Reduction of EMI Generated by a PWM Inverter-Fed AC Motor Drive System

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Abstract— **This paper deal with problems of leakage current, shaft voltage, bearing current, and EMI, in valiable-speed AC drives. The originating mechanism is illustrated with a high-frequency equivalent circuit. Reduction methods are classified in to six categories based on the equivalent circuit. Some experimental results show that a common-mode transformer (CMT) and a common-noise canceler (ACC) can solve the problems, which have been proposed by the authors.**

I. Introduction

In recent years, accompanied with development of high-speed power semiconductor devices, it is pointed out that increase in carrier frequency of voltage-source PWM inverter causes the following serious problems:

- high frequency leakage current [1], [2],
- conductive and radiative electromagnetic interference (EMI) [3], [4],
- shaft voltage and bearing current of a motor [5]–[9],
- surge voltage and deterioration of motor winding isolation [10]–[13].

These problems are caused by a steep change of voltage and/or current occurring at a switching time of inverter. For this reason, when power converters using high-speed power devices such as IGBT's are introduced, these problems tend to become conspicuous.

This paper discusses originating mechanism of leakage current, surge voltage, shaft voltage, bearing current, and EMI in a variable-speed AC drive using a voltage-source PWM inverter. A high-frequency equivalent circuit is derived from some consideration of stray capacitance, and already proposed reduction methods are classified theoretically based on the equivalent circuit. Some experimental results using a common-mode transformer (CMT), normal-mode filters (NMF's), and an active common-noise canceler (ACC) are shown, which are proposed by the authors.

II. Common-Mode Voltage of Voltage-Source Inverter

Fig.1 shows a three-phase voltage-source inverter connecting an LR load. A voltage current equation of each phase is shown by the following equations.

$$v_u - v_c = Ri_u + L\frac{di_u}{dt} \tag{1}$$

$$v_v - v_c = Ri_v + L\frac{di_v}{dt} \tag{2}$$

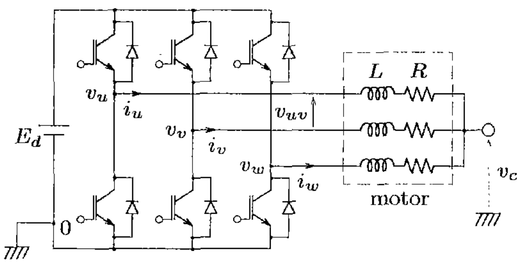


Fig. 1. Three-phase voltage-source inverter.

$$v_w - v_c = Ri_w + L\frac{di_w}{dt} \tag{3}$$

Here, v_u, v_v, v_w, i_u, i_v, i_w express a voltage and current of each phase, respectively, and v_c means a neutral point potential of the load. Adding Eqs.(1)~(3) gives

$$v_u + v_v + v_w - 3v_c = \left(R + L\frac{d}{dt}\right)(i_u + i_v + i_w). \tag{4}$$

Here, $i_u + i_v + i_w = 0$ from the Kirchhoff's current law (KCL).

$$v_c = \frac{(v_u + v_v + v_w)}{3} \tag{5}$$

The above equation shows that the load currents and impedances have no influence on v_c. Eq.(5) defines a common-mode voltage which can be considered as a total potential of the load with respect to a referenced potential. [1]

Each phase of voltage-source inverter can be treated as a voltage source providing two output voltages, i.e., 0 and E_d. For example, we regard a case that u-phase voltage v_u is switched from 0 to E_d when the other phase voltages are 0, as show in Fig.2(a). Then, the u-v and u-w line-to-line voltages change from 0 to E_d and the common-mode voltage v_c also changes from 0 to $E_d/3$. Therefore, in the case of the u-phase switching, the inverter output voltage can be separated into two components of the common-mode voltage and a normal-mode voltage, which are shown in Fig.2(b). The load current depends on only the normal-mode voltage in the

[1]Physical meaning of the common-mode voltage is identical to the zero-phase sequence voltage used in coordinate transformation. However, note that these are different in amplitude, because absolute transformation is adopted in the coordinate transformation.

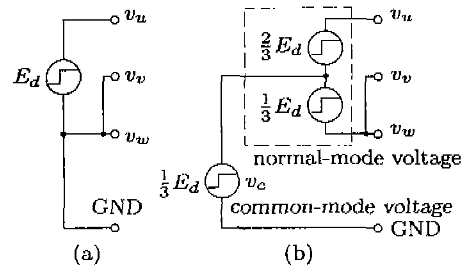


Fig. 2. Common-mode voltage and normal-mode voltage.

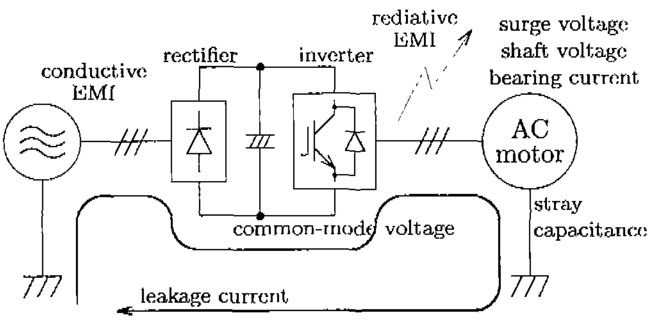


Fig. 3. Variable-speed AC drive system.

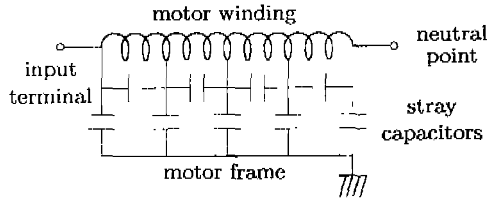


Fig. 4. Equivalent circuit for a motor winding taking stray capacitors into consideration.

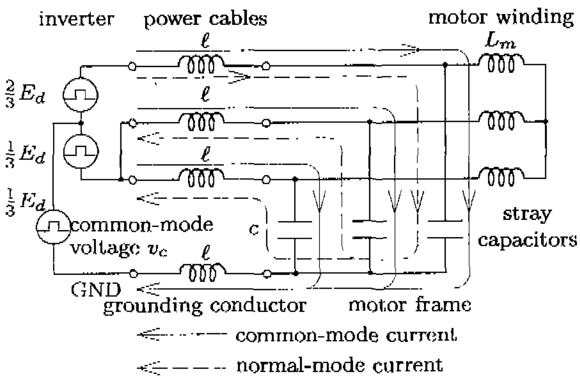


Fig. 5. High-frequency equivalent circuit of a motor.

case of non-grounded load shown in Fig.1, and the load current has no influence on the common-mode voltage. The common-mode voltage of the inverter changes by $E_d/3$ every switching. As a result, there are four kinds of amplitude in the common-mode voltage, i.e., 0, $E_d/3$, $2E_d/3$, and E_d.

III. High-Frequency Equivalent Circuit of Variable-Speed AC Drive

Fig.3 shows configuration of a variable-speed AC drive system. A diode rectifier converts three-phase AC power to DC power, and an AC motor is driven by a voltage-source PWM inverter which supplies variable-frequency AC power. When a switching occurs in the voltage-source PWM inverter, leakage current flows from the motor frame to earth terminal through stray capacitors of the motor windings, because steep and stepwise change occurs in the common-mode voltage at the inverter output terminals with respect to earth potential. The leakage current may cause radioactive and/or conductive EMI. Moreover, the common-mode voltage may cause shaft voltage and bearing current in the AC motor.

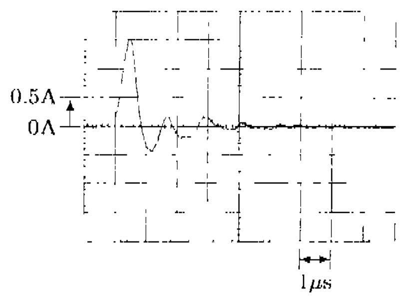
Since stator windings of the motor are embedded in slots of a stator core, relatively large stray capacitance exists between the stator winding and the motor frame rather than between two stator windings. Fig.4 shows an equivalent circuit of a stator winding, which expresses the stray capacitance existing distributively between the stator winging and the motor frame.

It is reported that breakdown or deterioration of insulator occurs near input terminal of the stator winding, when a surge voltage is applied to the motor [10]–[13]. The reason is that the surge voltage concentrates on the stator coil end owing to non-uniform voltage distribution caused by the stray capacitance existing distributively. This phenomenon is the same as the voltage concentration on the high-voltage side winding of a power transformer [14], [15]. The fact means that the high-frequency current hardly flows in winding conductor due to the inductance, but it flows to the motor frame through the stray capacitance near the input terminal.

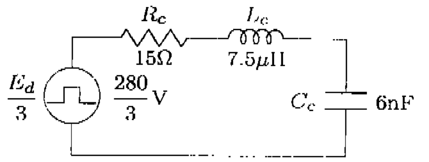
Fig.5 shows an equivalent circuit of the motor for high-frequency component [2]. By above-mentioned reason, stray capacitance of each winding is represented by a lumped capacitor c connecting between a motor input terminal and motor frame. Furthermore, stray capacitance between two windings is ignored because it is smaller than stray capacitance between a winding and frame. Here, ℓ means line inductance of a power cable between the inverter output and motor input terminals. [2]

Fig.5 expresses a case that one phase voltage is switched from 0 to E_d while the other phase voltages are 0. Here, the inverter output voltages can be decomposed into the common-mode and normal-mode voltages, as shown in Fig.2. The common-mode and the normal-mode voltages generate the common-mode and normal-mode currents represented by solid and broken lines, respectively, through the power cables, the stray capacitors, and the grounding conductor. Each of the oscillatory high-frequency current forms an LC series resonance circuit so that the current causes various prob-

[2] It is assumed that the motor frame is connected to earth terminal on a switchboard being adjacent to the inverter by a grounding conductor the line inductance of which is the same as ℓ. Practically, the common-mode current returns to the inverter from earth terminal though an AC power supply, power cables between the switchboard and inverter, and a diode rectifier. However, we ignore the additional impedance for simplicity.



(a) experimental waveform of common-mode current



resonant requency $f_c = 1/(2\pi\sqrt{L_c C_c}) = 750$(kHz)
characteristic impedance $Z_c = \sqrt{L_c/C_c} = 35.4(\Omega)$
damping factor $\zeta_c = R_c/(2Z_c) = 0.212$

(b) equivalent circuit

Fig. 6. Common-mode current.

lems.

Fig.6(a) shows an experimental waveform of the common-mode current flowing through the grounding conductor, in a 3.7-kW induction motor drive with a transistor PWM inverter. Compared with the motor rated current of 18.5 A, relatively large common-mode current of 1.5 A (peak) flows to earth terminal. Moreover, the common-mode current oscillating at 750 kHz may cause electromagnetic interference (EMI) to AM radio receiver. This common-mode current has the similar waveform to the damped oscillation current when a step voltage is applied to an LCR series resonant circuit shown in Fig.6(b). Here, C_c, L_c, and R_c in Fig.6(a) mean stray capacitance, line inductance, and damping resistance, respectively, and these parameters are estimated from the experimental waveform of Fig.6(a). [3] Comparing Fig.6(b) with Fig.5, L_c and C_c correspond $L_c = 4/3l$, and $C_c = 3c$, respectively. The common-mode current and voltage cause the various problems that occur accompanied by switching of a voltage-source inverter, e.g., conductive and radioactive EMI, etc.

IV. Reduction Methods of Common-Mode

A. Classification of reduction methods

Although the equivalent circuit of the common-mode or leakage current is represented by an LCR series resonant circuit shown in Fig.6(b), reduction methods of common-mode current and/or voltage can be classified into the following 6 kinds of categories.

(a) Increasing impedance. To reduce the leakage current, a common-mode inductor is inserted into the pass that the leakage current flows, and the total impedance is made to increase. This corresponds to the conventional common-mode choke.

(b) Damping. To damp the high-frequency oscillation, a series damping resistor is inserted into the LCR series resonant circuit that represents the common-mode circuit. This corresponds to the common-mode transformer (CMT) whose secondary winding shorted by a damping resistor is added to the conventional common-mode choke [2].

(c) Current bypassing. To bypass the leakage current, a low impedance circuit is connected in parallel to the circuit that should not make the leakage current flow. This corresponds to the conventional EMI filter and the combined output filters with a common-mode choke [1].

(d) Potential dividing. Potential divider is composed to reduce common-mode voltage and the divided common-mode voltage is applied to the load [1].

(e) Current canceling. The leakage current can be canceled by means of injecting a common-mode current opposite to it. This corresponds to an active EMI filter [16], [17].

(f) Voltage canceling. The common-mode voltage produced by the inverter can be canceled by means of superimposing a common-mode voltage opposite to it. This corresponds to an active common-noise canceler (ACC) [18] and a four-phase inverter [19], [20].

Among these reduction methods, *(a)*~*(d)* can be realized by using only passive elements, but *(e)* and *(f)* require an active element. Behavior of the used active circuit, moreover, can be classified into linear operation and switching operation. The following describes some reduction methods.

B. Using passive elements

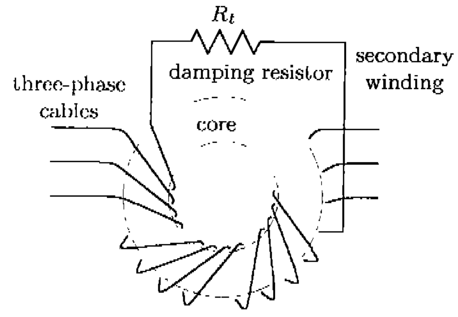


Fig. 7. Common-mode transformer (CMT).

Fig.7 shows a common-mode transformer (CMT) [2]. The CMT has the same structure as the conventional common-mode choke except for adding a secondary winding shorted by a damping resistor R_t. Therefore, the CMT acts as a resistor only for the common-mode, though it produces no power loss for the normal-mode.

In the case of $R_t = 0$, the CMT has no influence upon the leakage current, because of zero impedance. In the case of $R_t = \infty$, since the CMT acts as a conventional

[3] R_c is based on the loss that is mainly caused in a motor inside, and it is larger more than one figure than the line resistance taking skin effect into consideration. Though it is suitable to express the loss by a resistor in parallel with C_c, from the viewpoint of physical meaning, we treat it as a series resistor including the line resistance for simplicity.

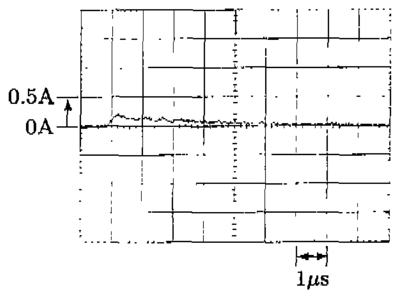


Fig. 8. Common-mode current with CMT.

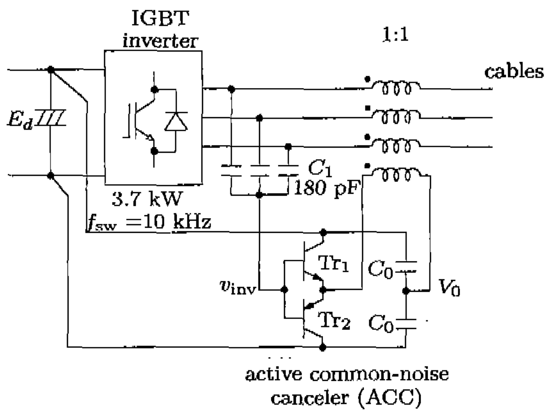


Fig. 9. Active common-noise canceler (ACC).

common-mode choke, the peak value of the leakage current is reduced but the rms value sometimes increases. When R_t is adjusted on an appropriate value, the CMT can act as a damping resistor. Therefore, the oscillatory common-mode current shown in Fig.6(a) becomes a non-oscillatory and exponential waveform as shown in Fig.8. The CMT is capable of reducing both the peak and rms values of the common-mode current.

C. Using active elements

Fig.9 shows an active common-noise canceler (ACC) connected to inverter output terminals [18]. The ACC is composed of a push-pull emitter follower circuit using complementary transistors, a common-mode transformer (1:1), DC capacitors C_0, and Y-connected capacitors C_1. A common-mode voltage produced by an inverter is detected as neutral-point potential of the Y-connected capacitors C_1. Since the capacitance of 180 pF is as small as the output capacitance of the power semiconductor device used in the inverter, the Y-connected capacitors do not affect the inverter operation. High impedance and wideband characteristics of the emitter follower circuit make a great contribution to precise and high-speed cancellation of the common-mode voltage.

A common-mode voltage is superimposed by the ACC on the inverter output through the common-mode transformer, which is opposite to a common-mode voltage detected by the Y-connected capacitors. As a result, the common-mode voltage produced by the inverter is canceled so that no common-mode voltage is applied to the motor, and then the common-mode current can be suppressed perfectly.

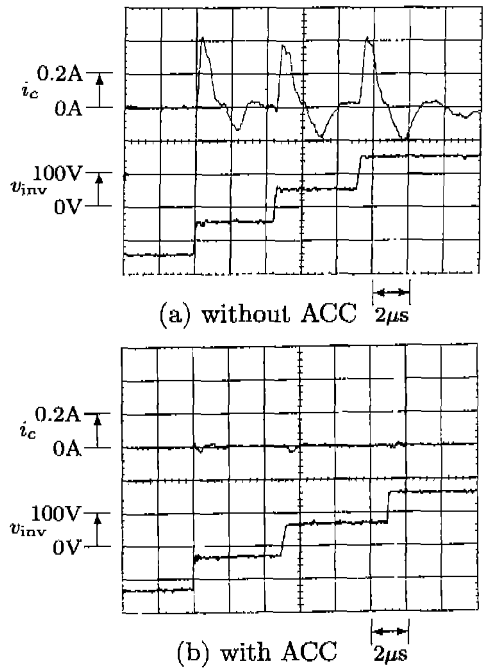


Fig. 10. Waveforms of common-mode voltage and current.

Fig.10 shows waveforms of the common-mode voltage and current. Here, the common-mode voltage v_{inv} is measured between the neutral points of the Y-connected capacitors and the DC capacitors. When the ACC is not used, a switching operation of the inverter generates the common-mode current whose peak value and oscillation frequency are 0.4 A and 290 kHz, respectively. However, in the case of connecting the ACC, the common-mode current i_c can be suppressed almost perfectly.

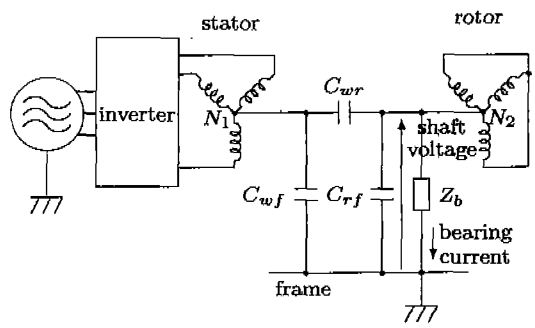
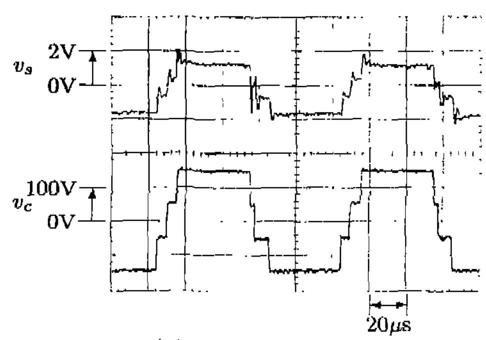


Fig. 11. Shaft voltage and bearing current.

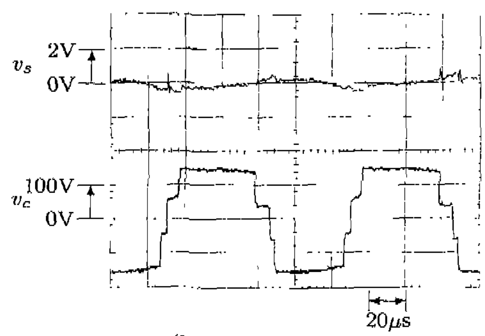
V. Other problems caused by common-mode voltage

A. Shaft voltage and bearing current

Fig.11 shows a high-frequency motor model to explain the generating mechanism of shaft voltage and bearing current. Here, C_{wr}, C_{wf}, and C_{rf} mean stray capacitances between the stator winding and the rotor, between the stator winding and the motor frame, and be-



(a) without ACC



(b) with ACC

Fig. 12. Waveforms of shaft voltage and common-mode voltage.

tween the rotor and the frame, respectively. The shaft voltage depends on the ratio of C_{wr} and C_{rf}, which divide the common-mode voltage produced by the inverter. [4]

Fig.12(a) shows measured waveforms of the shaft voltage v_s and common-mode voltage v_c. The shaft voltage is measured between the motor frame and a carbon brush touching the motor shaft. A motor shaft voltage of 2 V (peak) occurs every PWM period (100 μs) 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. When the shaft voltage v_s is larger, 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.

Fig.12(b) shows an experimental waveform of the shaft voltage v_s in the case of connecting the ACC. It is shown that the ACC is capable of suppressing the shaft voltage almost perfectly because of cancellation of the common-mode voltage. Canceling the common-mode voltage is effective in prevention of the shaft voltage and bearing current.

B. Surge voltage

Fig.13 shows an experimental waveform of a motor terminal voltage with respect to the motor frame. It

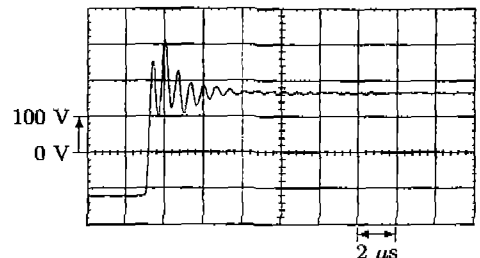


Fig. 13. Experimental waveform of motor terminal voltage with respect to motor frame.

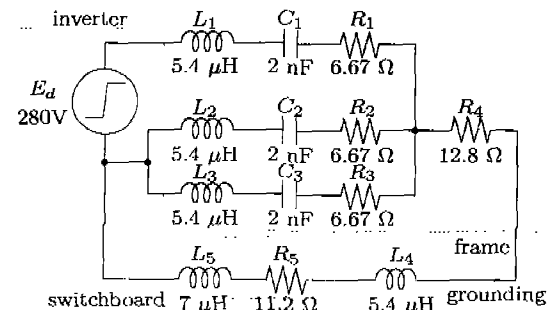


Fig. 14. Simulation circuit.

includes a fast oscillation at 1.5 MHz, superimposed on the other oscillation at 750 kHz, and the larger dv/dt may cause the more serious isolation deterioration or breakdown of the motor winding. The frequency of 750 kHz corresponds to the common-mode resonant frequency shown in Fig.5, and the normal-mode resonant frequency exists at 1.5 MHz. A normal-mode oscillation phenomenon, in addition to the common-mode, has large influence on the surge voltage at the motor terminal. To confirm it theoretically, a terminal voltage waveform with respect to the motor frame is obtained by a simulation using an equivalent circuit of Fig.14 which is made based on the high-frequency equivalent circuit shown in Fig.5. [5] Fig.15 shows a simulated waveform of the motor terminal voltage. It coincides with Fig.13 well, and this also shows appropriateness of the high-frequency equivalent circuit of Fig.5.

Damping technique is effective for suppressing the resonance phenomena. Fig.16 shows an experimental waveform of the terminal voltage in the case of con-

[4]Since Fig.11 corresponds to the common-mode circuit, it is expressed that the stray capacitances are connected to the neutral points of the stator and rotor windings. However, note that each winding can be treated as it has no influence upon the current in a high-frequency region, as mentioned in Section III.

[5]The circuit parameters are calculated from Fig.6(b). L_5 and R_5 are added and adjusted, taking an impedance inside the switchboard into consideration,

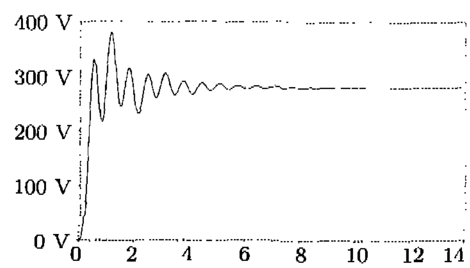


Fig. 15. Simulated waveform of motor terminal valtage with respect to motor frame.

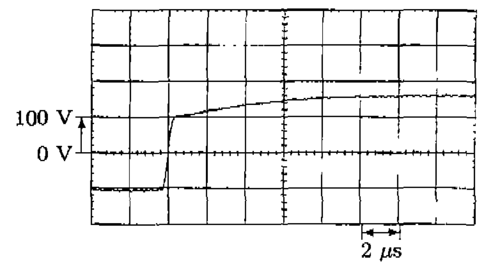


Fig. 16. Terminal voltage in the case of connecting CMT and NMF's.

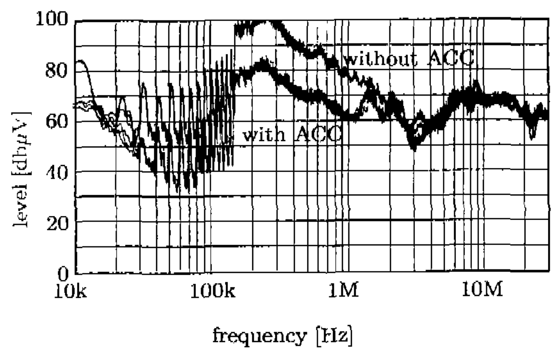


Fig. 17. Characteristics of conductive EMI.

necting both the common-mode transformer (CMT) and normal-mode filters (NMF's) [4]. [6] The oscillations are eliminated perfectly and dv/dt of the motor terminal voltage is reduced.

C. Conductive and radioactive EMI

Fig.17 shows measured conductive EMI of an induction motor drive system (3.7 kW) using an IGBT inverter. Impulse spectra placed at intervals of switching frequency (10 kHz) appear in a low frequency range, and it has a peak at 290 kHz that is a resonant frequency of the common-mode current. The conductive EMI is generated due to the common-mode current flowing out to earth, the spectrum of which is similar to that of common-mode current. In a high-frequency range beyond MHz, a power cable behaves like a distributed circuit. Moreover, a current loop formed by the common-mode and/or normal-mode current may result in radiative EMI [4].

Fig.17 also shows conductive EMI in the case of connecting an ACC. Since the ACC can cancel the common-mode voltage almost perfectly, it is demonstrated that the ACC is capable to reducing the conductive EMI by about 20 dB in a wide frequency range up to several MHz.

VI. Conclusions

This paper has discussed originating mechanism of leakage current, surge voltage, shaft voltage, bearing current, and EMI in a variable-speed AC drive using a voltage-source PWM inverter. Reduction methods have been classified into six categories. These contribute to overcome the various problems, i.e., leakage current, surge voltage, shaft voltage, bearing current, and EMI.

[6]NMF is a parallel connection of a small inductor and a resistor, which is connected in series to each cable. It acts as a damping resistor only for the high-frequency component, so that the normal-mode oscillation can be attenuated.

References

[1] Y. Murai, T. Kubota, and Y. Kawase: "Leakage Current Reduction for a High-Frequency Carrier Inverter Feeding an Induction Motor," *IEEE Trans. Industry Applications*, vol. 28, no. 4, pp.858-863, Jul./Aug., 1992.

[2] S. Ogasawara and H. Akagi: "Modeling and Damping of High-Frequency Leakage Currents in PWM Inverter-Fed AC Motor Drive Systems," *IEEE Trans. Industry Applications*, vol. 32, no. 5, pp. 1105-1114, 1996.

[3] E. Zhong and T. A. Lipo: "Improvement in EMC Performance of Inverter-Fed Motor Drives," *IEEE Trans. Industry Applications*, vol. 31, no. 6, pp. 1247-1256, 1995.

[4] S. Ogasawara, H. Ayano, and H. Akagi: "Measurement and Reduction of EMI Radiated by a PWM Inverter-Fed AC Motor Drive System," *IEEE Trans. Industry Applications*, vol. 33, No. 4, pp. 1019-1026, Jul./Aug., 1997.

[5] S. Chen, T. A. Lipo, and D. Fitzgerald: "Modeling of Motor Bearing Currents in PWM Inverter Drives," *IEEE Trans. Industry Applications*, vol. 32, no. 6, pp.1365–1370, 1996.

[6] S. Chen and T. A. Lipo: "Circulating Type Motor Bearing Current in Inverter Drives," *IEEE Industry Applications Magazin*, vol. 4, no.1, pp. 32-38, Jan./Feb. 1998.

[7] J. M. Erdman, R. J. Kerkman, D. W. Schlegel, and G. L. Skibinski: "Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltages," *IEEE Trans. Industry Applications*, vol. 32, no. 2, pp. 250-259. Mar./Apr., 1996.

[8] D. Busse, J. Erdman, R. J. Kerkman, D. Schlegel, and G. Skibinski: "Bearing Currents and Their Relationship to PWM Drives," *IEEE Trans. Power Electronics*, vol. 12, no. 2, pp. 243-252, Mar., 1997.

[9] D. Busse, J. Erdman, R. Kerkman, D. Schlegel, and G. Skibinski: "Characteristics of Shaft Voltage and Bearing Currents," *IEEE Industry Applications Magazin*, vol. 3, no. 6, pp. 21-32 Nov./Dec. 1997.

[10] A. von Jouanne, D. A. Rendusara, P. N. Enjeti, and W. G. Gray: "Filtering Technique to Minimize the Effect of Long Motor Leads on PWM Inverter-Fed AC Motor Drive Systems, " *IEEE Trans. Industry Applications*, vol. 32, no. 4, pp. 919-926, 1996.

[11] A. von Jouanne, P. N. Enjeti, and W. G. Gray: "Application issues for PWM Adjustable Speed AC Motor Drives," *IEEE Industry Applications Magazine*, vol. 2, no. 5, pp. 10-18, Sep./Oct. 1996.

[12] P. T. Finlayson: "Output Filters for PWM Drives with Induction Motors," *IEEE Industry Applications Magazine*, vol. 4, no. 1, pp. 46-52, Jan./Feb. 1996.

[13] A. H. Bonnett: "Available Insulation Systems for PWM Inverter-Fed Motors," *IEEE Industry Applications Magazine*, vol. 4, no. 1, pp. 14-26, Jan./Feb. 1998.

[14] B. Heller and A. Veverka: "Surge Phenomena in Electrical Machine," ILIFFE BOOKS LTD., 1968.

[15] R. E. Pretorius and A. J. Eriksson: "A basic guide to rc surge suppression on motors and transformers," *Transaction on SA Institute of Electrical Engineers*. pp. 201-209, Aug. 1980.

[16] A. Ogata and I. Takahashi: "Active Compensation Circuit of Leak Current in Inverter driven loads," *National Convention Rec. IEE Japan*, No.815, 1996 (in Japanese).

[17] I. Takahashi, A. Ogata, H. Kanazawa, and A. Hiruma: "Active EMI Filter for Switching Noise of High Frequency Inverter," *PCC-Nagaoka'97 Conf. Rec.*, pp. 331-334, 1997.

[18] S. Ogasawara, H. Ayano, and H. Akagi: "An Active Circuit for Cancellation of Common-Mode Voltage Generated by a PWM Inverter," *IEEE Trans. Power Electronics*, vol. 13, no. 5, sep. 1998.

[19] A. L. Julian, T. A. Lipo, and G. Oriti: "Elimination of Common Mode Voltage in Three Phase Sinusoidal Power Converters," *PESC 96 Conf. Rec.*, pp.1968-1972, 1996.

[20] G. Oriti, A. L. Julian, and T. A. Lipo: "A New Space Vector Modulation Strategy for Common Mode Voltage Reduction," *PESC'97 Conf. Rec.*, pp. 1541-1546, 1997.