# Conductive Noise Analysis of Inverter Circuits for Vehicle Equipments Using an Equivalent Circuit

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***Abstract*— Conductive noise from vehicle equipments which contain inverter circuits has been increased by the demand of higher switching operation of power devices in order to improve the power efficiency. On the other hand, since the vehicle equipments are required to minimize the volume, the noise filters should be built-in the housing of inverter circuits. In this case, it is necessary that the conductive noise is predicted at design stage in order to optimize the size and performance of the noise filters. In this paper, we propose precise equivalent circuit to predict the conductive noise for the vehicle equipment. The equivalent circuit for the vehicle equipment consists of noise filters, switching devices, and motors with parasitic inductance and stray capacitance in each part so as to obtain higher accuracy. Futuremore, the accuracy of the conductive noise calculation using the proposed equivalent circuit is verified quantitatively by an experiment. The difference between the calculated and measured results is within 10dB in the frequency range between 150kHz to 6MHz.**

***Keywords*— Invertors, Conductive Noise, Equivalent Circuit, Motors, Noise Filters**

## I. INTRODUCTION

Many inverter circuits have been utilized in the power supply circuit in order to improve energy efficiency. In the vehicle equipment with the inverter circuits, the conductive noise problems become more serious of recent application of high speed switching. Noise filters are effective parts which solve the conductive noise problems. Therefore it is important for the noise filters to increase attenuation against noise. On the other hand, embedding the noise filters inside the vehicle equipment has the advantage of miniaturization and light weight.

It is necessary to decide the storage space of the noise filters at the design stage to embed the noise filters in the vehicle equipment. If the size of the noise filters is changed after the trial stage, all of the vehicle equipment should be redesigned. Therefore it is required that configuration and constants of the noise filters should be decided at the design stage.

We have developed the prediction technique of the conductive noise to decide the specs of the noise filters. The forecast technology using equivalent circuits was already reported about LED lighting and IH cooker [1,2]. Moreover the numerical analysis which estimates the conductive noise from power electronic devices has been reported [3]. The technique of estimating the conductive noise from vehicle equipment containing motors has not been reported. This paper firstly constituted highly accurate equivalent circuit that has the original structure by considering the parasitic factors for the motors, the filters and the switching elements. Secondly, the conductive noise that leaked to the power supply was calculated by the equivalent circuit in the vehicle equipment. Finally, the validity of the equivalent circuit was verified by comparing analytical results with measurement results.

## II. CONFIGURATION OF EQIVALENT CIRCUIT FOR VEHICLE EQUIPMENT

### A. *Configuration of vehicle equipment*

As shown in Fig.1, the vehicle equipment consists of inverter circuits, a three-phase synchronous motor, and noise filters. In the vehicle equipment, the three-phase synchronous motor is operated by switching MOSFETs (metal-oxide-semiconductor field-effect transistor). The switching frequency of MOSFETs is 20kHz. The noise filters are mounted so that an electromagnetic noise generated by MOSFETs should not leak to the power supply side. Line impedance stabilization networks (LISN) are connected to the power supply side in order to measure the electromagnetic noise as a conductive noise.

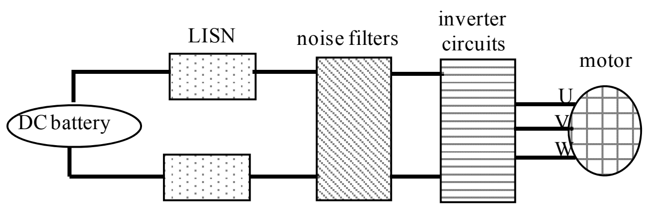


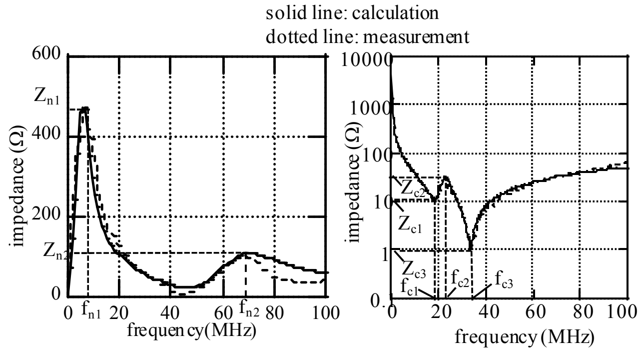

Fig.1 Configuration of vehicle equipments.

### B. *Equivalent circuit of motor*

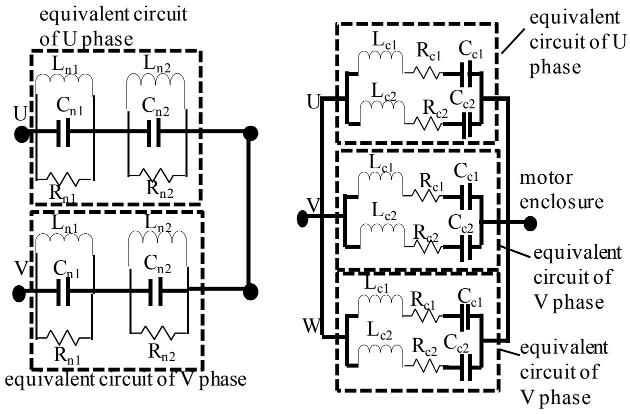
This chapter shows how to decide configuration and constants of equivalent circuits from measurement results about the impedance of the motor. The equivalent circuits of the motor are constructed about the normal mode and about the common mode. The impedance of normal mode was defined as impedance between U terminal and V terminal, because the impedances between U terminal and V terminal, between V terminal and W terminal, and between U terminal and W terminal are almost equal. The impedance of the common mode was defined as between three terminals (U terminal, V terminal and W terminal) and motor enclosure. The impedances of normal mode and common mode were measured by the network analyzer. Figure 2 shows the measured results.

From Fig. 2 (a), since there are two resonance frequencies which become peak, the configuration of the equivalent circuit for the normal mode is RLC parallel circuit that is connected in series as shown in Fig.3(a). Since the equivalent circuits of U phase and V phase are equal, the equivalent circuit, divided into U phase and V phase, is constructed as shown in Fig. 3(a). The constants $L_{n1}$ and $C_{n1}$ of the equivalent circuit are calculated from the impedance up to resonance frequency $f_{n1}$ and resonance frequency $f_{n1}$. The constants $R_{n1}$ of the equivalent circuit are decided from the peak value $Z_{n1}$ at the resonance frequency $f_{n1}$. The constants $L_{n2}$ and $C_{n2}$ of the equivalent circuit are calculated from the impedance up to resonance frequency $f_{n2}$ and resonance frequency $f_{n2}$. The constants $R_{n2}$ of the equivalent circuit are decided from the peak value $Z_{n2}$ at the resonance frequency $f_{n2}$. The equivalent circuit constants of W phase are equal to those of U phase and V phase.

From Fig.2(b), since there are two resonance frequencies which become local minimum values, the configuration of the equivalent circuit for the common mode is RLC series circuit that is connected in parallel as shown in Fig.3(b). Since the equivalent circuits of U phase, V phase and W phase are equal, the equivalent circuit, divided into U phase, V phase and W phase, is constructed as shown in Fig. 3(b). The constants $L_{c1}$, $C_{c1}$, $L_{c2}$ and $C_{c2}$ of the equivalent circuit are calculated from the resonance frequencies $f_{c1}$, $f_{c2}$ and $f_{c3}$. When frequency is low, the impedance characteristic of the equivalent circuit shown in Fig. 3(b) is in agreement with the impedance characteristic calculated by the parallel circuit of $C_{c1}$, and $C_{c2}$. Therefore, less than resonance frequency $f_{c1}$, $C_{c1}+C_{c2}$ is determined so that the impedance characteristic calculated by the parallel circuit of $C_{c1}$ and $C_{c2}$, may be in agreement with the measurement result as shown in Fig.2(b). Table 1 shows the constants of the equivalent circuits for the normal mode and the common mode. The impedance characteristics calculated by the equivalent circuits agree with the measurement results as shown in Fig.2.




(a) normal mode (b) common mode
Fig.2 Impedances characteristics of motors.




(a) normal mode (U-V terminal) (b) common mode (U,V,W terminal – motor enclosure)
Fig.3 Equivalent Circuits of motor.

Table 1 Equivalent circuit constants of motors.

(a) normal mode

| inductance (μH) | | capacitance (nF) | | resistance (Ω) | |
|---|---|---|---|---|---|
| $L_{n1}$ | $L_{n2}$ | $C_{n1}$ | $C_{n2}$ | $R_{n1}$ | $R_{n2}$ |
| 5.0 | 0.04 | 0.15 | 0.14 | 240 | 50 |

(b) common mode

| inductance (μH) | | capacitance (nF) | | resistance (Ω) | |
|---|---|---|---|---|---|
| $L_{c1}$ | $L_{c2}$ | $C_{c1}$ | $C_{c2}$ | $R_{c1}$ | $R_{c2}$ |
| 1.35 | 0.35 | 0.053 | 0.067 | 39 | 3 |

*C. Equivalent circuit of noise filters*

Figure 4 shows the equivalent circuit configuration of a noise filter. The noise filter consists of a normal inductor, a normal capacitor, and common capacitors.

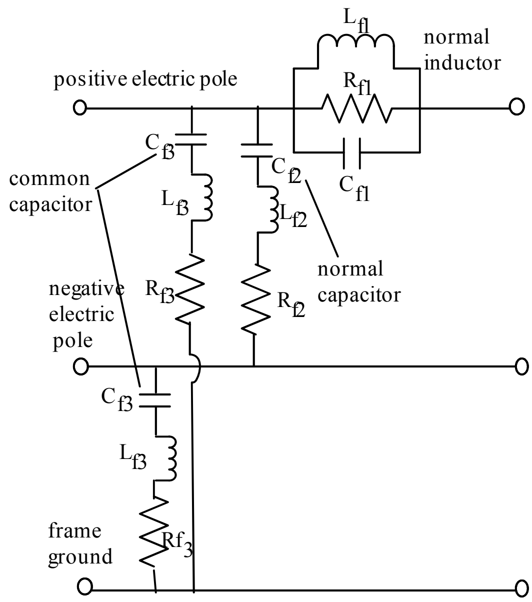



Fig.4 Equivalent circuit of noise filters.

The normal mode inductor is composed by winding the coil of six turns in the ferrite core of the column shape. The inductance of the normal inductor is decreased by eddy current flowing on the metal surrounding the case, because the inductor is mounted around a metal such as a heat sink. The impedance of the inductor was measured by the network analyzer, on condition that inductor was mounted around the metal. These configuration and constants were adjusted to be matched to impedance results measured by the network analyzer.

Figure 5 shows the impedance characteristics of the normal inductor by the measurement. From Fig.5, since there are one resonance frequency which become peak, the configuration of the equivalent circuit for the normal mode is RLC parallel circuit as shown in Fig.(4). When frequency is low, the impedance characteristic of the equivalent circuit as shown in Fig. 4 is in agreement with the impedance characteristic of $L_{f1}$. Therefore, less than resonance frequency, $L_{f1}$ is determined so that the impedance characteristic of $L_{f1}$ may be in agreement with the measurement result as shown in Fig.5. The constants $C_{f1}$ and $R_{f1}$ are calculated by the resonance frequency and peak value of impedance respectively. Table 2 shows the constants of the equivalent circuits for the normal inductor. The impedance characteristics calculated by the equivalent circuits agree with the measurement results as shown in Fig.5.

In the equivalent circuit of the normal capacitor and the common capacitors, parasitic inductances and resistances were considered. The parasitic inductance and resistance were calculated approximately by wire length. Table 2 shows the equivalent circuit constants of normal capacitors, common capacitors, and normal inductors.

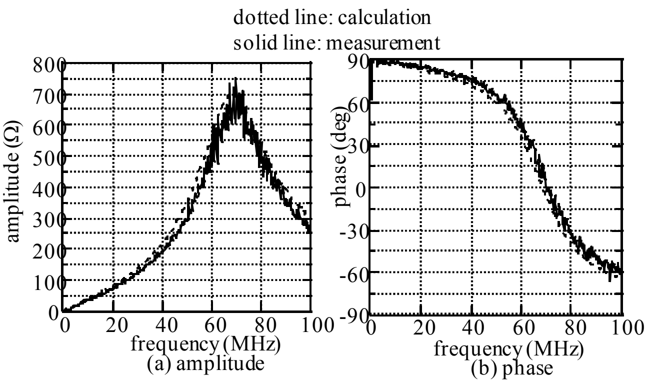



Fig.5 Impedance characteristics of normal inductor.

Table 2 Equivalent circuit constants of noise filters.

| normal inductor | | | normal capacitor | | | common capacitor | | |
|---|---|---|---|---|---|---|---|---|
| $L_{f1}$ (μH) | $C_{f1}$ (μF) | $R_{f1}$ (Ω) | $C_{f2}$ (μF) | $L_{f2}$ (μH) | $R_{f2}$ (Ω) | $C_{f3}$ (μF) | $L_{f3}$ (μH) | $R_{f3}$ (Ω) |
| 0.6 | 0.009 | 700 | 10 | 0.05 | 0.03 | 10 | 0.04 | 0.02 |

*D. Stray capacitance of MOSFETs*

The inverter circuit includes U phase, V phase and W phase mold modules. Figure 6 shows configuration of a mold module of U phase. The mold module of V phase and W phase is the same composition as the mold module of U phase. The upper MOSFET, lower MOSFET and motor relay are built into the mold module. The operation mode of motor relay was always turn-on status, though MOSFETs operated as switching elements. The mold modules are mounted on the heat sink as shown in Fig.6. The mold modules are fixed to the heat sink by adhesives. The electromagnetic noise generated by MOSFETs leaks to the heat sink via the adhesive. The stray capacitances between the mold modules and heat sinks were calculated from the sectional area of the drain layer, the thickness of the adhesive, and the permittivity of the adhesive as shown in Table 3.

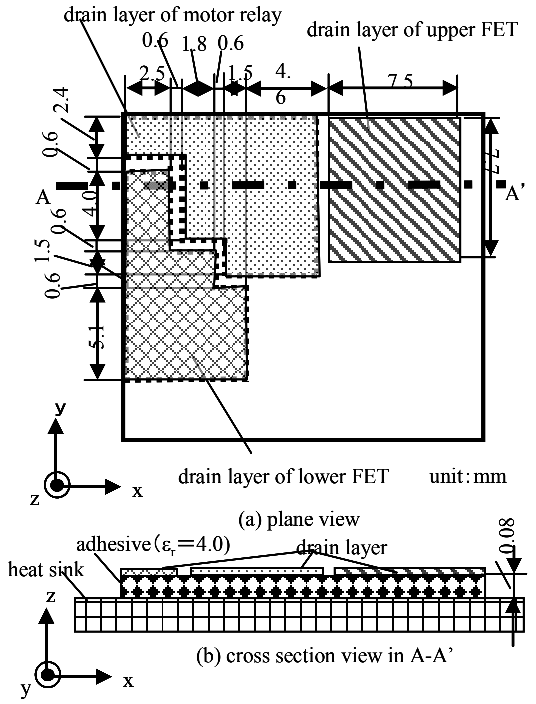



Fig.6 Configuration of mold module.

Table 3 Stray capacitances of mold module.

| | upper FET | lower FET | motor relay |
|---|---|---|---|
| cross-section area($mm^2$) | 58.8 | 57.5 | 79.8 |
| thickness (mm) | 0.08 | 0.08 | 0.08 |
| relative permittivity | 4.0 | 4.0 | 4.0 |
| capacitance (pF) | 26.2 | 25.6 | 35.5 |

### III. VERIFICATION OF EQUIVALENT CIRCUIT BY MEASUREMENT

The equivalent circuit of the vehicle equipment consists of the equivalent circuit of the motor, the noise filters, and the mold modules. Moreover the equivalent circuit of the whole vehicle equipment as shown in Fig.7 was constructed by adding the equivalent circuit of FG line and LISN. In the equivalent circuit, the voltage induced to LISN is calculated as the conductive noise.

The calculated results of the conduction noise were verified by measurement. The comparison about the conductive noise between the calculation results and the measurement results is shown in Table 4. The calculated results were within 10dB to measured results in the frequency range between 150kHz to 6MHz and the validity of equivalent circuit verified quantitatively. The difference of the calculated results and the measured results is large in the frequency range between 30MHz to 100MHz._The difference of the conductive noise between the calculation and the measurement is large above 30MHz, because rise time and fall time of switching waveforms used as calculated conditions are earlier than those used as measured conditions. The rise time and the fall time of actual switching waveforms are 150 ns. However the rise time and the fall time of switching waveforms are 10ns in the calculation, because the switching waveform is approximated with an ideal.

Table 4 Investigation for calculation results of conductive noise.

| band width | LW | AM | SW | VHF | FM |
|---|---|---|---|---|---|
| frequency (MHz) | 0.15～0.3 | 0.53～1.8 | 5.9～6.2 | 30～54<br>68～87 | 76～108 |
| max different between measurement and calculation (dB) | 2 | 10 | 3 | 15 | 15 |

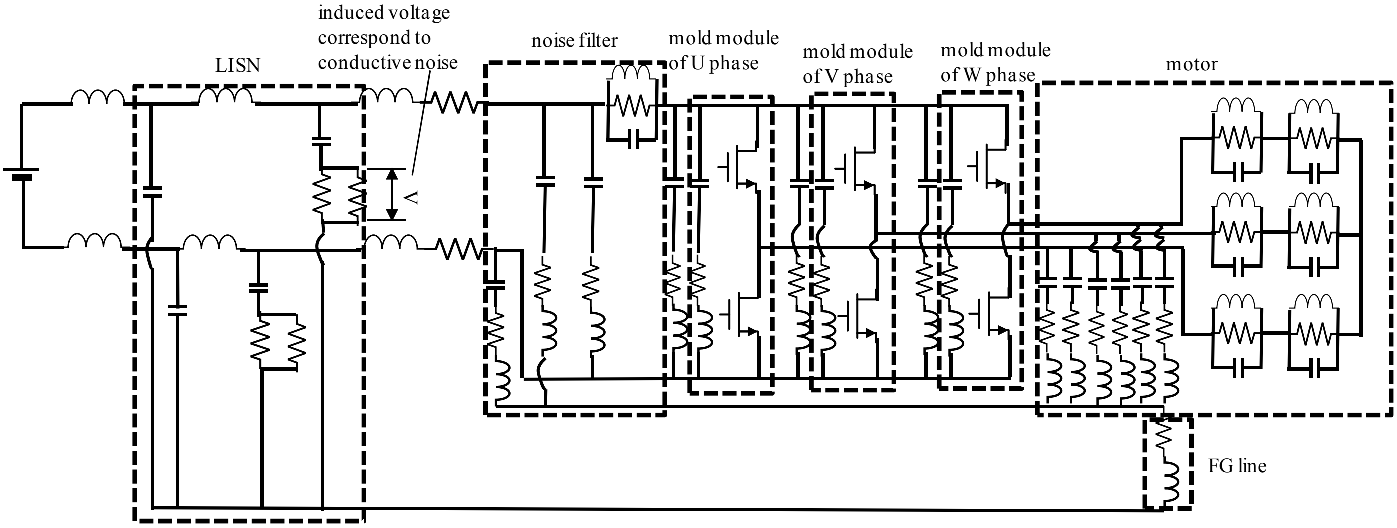



Fig.7 Equivalent circuit of whole vehicle equipment.

### IV. CONCLUSION

In this paper, the equivalent circuit of the automotive equipment was constructed for predicting the conductive noise. The equivalent circuit which consists of the motor, the noise filters, and the model modules was calculated with high precision in consideration of stray capacitance and wire inductance. The calculated results of the vehicle equipment were verified by measurement. The difference between calculated results and measured results were within 10dB in the frequency range between 150kHz to 6MHz and the validity of equivalent circuit verified quantitatively.

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