise with and without ACC (DC bus voltage: 280 V)

mode voltage fluctuation of the grounding capacitance is detected, and a voltage of the opposite phase is applied by the common-mode transformer. As a result, in principle, the leakage current flowing to the power source side can be suppressed entirely. Moreover, because the voltage outputted by the ACC circuit is only the voltage divided between the grounding capacitance and the motor stray capacitance, the circuitry can be configured from lower voltage parts than in a conventional ACC circuit. Since low voltage parts generally have excellent high-frequency characteristics, it is possible to compensate higher frequency component. Moreover, because their cost is low, a noise filter can be configured inexpensively. Additionally, because the compensating voltage can be reduced, the transformer is unlikely to saturate magnetic flux and the common-mode transformer can be miniaturized.

3.3 Experimental result

Figure 9 shows the measured waveforms of leakage currents when a low-voltage ACC circuit is combined with a chopper circuit that uses the parameters shown in Table 1. The peak value of LISN leakage current with ACC was reduced to approximately a quarter of

the peak value shown in Fig. 2.

For the copper base and the motor leakage currents, a large difference was not observed between with and without ACC. The reason is because the proposed method focuses only on the leakage current to the power source. The simulated waveforms under the same conditions are shown in Fig. 10. The simulated results tend to agree closely with the measured data, and the effectiveness of the modeled simulation circuit was verified.

Figure 11 shows the measured results of the conducted emission spectrum, with and without the proposed ACC. The DC bus voltage was set at 280 V. This experiment is a chopper circuit experiment that simulates an inverter, and the conducted emission voltage was lower than in the case of an inverter. In Fig. 11, "without ACC" indicates the conduction noise when there is no filter and "with ACC" indicates the conduction noise when a proposed low voltage ACC has been inserted. With this proposed method, the conducted

emission noise was decreased significantly at frequencies of 3 MHz or lower, at 150 kHz and at 300 kHz, the conducted emission noise was decreased by 10 dB and 17 dB, respectively. At high frequencies above 3 MHz, the noise reduction effect is negligible. The reason for the lack of noise reduction is due to the limited high frequency response of active components such as transistors and op-amps used in the proposed ACC circuit.

4. Postscript

This paper has described the modeling of conduction EMI noise and technology for noise reduction using a low voltage active common-mode filter. We proposed a low voltage ACC circuit that was found to reduce significantly the common-mode noise at the power source. Moreover, the proposed circuit configuration has a lower cost than a conventional noise filter and can be miniaturized. In the future, Fuji Electric intends to make the ACC circuit compatible with integrated circuit technology and to develop a commercial product.

Reference
(1) Akagi. H. et al. Design and performance of a passive EMI filter for use with a voltage-source PWM inverter having sinusoidal output voltage and zero common-mode voltage. IEEE Transaction on Power Electronics. Vol. 19, no. 4, 2004, p. 1069-1076.
(2) Ogata, A. et al. Active compensation circuit of leak current in inverter driven load. 1996 National convention record IEEJ, no. 852.
(3) Ogasawara, S. et al. Active cancellation of the common-mode voltage produced by a voltage-source PWM inverter. IEEJ D, vol. 117, no. 5, 1997, p.565-571.
(4) Aoki, M. et al. Frequency analysis of conduction EMI generated by a PWM inverter. SPC-07-17, p. 37-42.
(5) Ogasawara, S., Akagi, H. Modeling and damping of high-frequency leakage currents in PWM inverter-fed AC motor drive systems. IEEE. Vol. 32, no. 5, Sep/Oct 1996, p. 1105-1114.

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