New Methods to Suppress EMI Noises in the Motor Drive System

Nobuyoshi Mutoh*, Mitsukatsu Ogata, Kayhan Gulez, and Fumio Harashima
Tokyo Metropolitan Institute of Technology
6-6, Asahigaoka, Hinoshi-shi, Tokyo, 191-0065, Japan

Keywords <Drives, EMC/EMI, Harmonics, IPM, Modeling, Packaging>.

Abstract –New methods are studied that can suppress EMI noises, especially common mode currents produced in the motor drive system. One is a packaging technique that forms power converters using a four-layer printed power circuit board. The other is a method based on the generation mechanism of common mode currents which was developed from experimental analyses. It is proved by experiments that the former can effectively control common mode currents, including radiated emissions, and the latter can suppress them without any compensators between the inverter and the motor.

1 Introduction

Motor drive systems using power converters are applied to various kinds of electric apparatuses such as AC servo systems, elevators, and electric vehicles. As switching speeds of power devices used in motor drives have become higher and higher, electromagnetic interference (EMI) noises have begun to surface in these application areas [1]. Thus, EMI noises, especially the common mode currents, flowing into the earth via stray capacitors distributed between the PWM inverter and the motor have been studied [2]-[4]. The micro-surge voltage and the shaft voltage generated on the motor terminals have also become occurring by the increase in switching speeds [5]-[7]. These studies of EMI noises have mainly been done as problems produced in individual parts such as the PWM inverter or the motor. Thus, hardly any methods to reduce EMI noises have been proposed that came from complete studies including packaging methods of the power converters. Moreover, although methods have been proposed that prevent common mode noises by inserting a common mode noise canceller [8] and filter circuits [9] between the inverter and the motor, there is the new possibility that EMI noises are generated from these compensators.

So, two new methods are studied in this paper which prevent common mode currents, one using a packaging technique and the other eliminating any compensators between these apparatuses.

2 Packaging method for the motor drive system

2.1 Need for a packaging method to suppress common mode currents

EMI noises of the motor drive system shown in Fig.1 are studied. The system has a PWM converter and inverter, power supplies (AC/DC and DC/DC converters), controllers and a motor. There are two kinds of noises, i.e., differential mode (normal mode) noises and common mode noises [10]. The former are prevented using noise suppression measures such as EMI filters which conduct EMI noises produced by the differential voltage generated between line voltages. The latter noises are produced by common mode currents flowing through stray capacitors distributed in the motor drive system, as shown in Fig.2 [10]. The distribution of stray capacitors formed in the motor drive system strongly depends on packaging methods. Thus, study of the packaging method is needed to control the common mode currents.

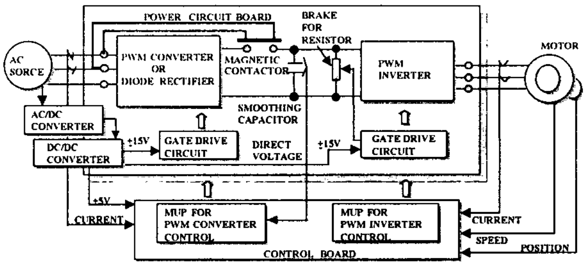


Fig.1 Structure of motor drive system using a printed circuit board.

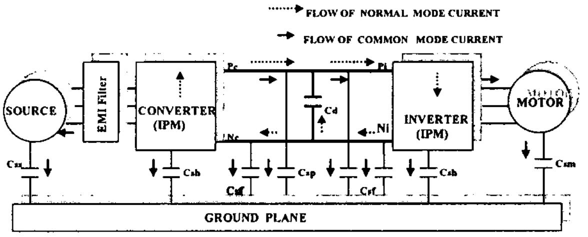


Fig.2 Normal mode current supplying electric power to a motor, and paths of common mode currents flowing through stray capacitors formed on the power circuit.

2.2 Proposed packaging method

Fig.3 shows a new packaging structure proposed to control common mode noises generated in power converters. The structure is characterized by forming power converters including their control units using four-layer printed power circuit board: first layer, gate circuits, voltage and current detectors, and power transmission lines for source supplies; second layer, P-power transmission line connected to the pulse terminals between the PWM converter and the PWM inverter; third layer, N-power transmission line connected to the minus terminals between the PWM converter and PWM inverter; fourth layer, three kinds of ground planes for the PWM converter, the PWM inverter, and source supplies. The size of the printed power circuit board is 480mm long × 280mm wide, and the rated capacity of IPMs used for power converters is 100A. The dielectric strength (in thickness 0.4 mm) and the dielectric constant of the insulator in this printed power board are 7.5kV and 4.7, respectively. The P- and N-power transmission lines are designed so that they may have a symmetrical structure with the dielectric substrate sandwiched between them. The differential mode voltage ΔV which appears between the P-and N-power transmission lines is given by eq.(1), as the assumption is satisfied in the structure that the differential of the current i1 in the P- power transmission line (di_1/dt) is equal to the negative of the differential of the current in the N- power transmission line.

$$\Delta V = (L_{s1} + L_{s2} - 2M)d i_1 / dt = L_{eff}\, d i_1 / dt \tag{1}$$

where L_{s1}, self-inductance of the P-power transmission lines; L_{s2}, self-inductance of the N-power transmission line; M, mutual inductance; and L_{eff}, effective inductance when P- and N-power transmission lines are laid out. Thus, an effective inductance L_{eff} smaller than the combined inductance L $(=L_{s1} + L_{s2})$ can be obtained. As the differential mode voltage, which excites differential mode noises is reduced, differential mode noises produced between P- and N-power transmission lines are prevented. As a result, EMI noises generated by the converter and the inverter are almost completely limited to the common mode noises. These appear as common mode currents flowing into the ground plane laid in the fourth layer. Thus, the currents can be confined to the area where power transmission lines are laid out.

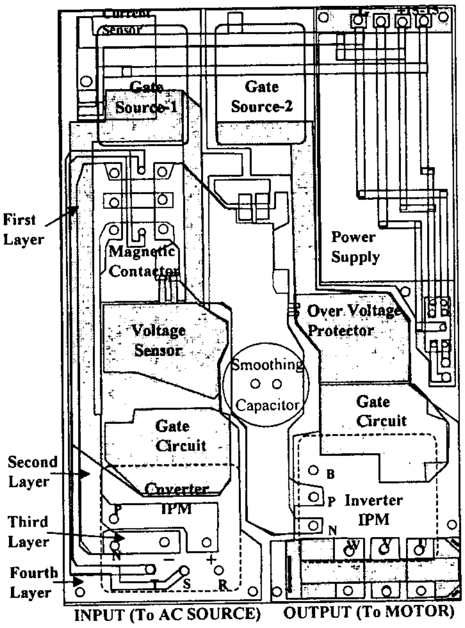


Fig.3 Structure of power converters fully printed in the motor drive system shown in Fig.1.

2.3 Magnetic fields produced on the board

The magnetic field distributions produced on the board shown in Fig.3 are studied to investigate whether common mode noises are confined to the area where P- and N- power transmission lines are laid out in the proposed structure.

The magnetic fields are calculated by using the moment method [10][11] on the condition that the impedance of the smoothing capacitor can be recognized as zero, and the terminals of the P-and N- power transmission lines on the side of the PWM inverter are electrically shorted. In the calculation, a unit voltage is applied to the converter terminals between the P- and N-power transmission lines so that the currents with the same direction, i.e. the common mode currents, can flow in both power transmission lines.

The relationship between the current flowing on the surface of the transmission lines and the incident electric field is given by eqs. (2) and (3).

$$\vec{J}_c(\vec{r}') = \sum_{i=1}^{N} \vec{W}_i \cdot I_i \tag{2}$$

Here, N is the number of unknown quantities and the weight function $\vec{W}$ is defined by Refs [10][11].

$$j\omega \sum_{i=1}^{N} \left\{ \frac{\mu_0}{4\pi} \int_{S_j} \int_{S_i} \vec{W}_j \cdot \vec{W}_i dS_i dS_j \right\} \times I_i + \frac{1}{j\omega} \sum_{i=1}^{N} \left\{ \frac{-1}{4\pi\varepsilon_0} \int_{S_j} \int_{S_i} (\nabla \cdot \vec{W}_j) \cdot (\nabla \cdot \vec{W}_i) \varphi dS_i dS_j \right\} \times I_i = \int_{S_j} \vec{W}_j \cdot \vec{E}_0 dS_j \tag{3}$$

The coefficient '$j\omega$', coefficient '$1/j\omega$' and the right side of the equation are expressed the inductance, the reciprocal of stray capacitance, and the voltage source generated from the power converter, respectively. Eq. (3) is rewritten as eq. (4).

$$[Z_{ij}] \cdot [I_i] = [Vi] \tag{4}$$

Unknown current $[Ii]$ can be obtained if the source voltage vector $[Vi]$ is given, and the impedance matrix [Zij] corresponding to the structure of the power transmission lines is determined. If the voltage source Vj is normalized as 1[V], the magnetic field $\vec{H}(\vec{r})$ is given by eq. (5) using Ii obtained from eq. (4).

$$\vec{H}(\vec{r}) = \sum_{i=1}^{N} I_i \left\{ -\frac{1}{4\pi} \int_{S_i} \vec{w} \times \nabla \varphi dS_i \right\} + \vec{H}_0 \tag{5}$$

Here, $\vec{H}_0$ is the incident magnetic field and it is set as zero.

Fig.4 shows magnetic near-fields when the common mode currents flow from the converter to the inverter. In this case, the frequency of common mode currents is 10MHz which is around the highest frequency of the harmonic components appearing in these currents [10]. The magnetic field distributions are concentrically generated so as to surround the power transmission lines and the magnetic field becomes strong around the regions where they are laid out. This means that the proposed method makes it possible to confine radiated EMI noises (emissions) generated by common mode currents to the narrow spaces around the power transmission lines. Thus, it is concluded that the structure is that is able to cope easily with radiated emissions. Also, as common mode currents can flow into the ground plane through the capacitor formed on the board using the dielectric, countermeasures can easily be taken on the ground plane side against these noises due to the common mode currents.

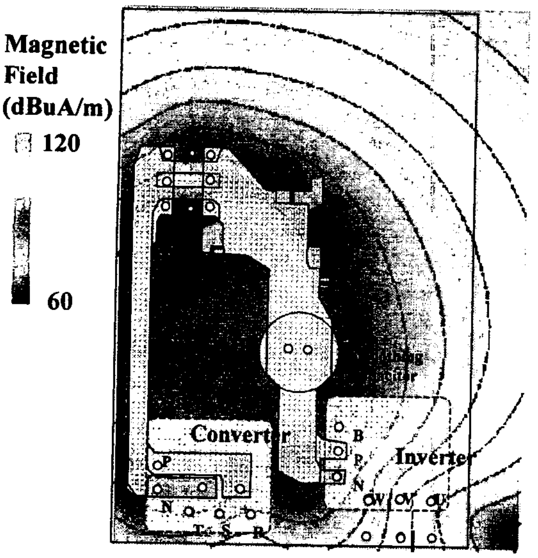


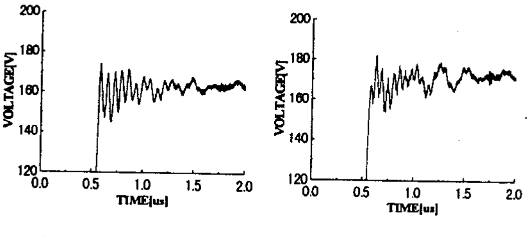
Fig.4 Magnetic near-fields generated by the common mode currents in the power converters of Fig.2 (excited frequency: 10MHz).

3 Experimental analyses of EMI noises

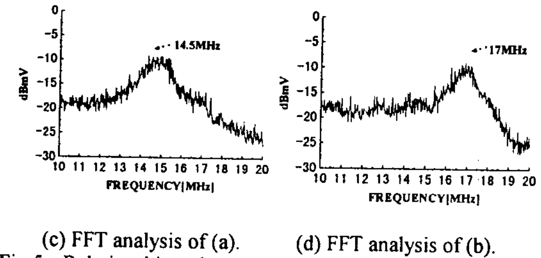
3.1 EMI noises affecting power converters

3.1.1 Factors producing EMI noises

EMI noises originate in switching operations when the PWM control is implemented. So, higher harmonics having a strong effect on common mode noises are examined through FFT analyses of transient waveforms when the phase voltages of the converter and inverter are changed by switching operations. Fig.5 (a) and (b) show the transient waveforms of the phase voltages when power devices of the R and U phases are changed from the on-state to the off-state. FFT analyses of their waveforms are given in Figs. 5(c) and (d). Sharp transient oscillations are generated that have high frequencies around 14.5MHz (converter side) and 17MHz (inverter side). These fluctuations of the voltage become exciting sources of EMI noises that produce the differential mode currents and the common mode currents. However, the differential mode currents are weakened because the structure of the power transmission lines is symmetrically formed, and then the differential mode currents have hardly any effect on emissions radiated from the printed power circuit. On the other hand, as the common mode currents diffuse into the ground plane via the capacitor distributed in the printed power circuit board. As a result, as shown in Fig.4, magnetic near-fields due to the flow of these common mode currents appear on the printed power circuit board. Accordingly, it is assumed that the voltage fluctuations having high frequencies that are produced by switching operations are the factors producing EMI noises, especially common mode noises.



(a) R phase voltage. (b) U phase voltage.

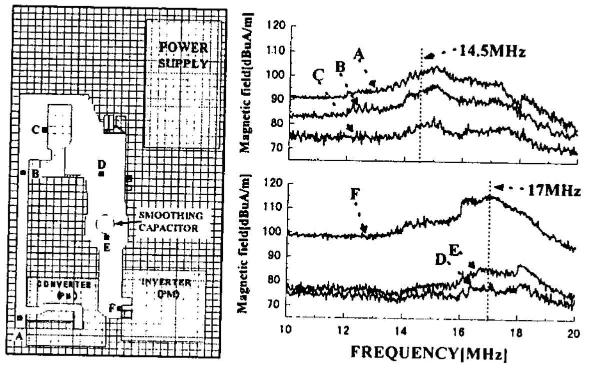


(c) FFT analysis of (a). (d) FFT analysis of (b).

Fig.5 Relationships between voltage waveforms of the converter and inverter, and the highest harmonics in their waveforms.

3.1.2 High frequency characteristics of the prototype printed power circuit board

The magnetic field at points shown in Fig. 6(a) is examined by measuring the surface currents with the same frequencies as shown in Figs.5(c) and (d) that flow in the P- power transmission line. For the measured magnetic fields shown by Fig.6(b), they appear on the power transmission line connected to the converter side, and they decrease more than 20[dBμA/m] when the measuring points are moved from "A" to "C". This means that the surface currents with the frequency of 14.5MHz are shunted to the ground plane by the sandwiched structure having low impedance at higher frequencies while they flow from the converter terminal near to "A" to "C". That is to say, surface currents generated by the switching operations of the converter that correspond to EMI noises almost all flow into the ground plane until arriving at "C". The same goes for surface currents generated from the inverter as shown in the lower graph of Fig.6 (b). Accordingly, the transmission lines and the ground plane. As a result,surface currents originating in EMI noises become common mode currents flowing between the power they are confined to the area where power transmission lines are laid out. The experimental results are same as the simulation results shown in Fig.4.



(a)Measuring points. (b) Magnetic field intensity.

Fig.6 Magnetic fields produced by high frequency currents flowing in the power transmission lines.

3.1.3 Common mode current leaking into cooling fins

In addition to the common mode currents cited above, there are common mode currents leaking into the cooling fins through the substrate of the IPMs in the power converter apparatus. Fig.7 shows the relationship between voltage variations by switching operations of power converters and the common mode currents. It is found from this figure that every time abrupt variations of the voltage are produced, large common mode currents are produced. Comparing FFT analyses of the common mode currents in Fig.8 with FFT analyses in Fig.5 shows that the high frequency voltage in Fig.5 becomes the source of common mode currents leaking into the cooling fins.

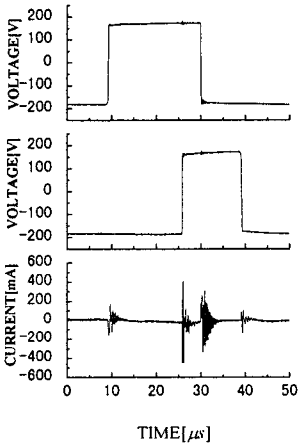


Fig.7 Common mode currents leaking to the cooling fin from IPMs by switching operations of the converter and inverter (upper, converter voltage; middle; inverter voltage, lower, common mode current).

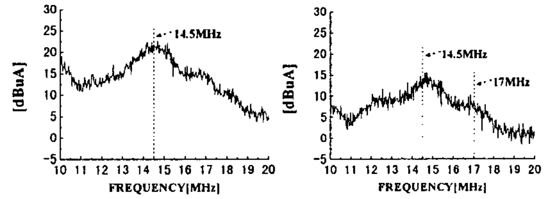


Fig.8 FFT analyses of common mode currents leaking from IPMs of the converter and inverter.

3.2 Common mode noises appearing at motor and AC source sides

The voltage fluctuations generated by switching operations are also transmitted to the motor terminal through power transmission lines. When the third wave (of Fig.9) with high *dv/dt* is output from the inverter and arrives at the motor terminal, the surge voltage appears in the line voltage of the motor terminal by the reflection of the wave [12], as shown by the second wave of Fig.9. The surge voltage is superposed on the common mode voltage. As a result, the waveform of the common mode voltage is altered as shown in the upper of Fig.9 and there is high frequency ripple around the timing when the level of the common mode voltage is changed. When the common mode voltage with high frequency ripple is applied between the motor terminal and the motor frame through the stray capacitors, abrupt displaced currents are produced in a short period while the level of the common mode voltage is changing. This leads to motor leakage currents shown in Fig.9, i.e., common mode currents that keep on flowing into the earth while the common mode voltage is changing. The fact cited above is verified by comparing FFT analyses of the common mode currents with those of the common mode and line voltages. As shown in the left graph of Fig.10 (a), both the harmonic component of3.5MHz produced by the surge voltage and that of 17MHz produced by the switching operations that appear in the line voltage appear even in the common mode voltage.Examining the harmonic components of the common mode currents shows they have a frequency spectrum corresponding to that of the common mode voltage and the line voltage. Accordingly, it is concluded that the exciting source causing the common mode currents to flow is made by superposing the transient voltage produced by switching of power devices and the surge voltage which appears at motor terminals on the common mode voltage.

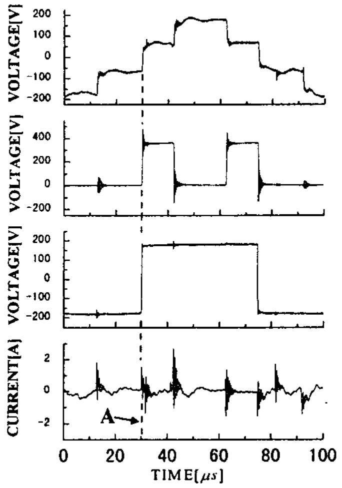
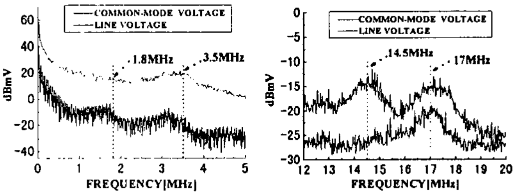
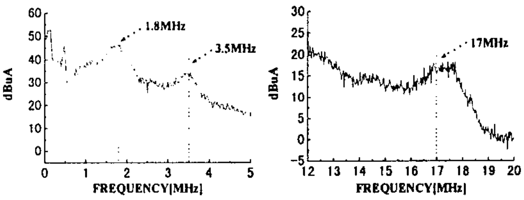


Fig.9 Motor leakage currents generated by fluctuations of the common mode voltage (first, common mode voltage; second, line voltage of the motor terminal; third, phase voltage of the inverter and fourth, common mode currents (leakage current).



(a) Common mode and line voltages.



(b) Common mode currents leaking into the earth.

Fig.10 FFT analyses of the common mode voltage and currents shown in Fig.9.

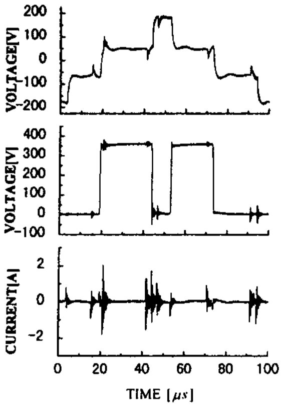
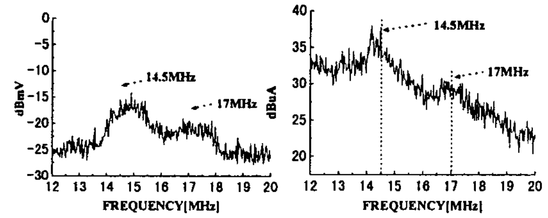


Fig.11 AC side common mode voltage fluctuated by reactor terminal voltage and common mode current (upper, common mode voltage; middle, line voltage of the AC reactor; and lower, common mode currents).



(a) Common mode voltage. (b) Common mode current.

Fig.12 FFT analyses of the common mode voltage and currents shown in Fig.11.

The same holds true for the common mode currents, which leak into the earth from the frame of the AC reactor. That is to say, as shown by Fig. 11, the fluctuations generated when the level of the line voltage of the AC reactor changes are reflected at the transient parts of the common mode voltage, and the common mode currents flow in accordance with variations of the common mode voltage.

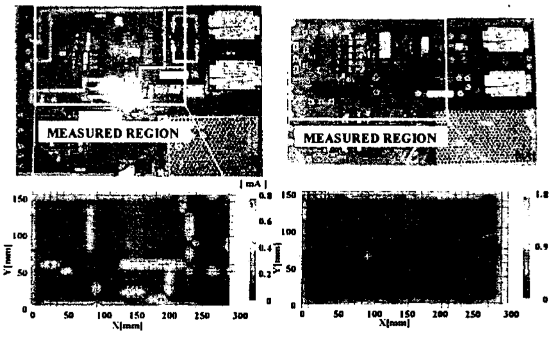
Analyzing waveforms of the common mode voltage and the common mode currents using the FFT method shows both have the same resonance frequencies, i.e. 14.5MHz and 17MHz. Thus, the same processes produce the common mode currents as on the motor side.

4 Suppression of common mode noises

4.1 Reduction effects of the proposed structure on radiated emissions

Reduction effects of the proposed structure on radiated emissions are verified using breadboards having the proposed and conventional structures. Fig.13 shows the surface currents flowing on the power transmission lines that were estimated based on near-fields measured by sweeping a three- dimensional probe at a point 3[cm] directly above the power transmission lines. In the measurements, the high frequency source of the voltage 0.4[V] and the frequency: 30MHz (the lowest frequency of the emission standard) was applied to between P- and N- power transmission lines terminated with 50[Ω].

In the proposed breadboard, the current was concentrated only around the terminal of the smoothing capacitor, and the peak was about 20[μA]. In the conventional breadboard, the current was almost on the power transmission lines and the peak was about 0.6[mA]. Thus the quantity was reduced to nearly 30 dB. The proposed breadboard effectively reduces radiated emissions.



(a)Conventional system (b) Proposed system

Fig.13 Suppression effects of the proposed system on radiated emissions.

4.2 Method to reduce common mode currents and its effects

First, a method to reduce common mode currents is studied. It was found through discussions in Section 3 that the common mode currents flowing into the earth from the frame of the machine (AC reactor or motor) were generated by fluctuations of the common mode voltage. It was found from Fig.10 (b) that the frequency was around 1.8MHz at which the common mode current becomes large. So, it is assumed that the common mode currents with the harmonic component of 1.8MHz flow every time the current is changed. If the transient wave of the leakage current is expressed by the envelop of the common mode currents, it is given by eq. (6).

$$i_c = \frac{E}{\sqrt{L/C}}\,\varepsilon^{-\frac{R}{2L}t} \qquad (6)$$

When eq. (6) is applied to the common mode currents beginning to flow at "A" in Fig.9, the peak value $E/\sqrt{L/C}$ and time constant $R/2L$ are 1.79[A] and 0.76[μs], respectively. Thus, as the common mode voltage is 350[V]/3, $\sqrt{L/C}$ becomes 86.8. Here, assuming that the abrupt peak of the common mode currents is generated due to series resonance phenomena, the resonance frequency f_r is given by eq. (7).

$$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2} \qquad (7)$$

Accordingly, the inductance L is expressed by eq. (8), as a function of (L/C) and $(R/2L)$.

$$L = \sqrt{\frac{\left(\sqrt{L/C}\right)^2}{4\pi^2 f_r + (R/2L)^2}} \qquad (8)$$

By substituting the above values 0.76 [μs], (=2L/R), 86.8(=$\sqrt{L/C}$), and 1.8MHz(=f_r) into eq.(8), 7.63 [μH] is obtained as the inductance L . Using the numeric values obtained, other circuit parameters C and R can be obtained as 1[nF] and 20.2[Ω], respectively. If the assumption is true that the peak appearing in the transient wave of the common mode current is generated due to series resonance phenomena, the common mode currents should be prevented by inserting a damping resistance of more than 20 [Ω] between the earth and the machine frame.

Next, the suppressing method is verified by experiments and simulations. Fig.14 shows suppression effects of the common mode currents when resistances inserted between the earth and the machine frame are varied. The common mode currents can be remarkably reduced when the resistance inserted is increased more than ten times the resistance of 20 [Ω] obtained under the series resonance conditions. Fig. 15 shows experiments when the series resonance phenomena are suppressed by the damping resistor. Fig.15(a) indicates that the common mode currents can be almost completely prevented by increasing the resistance inserted up to 1.3 [kΩ]. Also, it is found from Fig.15(b) that the frequency spectrum of 1.8MHz that was recognized as the series resonance frequency is reduced as much as 30[dBμA]. Accordingly, it is concluded through the above discussions that the abrupt peak which appears when common mode currents begin to flow is due to series resonance phenomena, and common mode currents can be completely prevented by inserting a damping resistance between the machine frame and the earth which is more than ten times the series resonance resistance.

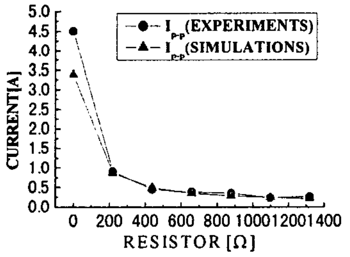
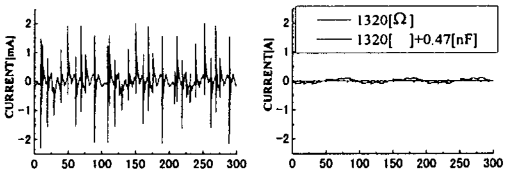
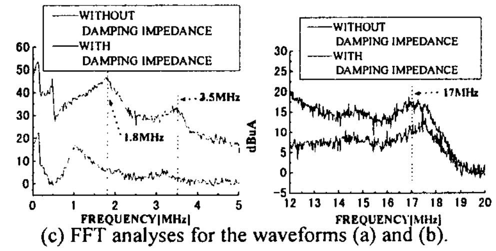


Fig.14 Suppression effects of the resistance inserted between the earth and the motor frame on the common mode currents.



(a) Without control. (b) With control.



(c) FFT analyses for the waveforms (a) and (b).

Fig.15 Suppression effects of the method to prevent series resonance by adding damping impedances to the common mode current path.

5 Conclusions

The generation mechanism and a suppressing method of EMI noises, especially the common mode noises generated in the motor drive system were studied using a multi-layer printed power circuit board.

1) The common mode noises produced in the power converters could be confined to the area where the power transmission lines were laid out by forming a symmetrical structure of power transmission.

2) When the fluctuations of the voltage generated by the switching operations were transmitted outside the machine, such as to the AC reactor and the motor, they were superposed on the common mode voltage. This lead to increased common mode currents.

3) The common mode currents flowing into the machine installed outside of the power converters could be completely controlled by inserting the damping resistor between the earth and the motor frame so as to prevent series resonance phenomena.

References

[1] G. L. Skibinki, R. J. Kerkman, and D. Schelegel, "*EMI Emissions of Modern PWM AC Drives,*" *IEEE IA Magazine*, Nov./Dec. pp.47-81, 1999

[2] A. Consoli, G. Oriti, A. Testa, and A.L. Julian, "*Induction Motor Modeling for Common Mode and Differential Mode Emission Evaluation*", IEEE IAS'96, Vol.1, pp.598-602, Oct. 1996

[3] G. Oriti, A. L. Julian, T. A. Lip, "*A New Space Vector Modulation Strategy for Common Mode Voltage Reduction*", IEEE IAS'97 Vol.1, pp587-592, Oct. 1997

[4] M. Cacciato, A. Consoli, G. Scarcella, A. Testa, "*Reduction of Common-Mode Currents in PWM Inverter Motor Drives*", IEEE IA, Vol.35, No.2, pp.469-476, 1999

[5] G. Skibinski, "*Design Methodology of a Cable Terminator to Reduce Reflected Voltage on AC Motors*", IAS' 96, Vol.1, pp.153-161, 1996

[6] R. J. Kerman, D. Leggate, G. L. Skibinski, "*Interaction of Drive Modulation and Cable Parameter on AC Motor Transients*", IEEE I A., Vol. 33, No.3, pp.722-731, 1997

[7] J. M. Erdman, R. J. Kerkman, D. W. Schlegel, G. L. Skibinski," *Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltage*", IEEE I A.., Vol. 32, No.2, pp.250-259, 1996

[8] S. Ogasawara, H. Ayano, H. Akagi, "*Active Cancellation of the Common-Mode Voltage by a Voltage-Source PWM Inverter*", Trans. IEE of Japan, Vol. 117-D, No.6, pp.565-571, 1997

[9] E. Zhong, T. A. Lipo, "*Improvement in EMC Performance of Inverter-Fed Motor Drives*", IEEE I A, Vo.31, No.6, pp1247-1256, 1995

[10] N. Mutoh, S. Shirakawa, K. Komatu, N. Ohnuma, S. Hokari, F. Harashima, "*Electromagnetic Characteristics of a High Density Motor Drive System Using a Printed Power Circuit Board*" Trans. IEE of Japan, Vol. 121-D, No.1, 2001

[11] S. Shirakawa, N. Mutoh, K. Komatu, "*Using Computer Simulation to Analyze Electromagnetic Emissions Generated in PWM Inverter,*" Trans. IEE Japan, Vol.119-D, No.2, pp.195-203, 1999

[12] R.J. Kerkmam, D. Leggate, G. L. Skibinski, "*Interaction of Drive Modulation and Cable Parameters on AC Motor Transients*" , IEEE Trans. I A, Vol.33, No.3, 1997