Z-matched Active Common-mode Canceller for the Suppression of Common-mode Current in an Inverter System

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In a vehicle, radiational noise generated by the common-mode current in an inverter system is the cause of electromagnetic issues affecting in-vehicle radio antennas. This paper proposes a new method “Z-matched ACC” for suppressing the common-mode current at the AM band. Using this method, the exciting current of the common-mode transformer, which reduces the common-mode current suppression effect higher than 100kHz in conventional voltage-cancellation ACC, flows into a Z-matched circuit rather than into a motor parasitic capacitor. Therefore, the Z-matched ACC can suppress the common-mode current at the AM band. The suppression effect of the Z-matched ACC is superior to the conventional ACC from 100kHz to 10MHz. In addition, the Z-matched ACC can reduce the size of the common-mode transformer compared to the conventional ACC by reducing the ET product applied to the common-mode transformer.

Keywords: active common-mode canceller, suppression of common-mode current

1. Introduction

In an inverter system, common-mode current flows through a motor parasitic capacitor and a grounding capacitor. Since electromagnetic waves conducted and emitted by common-mode current cause malfunctions and electromagnetic interference in other devices**, there are standards defining a common-mode current value for each frequency. In automobiles, common-mode current generates electromagnetic radiation noise and causes electromagnetic problems with the in-vehicle radio**. Electromagnetic field analysis is also studied, and effective methods for suppressing common-mode current are required for AM bands (510kHz–1.7 MHz) as well as FM bands (76MHz–108MHz).

As representative examples, active common-mode cancellers are in use, and these are broadly divided into voltage cancellation methods and current cancellation types. In the voltage cancellation type, common-mode current is suppressed by applying the detected common-mode voltage to the inverter output via the common-mode transformer to cancel out the common-mode voltage of the inverter. The current cancellation type is a method for suppressing common-mode current by inputting the detected common-mode current into a complementary transistor circuit (a low-impedance current amplification circuit), and supplying the amplified compensating current to the noise path via a capacitor.

However, in both cases the common-mode current suppression effect diminishes as the frequency of the band extends into the MHz range. The reason for this is because, in the case of the voltage cancellation method, common-mode current cannot be suppressed due to the effects of the phase characteristics of the common-mode path of the motor and the phase characteristics of the DC power supply capacitor used in the active common-mode canceller circuit. In the authors’ experimental devices, the suppression effect diminished where the frequency band extended higher than 200kHz, and a suppression effect of only 8dB was obtained at 1MHz when using only a common-mode choking coil. Moreover, in the current cancellation method, due to the response restriction of the current amplifier, it is difficult to completely cancel the common-mode current in frequency bands in the MHz range.

In this paper, we propose an impedance matching-type active common noise canceller improving on conventional voltage cancellation methods with the aim of suppressing common-mode current in AM bands. An impedance-matching circuit matching the phase characteristic of the motor common-mode path is installed between a common-mode transformer and the ground potential, solving the problems of the conventional voltage cancellation method. It was confirmed by experiment that a suppression effect of 33dB was obtained against a common-mode choking coil at 1MHz and 25dB against the conventional voltage cancellation method.

In this paper, problems with the voltage cancellation method will be explained in detail in Section 2. Section 3 describes the configuration and principles of the proposed impedance-matching type active common-mode canceller. Section 4 shows the results of simulation and Section 5 the
experimental results, validating the utility of the proposed method.

2. An Overview of the Voltage-Method Active Common-Mode Canceller

2.1 Common-Mode Current in Inverter Systems

First, we will describe the common-mode current of the inverter system which is the target for suppression in this paper. Figure 1 shows a schematic diagram of an inverter system with a battery as a power source. Point g is the ground potential, and the motor frame is connected to the ground potential. $C_{Y1}$, $C_{Y2}$ are Y capacitors, $C_m$ is the parasitic capacitance between the motor winding and the frame, and $L_{pu}$, $L_{pv}$, $L_{pw}$ are the wiring inductors of each phase between the inverter and the motor. Common-mode voltage is generated by the switching motion of the inverter, and common mode current $i_{com}$ flows across the inverter - motor - motor frame - ground line - Y capacitor.

Figure 2 shows common-mode current $i_{com}$ where using a battery voltage of 25 V, Y capacitors $C_{Y1}$, $C_{Y2}$ with a capacitance of 4.7 nF and 6MBI120A (Fuji Electric) as a 3-phase module for the inverter; Fig. 3 shows the spectrum waveform. The common-mode current $i_{com}$ being a 4.7 MHz oscillating current, the presence of a peak (5) can be confirmed at 4.7 MHz in the spectrum waveform.

The peaks and dips of the common mode current spectrum are caused by the impedance characteristics of the path across which the common-mode current flows. Figure 4 shows the motor-side impedance between the 3-phase lines and the ground potential point g (hereinafter referred to as the motor common impedance) $Z_m$, when short-circuiting the inverter outputs u, v and w, while Fig. 5 shows the measured values of the frequency characteristics of the battery-side Y joint impedance $Z_Y$ between the inverter input and the ground potential point g when short-circuiting the inverter inputs a and b. Peaks (1) and (5) of the spectrum waveform shown in Fig. 3 are the series resonances of motor common impedance $Z_m$, while dip (2) is the parallel resonance. Moreover, peak (3) and dip (4) correspond to the series resonance of Y joint impedance $Z_Y$ and the parallel resonance respectively.

Note that while Y joint impedance $Z_Y$ also has other resonance points, the size of the motor common impedance $Z_m$ becomes dominant at these resonant frequencies and these are not shown on the spectrum.
If there is provisionally a series resonance point in the AM band, electromagnetic noise in the AM band is generated corresponding to the loop area of the path across which the common-mode current flows, and this may cause electromagnetic interference in the in-vehicle radio antenna.

### 2.2 Construction and Suppression Effect of the Voltage Method Active Common Mode Canceller

Next we will explain the principles and experimental results of the voltage method active common-mode canceller (hereinafter referred to as ACC; Active Common-mode Canceller) that suppresses the common-mode current $i_{com}$ of the inverter.

Figure 6 shows the construction of the voltage-type ACC. The voltage method ACC consists of a common-mode transformer $T_{com}$, an emitter-follower current amplifier, common-mode voltage detection capacitors $C_{d1}$, $C_{d2}$, and $C_{d3}$, and DC bus capacitors $C_{dc1}$ and $C_{dc2}$. The basic principle of its operation is that common-mode current $i_{com}$ is suppressed by applying the detected common-mode voltage to the inverter output via the common-mode transformer $T_{com}$, cancelling out the common-mode voltage.

Figure 7 shows the spectrum waveform of common-mode current $i_{com}$ where applying each suppression method to the inverter system and compares the suppression effects. The recorded conditions are (i) inverter-only (no suppressor), (ii) a common-mode choke, and (iii) a conventional voltage method ACC.

The circuit of the conventional voltage-method ACC is structured as shown in Fig. 6: FINEMET (Hitachi Metals) is used as the core material of the common-mode transformer $T_{com}$ with 6 turns and a turn ratio of 1:1. A 2SC4615 (SANYO) was used for transistor $T_{r1}$ and a 2SA1772 (SANYO) was used for transistor $T_{r2}$. Other circuit constants are shown in Table 1. The circuit structure of the common-mode choke (ii) was created by removing the windings connecting the emitter-follower current amplifier and the current amplifier from the conventional voltage method ACC circuit and using this as a common-mode choke without changing the core material or the number of turns.

![Fig. 6. Configuration diagram of the Conventional ACC](image)

![Fig. 7. Measured spectrum of the common-mode current](image)

![Fig. 8. Impedance frequency characteristic of the common choke coil](image)

<table>
<thead>
<tr>
<th>Table 1. circuit parameters</th>
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<tr>
<td>$C_{d1}$, $C_{d2}$ [(F)] 1 n</td>
</tr>
<tr>
<td>$C_{dc1}$, $C_{dc2}$ [(F)] 1 μ</td>
</tr>
<tr>
<td>$C_{yd1}$, $C_{yd2}$ [(F)] 4.7 n</td>
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</table>

Figure 8 shows the measured values of the frequency characteristics of common-mode choke impedance $Z_{chk}$. Although impedance decreases above 5 MHz, it has high impedance characteristics with respect to the motor common shown in Fig. 4, and when applying the common-mode choke (ii), it was able to suppress common-mode current up to the 10 MHz noise level.

Similarly, the noise level when applying the conventional voltage method ACC (iii) across the entire 100 kHz–10 MHz frequency band is improved compared to when a suppressor is not used (i).

Conversely, in frequency bands higher than 300 kHz, the noise level becomes large when applying the common-mode choke (ii) and the suppression effect is inferior. In Section 2.3 we consider the factors causing this phenomenon.

### 2.3 Issues with Conventional Voltage-method ACCs

We will explain the factors causing the reduction of the suppression effect in high frequency bands using a circuit equivalent to a conventional voltage-type ACC as well as experimental results. Figure 9 shows the equivalent circuit for a conventional voltage-method ACC, $Z_{Cdc}$ is the impedance of DC bus capacitor $C_{dc}$, $Z_{m}$ is the motor common impedance, and $Z_{Y}$ is the joint impedance of Y capacitors $C_{Y1}$ and $C_{Y2}$. The conventional voltage method ACC applies common-mode voltage $v_{com}$ to the common-mode transformer $T_{com}$ as well as DC bus capacitor $C_{dc}$ through the current amplifier. Where the impedance of DC bus capacitor $C_{dc}$ is sufficiently smaller than that of common-mode transformer $T_{com}$, applying voltage $v^{'com}$, roughly equivalent to the common-mode voltage, to common-mode transformer $T_{com}$, common-mode current
The factor reducing the suppression effect even in high frequency bands.

\[ \theta = \angle \frac{Z_{all}}{Z_{Cdc}} \]

where, \( \theta = \angle \frac{Z_{all}}{Z_{Cdc}} \) is the phase of \( Z_{all} \) and \( Z_{Cdc} \) as \( a \), and phase difference \( \theta_2 - \theta_1 \) as \( \Delta \theta \), \( i_{com} \) and \( I_{com} \) become:

\[ i_{com} = \frac{1}{1 + ae^{\Delta \theta}} i_e \]

\[ I_{com} = \frac{1}{\sqrt{(1 + a \cos \Delta \theta)^2 + (a \sin \Delta \theta)^2}} I_e \]

In Equation (3), where \( \Delta \theta = 0 \), the amplitude of common-mode current \( I_{com} \) is at a minimum, and can be expressed using the equation below:

\[ I_{com} = \frac{1}{1 + a} I_e \]

In this way, where \( \theta_1 = \theta_2 \), the flow of common-mode current \( i_{com} \) can be obtained by dividing the excitation current \( i_e \) by the impedance ratio. The motor common impedance \( Z_m \) exhibits capacitance in low frequency bands. As shown in Fig. 4, in this experiment’s test apparatus, this was \(-90\) deg up to \( 200 \) kHz. However, as the frequency increases, the effects of the wire inductance increase and the phase of \( Z_m \) changes, and if \( Z_{Cdc} = 90 \) deg, then \( \theta_1 \neq \theta_2 \). In Equation (3), the right-hand side portion becomes smaller where \( \theta_1 \neq \theta_2 \) than where \( \theta_1 = \theta_2 \). Therefore, in the frequency band \( Z_{Cdc} \neq Z_{all} \), the amplitude of common-mode current \( I_{com} \) increases.

The noise level of common-mode current of the conventional voltage method ACC shown in Fig. 7 begins to increase above \( 200 \) kHz, and at \( 300 \) kHz and higher frequency bands this becomes higher even than when only using a common mode choke. Therefore, even when using an amp with good high-frequency characteristics, a perfect effect cannot be obtained in the frequency band where \( \theta_1 \neq \theta_2 \).

3. Proposing a New Method for Common-Mode Current Suppression

3.1 Construction of an Impedance Match-type ACC

In this section, we propose a new impedance matching ACC that maintains a common-mode current suppression effect even in high frequency bands.
As explained in section 2.3, common-mode current increases in frequency bands where the phase angle of the impedance of the motor common path and the DC bus capacitor are not equal, degrading the suppression effect of the conventional voltage-type ACC. Viewed from the other side, it is desirable for the phase angles of both paths’ impedances to align in frequency bands where a common-mode current suppression effect is required. Figure 12 shows the configuration of the impedance matching ACC proposed in this paper that fulfills this requirement; note there are two distinctions from conventional voltage-type ACCs. The first point is that the impedance matching circuit is connected between one end of the fourth winding of the common-mode transformer and the ground line, and the second point is that the current path through the fourth winding of the common-mode transformer is not the DC bus capacitors $C_{dc1}$ and $C_{dc2}$ of the conventional ACC shown in Fig. 6, but instead the impedance matching circuit as well as Y capacitors $C_{Y1}$ and $C_{Y2}$. We will set out the principles and efficacy of the proposed method.

### 3.2 The Principles of the Impedance Matching ACC

A circuit equivalent to the proposed impedance matching ACC is shown in Fig. 13. Here, $Z_{mat}$ is the impedance of the impedance matching circuit. The impedance matching circuit is configured to satisfy the following equations in desirable frequency bands:

\[
\left| Z_{mat} \right| = \frac{1}{a} \left| Z_m \right| \quad \text{........................................... (5)}
\]

\[
\angle Z_{mat} = \angle Z_m \quad \text{........................................... (6)}
\]

The frequency characteristics of the impedance matching circuit are the same as motor common impedance $Z_m$, the phase is the same, and the size is $1/a$. Therefore, dividing frequency components matching the phase of the common-mode transformer’s excitation current $i_e$ by the impedance ratio, a flow $1+a$ times greater than the motor common path can be achieved in the impedance matching circuit. Common-mode current $i_{com}$ when using the impedance matching ACC is given by the following equation:

\[
i_{com} = \frac{\left| Z_{mat} \right|}{\left| Z_{mat} \right| + \left| Z_m \right|} i_e = \frac{1}{1+a} i_e \quad \text{........................................... (7)}
\]

For example, taking ‘a’ to be 10, the suppression effect of the impedance-matching ACC is 20.8 dB greater than when using a common mode choke.

### 3.3 Impedance Matching Circuit Configuration and Circuit Constants

We will explain the method of deriving the impedance matching circuit.

![Fig. 12. Configuration diagram of the Z-match ACC](image)

![Fig. 13. Equivalent common circuit of proposed Z-matched ACC](image)

![Fig. 14. Equivalent circuit of the motor common equivalent circuit](image)

### Table 2. Circuit parameters

<table>
<thead>
<tr>
<th>Circuit parameter</th>
<th>Motor common equivalent circuit</th>
<th>Z-matched circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$ [H]</td>
<td>900 nH</td>
<td>900 nH/a</td>
</tr>
<tr>
<td>$L_2$ [H]</td>
<td>20 μH</td>
<td>20 μH/a</td>
</tr>
<tr>
<td>$R_1$ [Ω]</td>
<td>200</td>
<td>200 Ω/a</td>
</tr>
<tr>
<td>$R_2$ [Ω]</td>
<td>4</td>
<td>4 Ω/a</td>
</tr>
<tr>
<td>$L_1$ [H]</td>
<td>40</td>
<td>40 Ω/a</td>
</tr>
<tr>
<td>$L_2$ [H]</td>
<td>1.4 nH</td>
<td>1.4 nH/a</td>
</tr>
<tr>
<td>$C_1$ [F]</td>
<td>2.2 nF</td>
<td>2.2 nF/a</td>
</tr>
</tbody>
</table>

Figure 14 shows an equivalent circuit derived from the motor common impedance characteristics shown in Fig. 4 (including the cable). The impedance matching circuit has the same circuit construction as that of the motor common path equivalent circuit. Table 2 shows the circuit constants of the motor common equivalent circuit. By substituting the constants of the motor common equivalent circuit into the equation below, we obtain the circuit constants of the impedance matching circuit with the same phase as the motor common path and a size of 1/a.

\[
L' = \frac{1}{a} L \quad \text{........................................... (8)}
\]

\[
R' = \frac{1}{a} R \quad \text{........................................... (9)}
\]

\[
C' = aC \quad \text{........................................... (10)}
\]

The circuit constants given in Table 2 are used in the simulation and practical evaluation of the impedance matching ACC shown below.

### 4. Simulation

#### 4.1 Circuit Simulation

Simulation was performed using the circuit shown in Fig. 15 in order to validate the results of the proposed impedance-matching ACC. The simulation circuit is a common mode equivalent circuit of the inverter system shown in Fig. 2. The motor common path
equivalent circuit and impedance matching circuit are constructed as explained in Section 3, and the values of their circuit constants are shown in Table 2. The value of ‘a’ in Equation (5) used in the impedance matching circuit was set to 10. If ‘a’ is made large then the common-mode current $i_{com}$ can be made smaller; however, since the wiring inductance of the impedance matching circuit parts cannot be ignored in practice, it takes a finite value. The ground capacitance equivalent circuit is the same as the motor common path equivalent circuit, and was derived from the impedance characteristics in Fig. 5.

4.2 Results of the Simulation

First, in order to confirm the validity of the common-mode equivalent circuit model, we compared the common mode current obtained from the results of the simulation with the actual waveform. Figure 16 shows the results of calculating the common mode current when operated with a battery voltage of 25 V. Note that an impedance matching ACC is not being operated in Fig. 16. The current value and the resonance frequency matched well with the actual waveform shown in Fig. 2, validating the results of our proposed method using this equivalent circuit.

Figure 17 shows the waveform of the common mode current $i_{com}$ and the impedance matching circuit current $i_Z$ where the impedance matching ACC is operated. By passing the majority of the excitation current of the common mode transformer through the impedance matching circuit, a reduction in common mode current $i_{com}$ was achieved compared to Fig. 16 in which the ACC was not operated.

5. Verification of the Real Device

5.1 Experiment Structure

The impedance match-type ACC was mounted on an actual inverter, and its suppression effect verified using an actual device. Figure 18 shows the configuration of the experiment bench used for the verification of the actual device. The inverter and common mode transformer were driven by a 3-phase synchronous signal at 50% duty with specifications as shown in Section 2; a power supply voltage of 25 V, and a switching frequency of 10 kHz. The impedance matching circuit consists of chip components with the constant ‘a’ from equation (5) set to 10, a 1 A inductor, a $\frac{1}{2}$ W resistor and a capacitor rated at 100 V. Figure 19 shows the frequency characteristics of the impedance matching circuit $Z_{mat}$ and that of the motor common impedance $Z_{com}$.

The size of the impedance of the impedance matching circuit was 1/10th that of the motor common impedance, including the cable impedance, and the phases roughly coincided up to 4.5 MHz. The common-mode current was measured using a 3-phase inverter output line using a 91550 (ETS-Lindgren) current probe. An N9020 (Agilent) was used as the spectrum analyzer. The frequency range was set to 100 kHz–10 MHz, RBW at 10 kHz and VBW at 30 kHz, and the frequency component of common-mode current $i_{com}$ was measured using the peak detection method.
5.2 Common-Mode Current Suppression Effects

Figure 20 shows the measured waveforms of common-mode current $i_{\text{com}}$ and of the impedance matching circuit current $i_z$. Similar to the simulated results in Fig. 17, common-mode current $i_{\text{com}}$ is suppressed. Indeed, the peak current value of 16 mA of current $i_z$ in the impedance matching circuit used in the experiment is smaller than the 23 mA of the simulation, and this is thought to result from insufficient consideration for the resistance components of the common mode choke and other damping factors.

Next, by comparing the spectra of common-mode current $i_{\text{com}}$ of conventional suppression technology and the proposed impedance matching method ACC, we show the efficacy of this method. Figure 21 shows the spectrum waveform of common-mode current $i_{\text{com}}$.

The conditions are those of (i)–(iii) in Fig. 7, with the addition of (iv), the impedance matching ACC. The suppression effect of the impedance matching ACC (iv) is superior to that of conventional ACC (iii) in the 100 kHz–10 MHz frequency band, with a suppression effect some 15 dB greater than that of the common-mode choke (ii) at 1 MHz, and remained superior up to 6 MHz. This effect is due to the extension of the creation of the shunt condition of the common-mode transformer’s excitation current by matching the phase of the impedance matching circuit and the motor common path across a wide range, as well as the impedance ratio. Even better, because the load current does not flow through the impedance matching circuit it can be constructed with chip components, and an effective suppression effect can be obtained without increasing its physical size compared to the common choke body.

Here, the difference between the experimental result of the suppression effect and that of the theoretical value (20.6 dB) is thought to be due to the transmission characteristics of the common-mode transformer and the frequency characteristics of the amplifier. Moreover, because this experiment focused on noise in the AM band, although an impedance matching circuit was identified for frequency bands up to approximately 3 times higher, 4.5 MHz, in frequency bands higher than this misalignment of the phase of the motor common path arises and the suppression effect is diminished.

5.3 The Suppression Effect on the Radiated Magnetic Field

Electromagnetic radiation noise causes electromagnetic interference in onboard radio antennae.

In this section, we refer to the suppression effect of the impedance matching ACC on electromagnetic radiation noise. Figure 22 shows the configuration of the test of magnetic field intensity. Mounting the impedance matching ACC inside the inverter, the magnetic field from the common-mode current that flows to the line between the inverter and the motor (hereinafter referred to as the motor line) was measured at a distance 5 cm from the motor line. A loop antenna (EM-6992, Electro-metrics) was used for magnetic field intensity. The experimental conditions, as well as the settings of the spectrum analyzer were the same as those used in the measurement of common-mode current.
Figure 23 shows the spectrum of the magnetic field strength emitted from the motor line. A suppression effect was obtained in the frequency band spanning 100 kHz to 10 MHz. For example, there was a reduction of 27 dB at 2 MHz. This is due to the majority of excitation current $i_e$ of the common-mode transformer of the impedance matching ACC being shunted to the impedance matching circuit and confined within the inverter. Note that the reduction in the strength of the emitted magnetic field is smaller than the amount by which the common mode current shown in Fig. 21 is reduced. The standing wave and cancellation of the emitted magnetic field caused by the flow of the common mode current returning across the copper plate located 5 cm below the motor line can be cited as the cause. Although the amount by which the radiated magnetic field strength is reduced differs depending on the length of the motor line wiring and the positional relationship to the ground potential, we believe that the proposed method can be expected to produce a constant effect.

5.4 The Size of the Common Mode Transformer

The size of the common mode transformer is related to the product (ET product) of the voltage applied to the transformer and its duration. Figure 24 shows the transformer voltage waveform when the impedance matching ACC is operated. When the common-mode voltage changes, various capacitance components in the inverter system with the impedance matching ACC (e.g., motor common capacitance, the impedance matching circuit capacitance, Y capacitor capacitance) are charged and discharged. Therefore, if the total capacitance is small, the ET product applied to the common-mode transformer becomes smaller.

In the impedance matching ACC, the fourth winding of the common-mode transformer is connected to Y capacitor $C_Y$, rather than the DC bus capacitor $C_{dc}$ as in conventional ACCs. Where the motor common capacitance is 3.6 nF and the Y capacitor capacitance is 4.7 nF, the ET product of the impedance matching ACC is $5.3 \times 10^{-5}$ Vs. For the transformer voltage of conventional ACCs, where the DC bus capacitance is $1.0 \mu$F and the common-mode voltage is approximately applied to the transformer, the ET product is $1.3 \times 10^{-3}$ Vs. From this result, the ET product of the impedance matching ACC is found to be $1/24$ that of the conventional ACC, and there is the further sizeable advantage that the number of windings and the cross-sectional area of the common mode transformer can be significantly reduced.

6. Conclusion

We have proposed an impedance matching-type active common-mode noise canceller as a method of reducing common-mode current in the inverter. By positioning an impedance matching circuit matching the phase characteristics of the motor common-mode path between the common-mode transformer and the ground potential and matching the phases of the impedance matching circuit and motor common path across a wide range, at the same time as aiming to widen the band for the shunting of the common-mode transformer’s excitation current, utilizing the impedance ratio more of the excitation current of the common-mode transformer is shunted to the impedance matching circuit than the motor common path, and we confirmed through experiment a suppression effect of 25 dB at 1 MHz was obtained using the conventional voltage cancellation method. In addition, since the load current does not flow through the impedance matching circuit it can be constructed using chip components, and moreover since the capacitance components to which common-mode voltage is applied can be made smaller, the ET product of the common-mode transformer can be suppressed, and there is the further sizeable advantage that the number of windings and the cross-sectional area of the common mode transformer can be significantly reduced. By placing the impedance matching ACC in the inverter, it becomes possible to confine most of the common-mode current within the inverter, and in our experiment we suppressed by 26 dB at 1 MHz and validated that it is effective for the suppression of electromagnetic noise from the wiring between the inverter and the motor.

In the future, we plan to extend the suppression effect frequency bands.
References


Appendix

1. Deriving the Simplified Equivalent Circuit for the Conventional Voltage Method ACC

Here we explain the method of deriving the simplified equivalent circuit for the conventional voltage-type ACC shown in Fig. 11 of Section 2.2. app. Fig. 1(a) is the conventional voltage method ACC-equivalent circuit, and is the same as the diagram shown in Fig. 9. Assuming the amplification factor of the current amplifier to be sufficiently large, the output impedance becomes small and common-mode voltage \( v_{com} \) can be applied independently of the load. Therefore, short-circuiting the current amplifier, it can be expanded as shown in Fig. 1(b). Furthermore, expanding the common-mode transformer \( T_{com} \) shown in app. Fig. 1(b) to a T-type equivalent circuit, it appears as shown in app. Fig. 1(c). Here, \( L_r \) is the exciting inverter of common-mode transformer \( T_{com} \), \( L_1 \) and \( L_2 \) are leakage inductors Assuming leakage inductors \( L_1 \) and \( L_2 \) to be sufficiently small, these can be overlooked as in app. Fig. 1(d), forming the simplified equivalent circuit of the conventional voltage method ACC as shown in Fig. 11.
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