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An Active Circuit for Cancellation of Common-Mode Voltage Generated by a PWM Inverter

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***Abstract*— This paper proposes an active common-noise canceler (ACC) that is capable of eliminating the common-mode voltage produced by a pulsewidth modulation (PWM) inverter. An emitter follower using complementary transistors and a common-mode transformer are incorporated into the ACC, the design method of which is also presented in detail. Experiments using a prototype ACC, whose design and construction are discussed in this paper, verify its viability and effectiveness in eliminating common-mode voltage in a 3.7-kW induction motor drive using an insulated gate bipolar transistor (IGBT) inverter. Some experimental results show that the ACC makes significant contributions to reducing a ground current and a conducted electromagnetic interference (EMI). In addition, the ACC can prevent an electric shock on a nongrounded motor frame and can suppress motor shaft voltage.**

***Index Terms*— Active common-noise canceler (ACC), bearing current, EMI/EMC, ground current, PWM inverter, shaft voltage.**

I. Introduction

THE EMERGENCE of high-speed switching devices such as insulated gate bipolar transistors (IGBT's) has enabled an increase in the carrier frequency of voltage-source pulsewidth modulation (PWM) inverters, thus leading to much better operating characteristics. High-speed switching, however, can be accompanied by the following serious problems originating from a steep change in voltage and/or current:

1) ground current escaping to earth through stray capacitors inside motors [1], [2];
2) conducted and radiated EMI [3]–[6];
3) bearing current and shaft voltage [7]–[9];
4) shortening of insulation life of motors and transformers [10]–[13].

The voltage and/or current change caused by high-speed switching produces high-frequency oscillatory common-mode and normal-mode currents at the instant of every switching because parasitic stray capacitors inevitably exist inside an ac motor. The oscillatory currents with a frequency range of 100 kHz to several megahertz can create a magnetic field and radiate electromagnetic interference (EMI) noises throughout, thus producing a bad effect on electronic devices such as AM radio receivers and medical equipment.

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Generally, common-mode chokes and EMI filters, based on passive elements, cannot solve the problems perfectly. The authors have proposed a common-mode transformer with an additional winding shorted by a resistor [2]. This can damp the oscillatory ground current, but a small amount of aperiodic ground current still remains. Some attempts to introduce active circuits have eliminated the ground current or common-mode voltage [14], [15].

This paper proposes an active common-noise canceler (ACC) for eliminating the common-mode voltage produced by a PWM inverter. The ACC superimposes a compensating voltage on the inverter output. The compensating voltage applied by the ACC has the same amplitude as, but opposite polarity to the common-mode voltage produced by the PWM inverter. As a result, the common-mode voltage applied to a load is canceled completely.

A prototype ACC was constructed and tested in a 3.7-kW induction motor drive using an IGBT inverter. Some experimental results show that the proposed ACC makes significant contributions to reducing common-mode current, i.e., ground current, and conducted EMI. The ACC can also prevent an electric shock from being received when someone touches a nongrounded motor frame. Furthermore, the ACC can suppress motor shaft voltage stemming from the common-mode voltage caused by the PWM inverter.

II. Principle of Active Common-Noise Canceler

Fig. 1 shows the configuration of an experimental system including the ACC proposed in this paper. A voltage-source PWM inverter using IGBT's drives an induction motor of 3.7 kW through three feeder wires, and the motor frame is connected to an earth terminal on a switch board. Shaft voltage is measured between the frame and a carbon brush touching the motor shaft. Measurement of conducted EMI is performed by using a line impedance stabilization network (LISN) and a spectrum analyzer. The ACC is connected between the inverter output terminals and the three feeder wires. It consists of the following elements: a push–pull emitter follower using transistors having complementary symmetry, a common-mode transformer [2], three capacitors to detect the common-mode voltage appearing at the inverter output terminals, and two dc-side capacitors to prevent a dc current from flowing in the additional winding of the common-mode transformer.

A common-mode current i_c flows to the earth terminal through stray capacitors between the windings and frame of the motor because a zero-sequence output voltage of the inverter, i.e., a common-mode voltage, varies every switching of the

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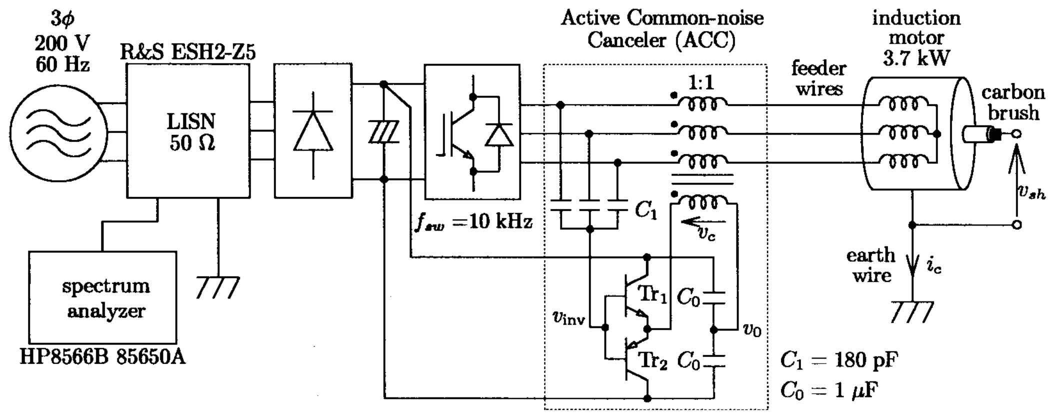

Fig. 1. System configuration.

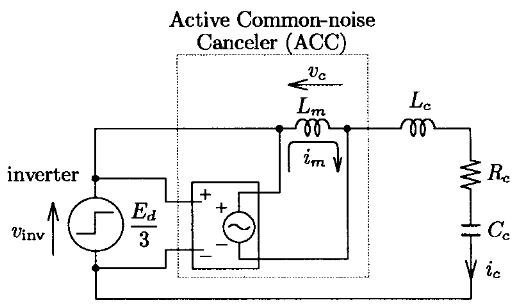

Fig. 2. Common-mode equivalent circuit.

inverter. The ACC is connected for the purpose of canceling this common-mode voltage perfectly so that no common-mode current flows, i.e., $i_c = 0$.

Fig. 2 shows a common-mode circuit equivalent to the experimental system. Here, C_c means the stray capacitor between the motor windings and the frame, and the total common-mode inductance and resistance are shown as L_c and R_c, respectively. In the equivalent circuit, the voltage-source inverter is modeled by a step voltage source $v_{\rm inv}$ because switching operation in one phase of the inverter causes a step change in the common-mode voltage by 1/3 of the dc-link voltage. If no ACC is connected, the step change makes an oscillatory common-mode current i_c flowing into the earth terminal.

The combination of a voltage-controlled voltage source and an inductor, which are surrounded by a dotted line, corresponds to the ACC. The emitter follower, along with the three capacitors, is represented as the voltage-controlled voltage source due to the following characteristics: voltage gain close to unity, high-input impedance, and low-output impedance. On the other hand, the common-mode transformer is the same as a conventional common-mode choke, except for connecting a tightly coupled additional winding (secondary winding) to the output of the emitter follower. Therefore, the common-mode transformer is expressed as a magnetizing inductor L_m in the equivalent circuit, neglecting the leakage inductances.

The purpose of the Y-connected capacitors in Fig. 1 is to detect the common-mode voltage produced by the inverter. The emitter follower applies the same voltage as the detected voltage to the common-mode transformer. The three primary windings of the common-mode transformer with the polarity shown by the dots in Fig. 1 are connected between the output terminals of the inverter and the feeder wires. Therefore, the polarity of the compensating voltage v_c is opposite to that of the common-mode voltage generated by the inverter. As a result, cancellation of the common-mode voltage is performed perfectly and no common-mode current flows.

TABLE I
ABSOLUTE MAXIMUM RATINGS OF TRANSISTORS

Model	2SA1772(SANYO)	2SC4615(SANYO)
V_{CBO} [V]	−400	400
V_{CEO} [V]	−400	400
I_C(DC) [A]	−1	1
P_C [W]	15	15

III. DESIGN OF ACTIVE COMMON-NOISE CANCELER

A. Power Dissipation in the Emitter Follower

The voltage-controlled voltage source in Fig. 2 requires the following properties:

1) a wide-frequency bandwidth up to several megahertz;
2) a low-output impedance for eliminating any influence of the output current on the compensating voltage;
3) a high-input impedance to minimize the capacitance of C_1.

The push–pull emitter follower using complementary transistors satisfies these requirements. Table I shows the absolute maximum ratings of the transistors that are operated in an active region.

If L_m were infinity in Fig. 2, the magnetizing current would be zero so that no power loss would occur in the voltage-controlled voltage source, i.e., the emitter follower. In practice, the magnetizing current is supplied from the emitter follower rather than from the inverter, due to the low-output impedance of the emitter follower.

Fig. 3 shows waveforms of the triangular magnetizing current and the rectangular common-mode voltage in which all three phases are being switched simultaneously at a switching frequency $f_{\rm sw} = 1/T$. As a result, the amount of power dissipation is at maximum. In intervals II and III, the magnetizing current is positive so that it flows not through $\rm Tr_2$, but through $\rm Tr_1$. During interval II, the common-mode voltage is $E_d/2$ so that no collector dissipation occurs in either transistor because the emitter–collector voltage of $\rm Tr_1$ equals zero. However, an

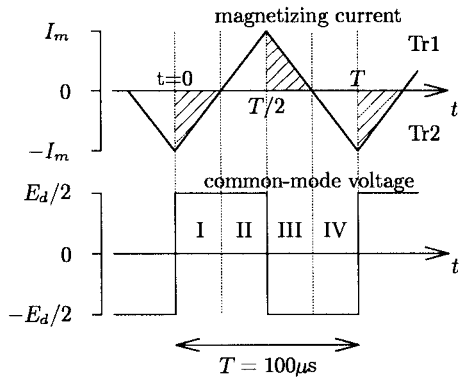

Fig. 3. Variation of magnetizing current.

TABLE II
SPECIFICATION OF TOROIDAL FERRITE CORE

core type		H1D T60×20×36	(TDK)
effective sectional area	A_e	235	mm^2
effective length of magnetic path	ℓ_e	144	mm
AL-value	AL	13.2±25%	$\mu H/N^2$
weight	Wt	172	g
saturation magnetic flux density	B_s	430 (at 25°C)	mT
		260 (at 100°C)	mT

amount of power dissipation appears in Tr_1 during interval III. Therefore, the average power dissipation of one transistor can be calculated by

$$P_c = \frac{E_d^2 T}{64 L_m}. \quad (1)$$

In the experimental system, the PWM period and the dc-link voltage of the inverter are $T = 100\ \mu$s and $E_d = 282$ V, respectively. Since the absolute maximum power dissipation of both transistors is rated at 15 W, the magnetizing inductance should be greater than 8.3 mH.

B. Design of the Common-Mode Transformer

Table II shows the specifications of the ferrite core used. The common-mode transformer should be designed so as not to cause magnetic saturation. Therefore, the product of the stack number k of core and the number of turns N satisfies

$$kN > \frac{E_d T}{8 A_e B_s}. \quad (2)$$

In the experimental system, four toroidal ferrite cores $(k = 4)$ are used for the common-mode transformer in consideration of margin, and the number of turns is selected as $N = 22$. Therefore, the magnetizing inductance of the common-mode transformer is given by

$$L_m = 4 \times 13.2 \times 10^{-6} \times 22^2 = 25.6 \text{ mH}. \quad (3)$$

In this case, the power dissipation P_c, the maximum magnetizing current I_m, and the maximum flux density B_m are calculated as follows:

$$P_c = 4.8 \text{ W} \quad I_m = 0.14 \text{ A} \quad B_m = 0.17 \text{ T}. \quad (4)$$

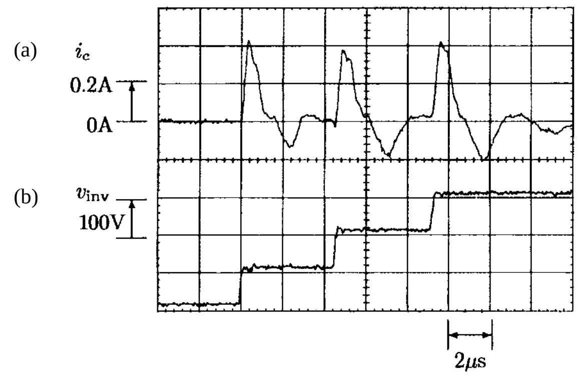

Fig. 4. Ground current without ACC: (a) ground current and (b) common-mode voltage.

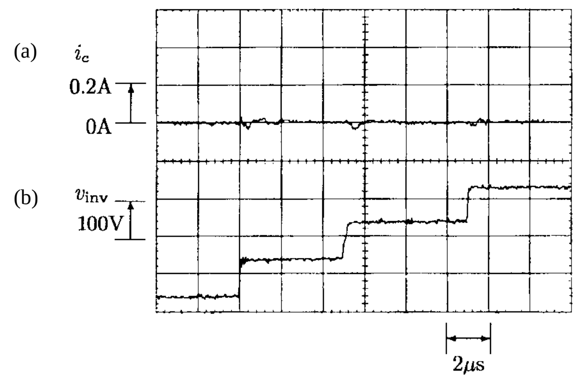

Fig. 5. Ground current with ACC: (a) ground current and (b) common-mode voltage.

The power dissipation in both transistors corresponds to 0.26% of the rated power of the induction motor.

C. DC-Side Capacitors

A dc component included in the output voltage of the emitter follower may cause excessive current to flow to the common-mode transformer, and the transistors may break down. In order to remove the dc component, two dc-side capacitors C_0 are connected as shown in Fig. 1. The smaller the capacitance of C_0, the larger the variation of the neutral point potential v_0. Because the voltage variation amounts to a voltage error in the compensating voltage, a large variation results in imperfect cancellation of the common-mode voltage produced by the inverter. Therefore, C_0 has to be chosen as a value large enough to reduce the voltage variation. In this experiment, a 1.2-μF capacitor is selected so that the voltage variation can be restricted within ± 1.5% of the dc-link voltage.

IV. EFFECT ON GROUND CURRENT

Fig. 4 shows experimental waveforms of the common-mode current and voltage without the ACC. The common-mode voltage v_{inv} is measured between the neutral points of the Y-connected capacitors and the dc-side capacitors. It is shown that a nonnegligible amount of common-mode current, i.e., the ground current, leaks to earth every switching of the PWM

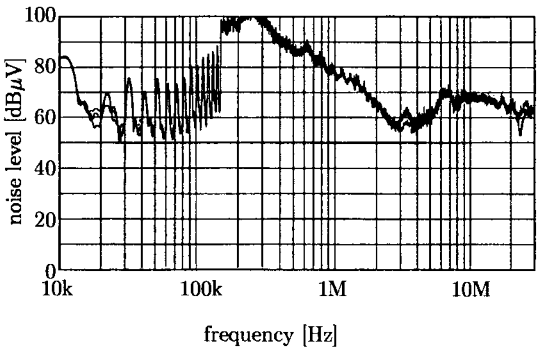

Fig. 6. Conducted EMI without ACC.

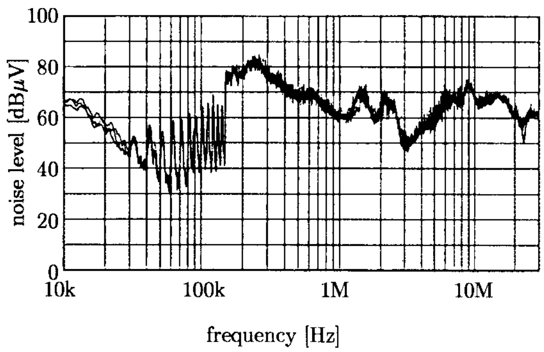

Fig. 7. Conducted EMI with ACC.

inverter. The common-mode current i_c oscillates at 290 kHz and the amplitude reaches 0.4 A (peak value). It may cause incorrect operation of an earth leakage breaker and/or radiated EMI [6].

In [2], the authors have proposed an equivalent circuit for the ground current, which forms an LCR series resonant circuit as shown in Fig. 2. The damped and oscillatory current in Fig. 4 is similar to the current waveform after a step voltage is applied to the equivalent resonant circuit. The equivalent circuit provides a simple way for analyzing the ground current with sufficient accuracy. It is considered that the equivalent circuit is the same as the reduced-order common-mode model for evaluating shaft voltage buildup [9].

Fig. 5 shows an experimental result with the ACC. These waveforms indicate that the ACC is capable of suppressing the common-mode current almost completely. A mere common-mode current remains due to a control delay of the emitter follower every switching. The ACC is effective in reduction of the common-mode or ground current.

V. Effect on Conducted EMI

Fig. 6 shows conducted EMI, measured in a frequency range from 10 kHz to 30 MHz. In a range from 10 to 150 kHz, it turns into a sequence of impulse spectra at intervals of the switching frequency of 10 kHz, where the spectrum analyzer used for measurement has a resolution bandwidth of 200 Hz. Since the resolution bandwidth is changed to 9 kHz in a range from 150 kHz to 30 MHz, it turns into a continuous spectrum. It is shown that conducted EMI beyond 100 dBμV occurs at the maximum point.

The frequency at the maximum point coincides with the oscillation frequency of the ground current shown in Fig. 4. This fact indicates that the conducted EMI is affected by the common-mode current. The conducted EMI is measured as a voltage drop when the common-mode current flows through a resistor in the LISN. Therefore, analysis of the conducted EMI can be achieved by using a common-mode equivalent circuit combined with the LISN.

Fig. 7 shows conducted EMI when the ACC is connected. The experimental result indicates that the ACC decreases the conducted EMI by about 20 dB in a frequency range from 10 kHz to 3 MHz. The ACC proposed in this paper makes great contributions to reducing conducted EMI in a wide frequency range.

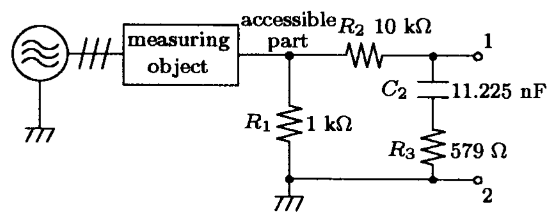

Fig. 8. Measuring circuit.

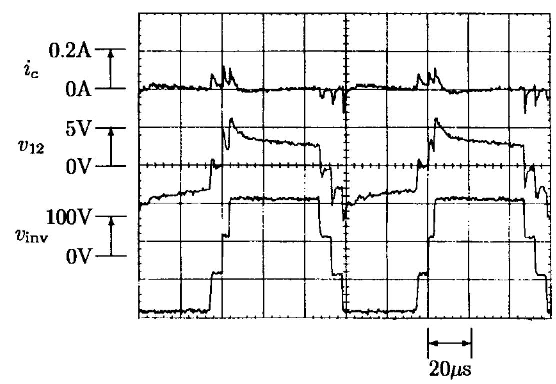

Fig. 9. Terminal voltage of measuring circuit without ACC.

VI. Effect on Prevention of Electric Shock

In Japan, a safety standard to prevent electric shock from being received on an accessible metal part of a nongrounded electric apparatus has been enacted, which is a similar standard to IEC 335. A measuring circuit complying with the Japanese standard is shown in Fig. 8. The measuring circuit is connected between a nongrounded motor frame and an earth terminal, and an rms value of voltage between output terminals 1 and 2 is measured. It was judged that there is no danger of electric shock when the terminal voltage is less than 1 V.

A. Analysis of Terminal Voltage

Fig. 9 shows waveforms of the common-mode current, the terminal voltage of the measuring circuit and the common-mode voltage when no ACC is connected. The rms value of the terminal voltage v_{12} is 3.54 V. Since the rms value exceeds 1 V, the motor frame has the potential of causing electric shock.[1]

[1] Generally, a frame of induction motor is grounded for safety.

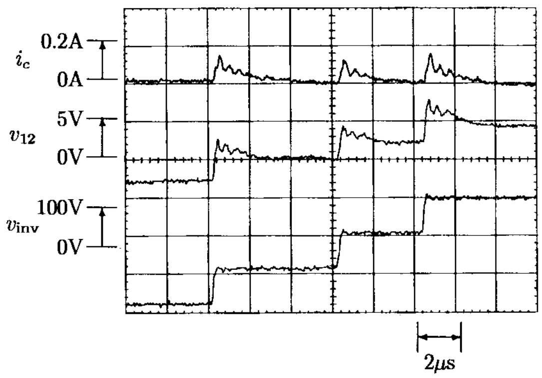

Fig. 10. Expanded waveforms of Fig. 9.

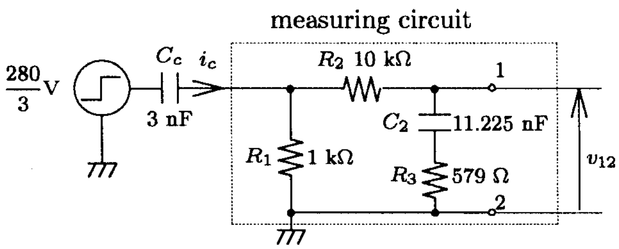

Fig. 11. Simulation circuit.

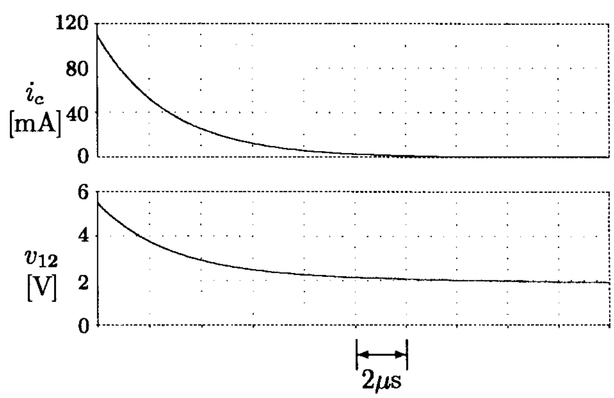

Fig. 12. Simulated waveforms.

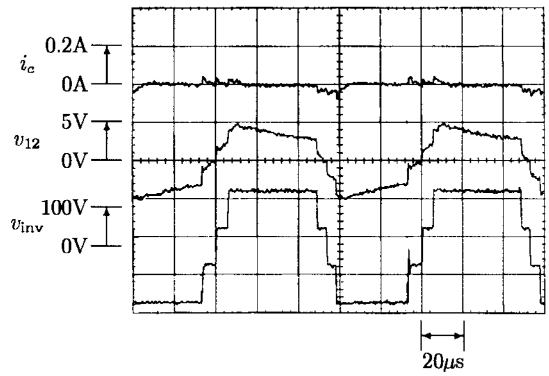

Fig. 13. Terminal voltage of measuring circuit when connecting common-mode transformer.

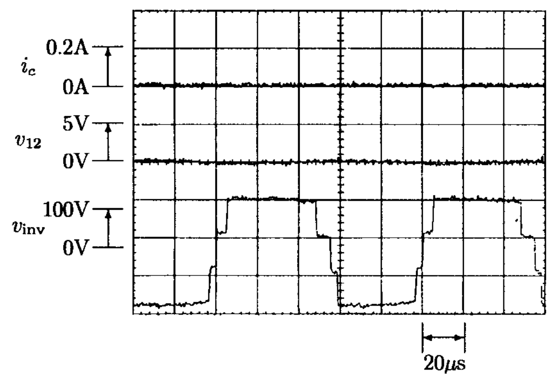

Fig. 14. Terminal voltage of measuring circuit when connecting ACC.

The terminal voltage waveform was analyzed by using a circuit simulator. The simulation circuit is shown in Fig. 11. Here, C_c means a stray capacitor between the windings and frame of the motor, and the value is measured by an LCR meter. The equivalent circuit with focus on the common-mode voltage and current is represented by capacitor C_c because the common-mode impedance included in both feeder wires and grounding conductor is negligible, compared with that of the measuring circuit. The amplitude of the common-mode voltage is 280/3 V, assuming that one phase of the inverter is switched.

Figs. 10 and 12 show expanded waveforms of Fig. 9 and a simulation result, respectively. Although the motor is treated in the simulation circuit as capacitor C_c, the simulated waveforms of i_c and v_{12} coincide with the experimental waveforms. The larger the value of C_c, the larger the rms value of the terminal voltage. Hence, reduction of C_c is effective in mitigating electric shock on the motor frame.

B. When Connecting a Common-Mode Transformer

Fig. 13 shows waveforms of the common-mode current: the terminal voltage and common-mode voltage when the common-mode transformer proposed in [2] is connected to output terminals of the inverter. Here, the secondary winding of the common-mode transformer is shorted by a resistor of 1 kΩ. Compared with Fig. 9, it is shown that the common-mode current decreases and that the overshoot of the terminal voltage occurring at every switching is mitigated. The reason is that the common-mode transformer acts as a damping resistor and limits the slope of common-mode voltage appearing on the motor terminals, like a soft-switching inverter. In this case, the rms value of the terminal voltage v_{12} is 3.46 V, which exceeds 1 V. This fact implies that soft-switching techniques have little effect on prevention of electric shock.

C. When Connecting the ACC

Fig. 14 shows waveforms of the common-mode current: the terminal voltage and common-mode voltage when the ACC is connected to the output terminals of the inverter. Compared with Fig. 9, it is indicated that the common-mode current i_c and the terminal voltage v_{12} are well reduced because the ACC cancels the common-mode voltage almost completely. The rms value of the terminal voltage 0.1 V is much smaller than the prescribed value 1 V. Therefore, the ACC can remove any danger of an electric shock received on a nongrounded motor frame.

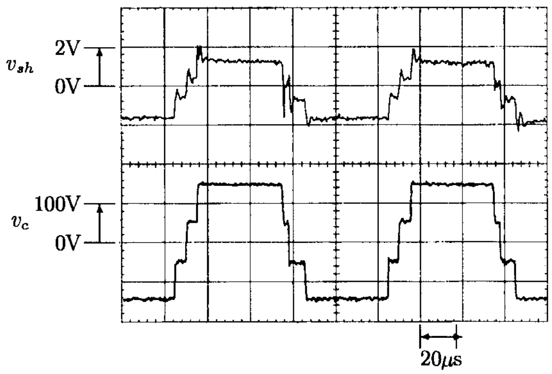

Fig. 15. Motor shaft voltage without ACC.

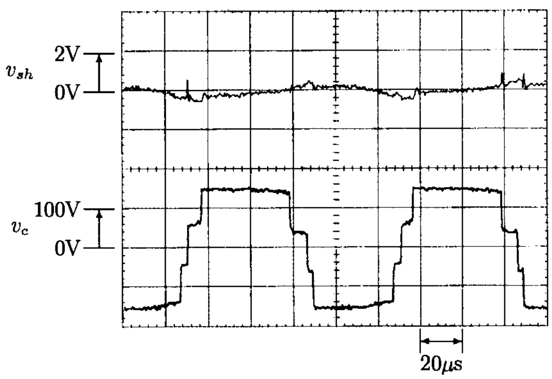

Fig. 16. Motor shaft voltage with ACC.

VII. Effect on Motor Shaft Voltage

Fig. 15 shows experimental waveforms of a common-mode voltage and a motor shaft voltage when no ACC is connected. A motor shaft voltage of 2 V (peak value) occurs every PWM period of the inverter. It is concluded that the motor shaft voltage is caused by the common-mode voltage because the shapes of the two waveforms are similar. The shaft voltage results from a capacitive coupling between the stator and rotor. It may induce electric field breakdown of a thin oil film existing between a bearing race and balls, thus resulting in bearing current. The bearing of the motor might be damaged by the bearing current, altering the chemical composition of the lubricant [9].

Fig. 16 shows experimental waveforms when the ACC is connected. Compared with Fig. 15, the motor shaft voltage is suppressed sufficiently. Therefore, the ACC produces a welcome side effect, i.e., "no flow of bearing current."

VIII. Conclusion

In this paper, an active common-mode canceler (ACC) has been proposed, which is capable of canceling a common-mode voltage generated by a PWM inverter. A prototype ACC has been constructed and tested to verify its effectiveness in a 3.7-kW induction motor drive using an IGBT inverter. As a result, it has been shown that the ACC can suppress a ground current almost perfectly. Moreover, the effect on prevention of electric shock is confirmed by using a measuring circuit complying with a Japanese standard. It is shown that the ACC can remove any danger of electric shock on the nongrounded motor frame. The ACC is also a promising way of reducing motor shaft voltage and conducted EMI.

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Dr. Ogasawara received two IEEE/IAS Committee Prize Paper Awards in 1996 and 1997. He is a Member of the Institute of Electrical Engineers of Japan.

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In 1979, he joined Nagaoka University of Technology, Niigata, Japan, as an Assistant and then Associate Professor in the Department of Electrical Engineering. In 1987, he was a Visiting Scientist at the Massachusetts Institute of Technology, Cambridge, for ten months. Since 1991, he has been a Full Professor in the Department of Electrical Engineering, Okayama University, Okayama, Japan. From March to August of 1996, he was a Visiting Professor at the University of Wisconsin-Madison and then the Massachusetts Institute of Technology. His research interests include ac motor drives, high-frequency resonant inverters for induction heating and corona discharge treatment, and utility applications of power electronics such as active filters, static var compensators, and FACTS devices.

Dr. Akagi has received seven IEEE/IAS Society and Committee Prize Paper Awards, including the First Prize Paper Award in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS for 1991. He is a Distinguished Lecturer of IEEE/IAS for 1998–1999.