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Method of Measuring Conducted Noise Voltage with a Floating Measurement System to Ground

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SUMMARY This paper describes a method of measuring the unsymmetric voltage of conducted noise using a floating measurement system. Here, floating means that there is no physical connection to the reference ground. The method works by correcting the measured voltage to the desired unsymmetric voltage using the capacitance between the measurement instrument and the reference ground plane acting as the return path of the conducted electromagnetic noise. The existing capacitance measurement instrument needs a probe in contact with the ground, so it is difficult to use for on-site measurement of stray capacitance to ground at troubleshooting sites where the ground plane is not exposed or no ground connection point is available. The authors have developed a method of measuring stray capacitance to ground that does not require physical connection of the probe to the ground plane. The developed method can be used to estimate the capacitance between the measurement instrument and ground plane even if the distance and relative permittivity of the space are unknown. And a method is proposed for correcting the voltage measured with the floating measurement system to obtain the unsymmetric voltage of the noise by using the measured capacitance to ground. In the experiment, the unsymmetric voltage of a sinusoidal wave transmitting on a co-axial cable was measured with a floating oscilloscope in a shield room and the measured voltage was corrected to within 2 dB of expected voltage by using the capacitance measured with the developed method. In addition, the voltage of a rectangular wave measured with the floating oscilloscope, which displays sag caused by the stray capacitance to ground, was corrected to a rectangular wave without sag. This means that the phase of the unsymmetric voltage can also be corrected by the measured stray capacitance. From these results, the effectiveness of the proposed methods is shown.

key words: *EMC, voltage measurement, ground capacitance measurement, unsymmetric voltage*

1. Introduction

During the operation of power supply systems, electromagnetic noise generated by switching circuits is transmitted to power lines and telecommunication lines [1]–[4]. The frequency of the noise is between several 10 kHz and several 10 MHz and sometimes leads to other equipment developing performance degradations and malfunctions [5]–[8]. To prevent such performance degradations, it is very important to ensure that on-site measurement of noise voltage is precise, and to identify the noise source and exactly where the noise is being induced in the affected equipment [9].

In general, asymmetric and unsymmetric voltages are one of the major causes of equipment performance degradations. Asymmetric voltage is the voltage appearing between the electrical mid-point of the equipment terminals and ground. Asymmetric mode noise propagating on the cable generates an electromagnetic field or is coupled onto other cables, and then affects the performance of other equipment. Unsymmetric voltage is the voltage appearing between one conductor of the terminal and ground. Unsymmetric mode noise is directly induced into other equipment and affects its performance.

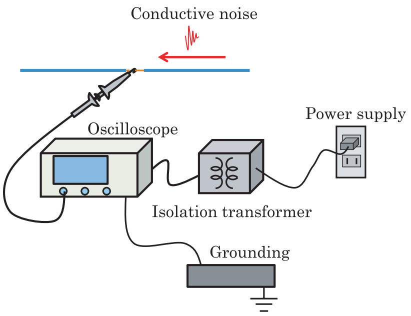

Fig. 1 On-site measurement of conducted noise unsymmetric voltage.

In the case of on-site voltage measurement, an example of which is shown in Fig. 1, the measurement instrument is generally powered through an isolation transformer so as to prevent electromagnetic noise interference from the public electricity network. In addition, the frame ground of the instrument has to be connected to a ground terminal or additional metallic ground plane of dimensions larger than 2 × 2 m. But in most cases, the ground terminal is missing or too far away to connect the measurement instrument to it, or such a large additional ground plane can not be exposed. Therefore, the precise on-site measurement of asymmetric and unsymmetric voltages is not practicable because of the unavoidable problem of how to set the voltage reference point.

In other words, if a measurement instrument is developed that does not need a ground connection, the issue mentioned above can be resolved. The voltage measurement instrument proposed here does not need a ground connection, and is therefore called a floating measurement system; the equivalent circuit representing the system is shown in Fig. 2. The unsymmetric-mode impedance Z_u, which means the equivalent terminal impedance between the conducted noise path and ground viewed from the noise source, is generally sufficiently small compared to the input impedance of

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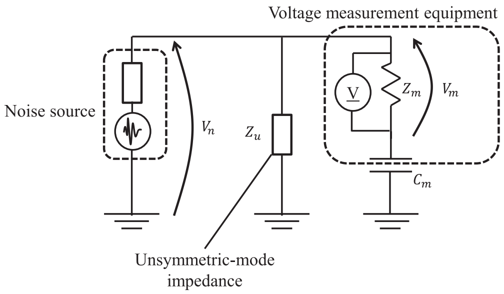

Fig. 2 Equivalent circuit of a floating measurement system.

the measurement instrument Z_m. It is necessary to obtain the voltage division factor that converts measured voltages V_m to desired noise voltages V_n One measurement method using the voltage division factor to calibrate the measured voltages to the noise voltages employs a capacitive voltage probe (CVP) [10]–[13]. A CVP is a tool that enables non-contact voltage measurement by using capacitances between an inner electrode and a cable conductor on which noise waves are propagating. Though the basic measurement concept of the CVP is the same as for the floating measurement system, the method of obtaining the voltage division factor with the CVP is not suitable for use with the floating measurement system because the ground capacitance C_m differs depending on the measurement environment. Thus, a method of estimating the capacitance C_m and correcting the measured voltages is needed.

In respect of the estimation of the stray capacitance, this can be very difficult to calculate theoretically because the geometrical configuration (i.e. distance and size), and relative permittivity of the intervening materials between the measurement instrument and ground plane are not clear.

There are two scenarios for troubleshooting with on-site measurement of conducted noise voltage. One is where the voltage measurement instrument can be placed relatively close to the voltage reference point, such as in a telecommunications center. In this case the reinforcing bars of the building and floors are electrically connected to the ground. The other scenario is where there is a large distance between the ground and the measurement instrument, as is the case in a residential or user premises, because there may be a wide space between the floor and ground.

In this paper, we deal with the scenario where the voltage reference point is relatively close to the place where the measurement instrument is installed, as is the case in a telecommunications center. In this case, the stray capacitance can be regarded as a parallel plate capacitor consisting of the ground plane and a conductor plate connected to the measurement instrument circuit ground.

2. The Principle of the Method of Voltage Measurement

This section describes the principle of the proposed method of measuring noise voltage with a floating measurement instrument, which features a method of estimating the capacitance between the measuring instrument and the ground, and correcting the measured voltage to match the desired unsymmetric voltage by using that estimate of the capacitance.

2.1 Method for Correcting Measured Voltage to Match Unsymmetric Voltage

A simplified equivalent circuit of conducted noise measurement using floating equipment is shown in Fig. 2. One of the reasons that measurement with floating equipment is inaccurate is the capacitance between the circuit ground of the measurement equipment and the return path of conducted noise. This capacitance makes the measured voltage lower than the unsymmetric voltage of the conducted noise. In order to estimate this capacitance, the ground plate, whose area is known and which is made of metal, is connected to the circuit ground of the voltage measurement equipment. The unsymmetric voltage V_n is given by

$$V_n = V_m\left(1 + \frac{1}{j\omega_n C_m}\frac{1}{Z_m}\right) \tag{1}$$

where V_m is the measured voltage, ω_n is the angular frequency of the conducted noise, C_m is the ground capacitance of the circuit ground of the voltage measurement equipment and Z_m is the input impedance of the voltage measurement equipment. Though it is necessary to use the unsymmetric-mode impedance to express the unsymmetric voltage V_n accurately, the impedance is omitted in this equation, because the input impedance of the voltage measurement equipment Z_m is much larger than the unsymmetric-mode impedance. The impedance is typically omitted when using voltage measurement equipment which has high input impedance.

The ground capacitance C_m is given by

$$\begin{aligned} C_m &= \frac{\varepsilon_0 S_m}{\delta} \\ \delta &= \sum_{k=1}^{N}\frac{d_{g_k}}{\varepsilon_{x_k}} \end{aligned} \tag{2}$$

where ε_0 is the electric constant, S_m is the area of the ground plate under the voltage measurement equipment which is connected to the circuit ground of said equipment, d_{g_k} and ε_{x_k} are the thickness and relative permittivity of the gap between the ground plate and the ground plane, N is the number of layers composing the gap between the ground plate and the ground plane. The relationship of the voltage measurement equipment and ground plane is shown in Fig. 3. If the parameter δ can be estimated, the ground capacitance C_m can be estimated by Eq. (2) and the unsymmetric voltage V_n can be calculated by Eq. (1) using the estimated ground capacitance C_m.

2.2 Method of Estimating the Parameter δ

The instrument configuration and equivalent circuit for estimating the ground capacitance are shown in Fig. 4 and Fig. 5

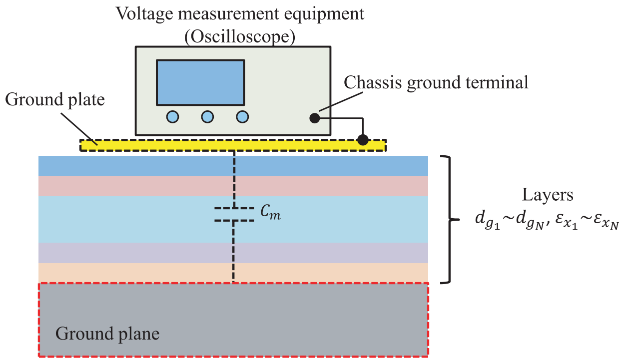

Fig. 3 Relationship of voltage measurement equipment and ground plane.

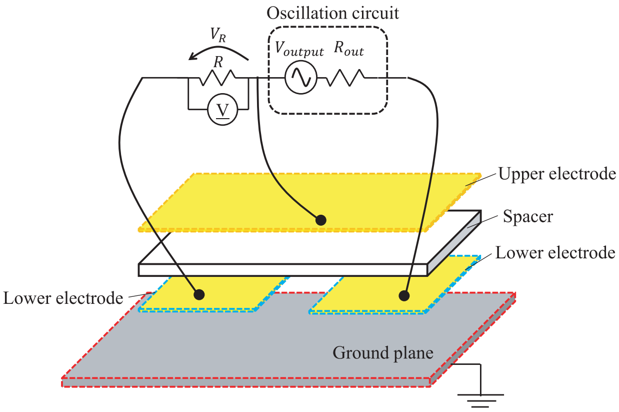

Fig. 4 Configuration of ground capacitance estimating device.

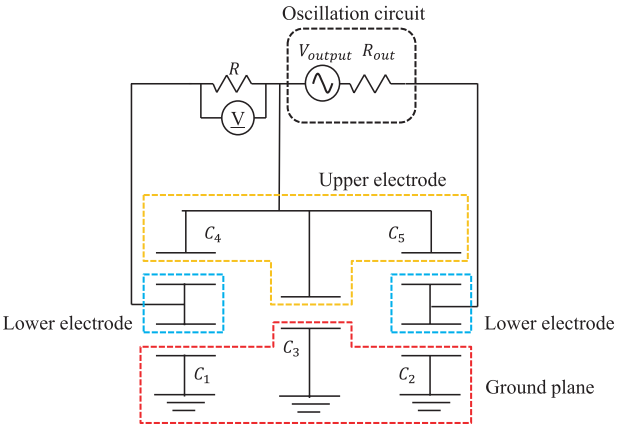

Fig. 5 Equivalent circuit of ground capacitance estimating device.

[14]. In this method, the instrument for measuring the capacitance to ground consists of one upper electrode, two lower electrodes, a spacer, and an oscillation circuit, and has a measurement resistance R. The capacitances C_1 and C_2 are the capacitances between the lower electrodes and the ground plane, and C_3 is the capacitance between the upper electrode and the ground plane. C_4 and C_5 are the capacitances between the upper electrode and the lower electrodes. The values of C_4 and C_5 can be calculated according to the distance and relative permittivity of the spacer between the upper and lower electrodes. V_{output} is the output voltage of the oscillation circuit, R_{out} is the output resistance of the oscillation circuit.

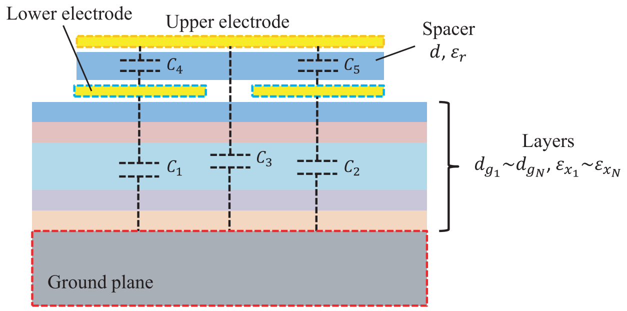

Fig. 6 Relationship of ground capacitance estimating device and ground plane.

This device must be placed such that the electrodes are parallel with the plane of the ground acting as the return path of noise. Even if there is no upper electrode and the oscillation circuit and the resistance are connected between the lower electrodes, it is possible to estimate the capacitance to ground from the voltage generated in the resistance where there is nothing to cause interference in the surroundings. However, when there is a metal object in the surroundings, stray capacitance is generated between the upper surface of the lower electrodes and the object, so a signal applied from the oscillation circuit flows through an unexpected path and it becomes impossible to estimate the ground capacitance. Attaching not only the lower electrodes parallel with the ground plane, but also the upper electrode makes it possible to isolate the signal path as shown in the equivalent circuit in Fig. 5, and the influence of any metal object in the surrounding can be eliminated.

The relationship of electrodes and ground plane is shown in Fig. 6. The capacitances C_1 to C_5 are given by

$$\begin{aligned} C_1 &= \frac{\varepsilon_0 S_1}{\delta} \\ C_2 &= \frac{\varepsilon_0 S_2}{\delta} \\ C_3 &= \frac{\varepsilon_0 (S_3 - S_1 - S_2)}{\dfrac{d}{\varepsilon_r} + \delta} \\ C_4 &= \varepsilon_0 \varepsilon_r \frac{S_1}{d} \\ C_5 &= \varepsilon_0 \varepsilon_r \frac{S_2}{d} \end{aligned} \tag{3}$$

where ε_r is the relative permittivity of the spacer, S_1 and S_2 are the surface areas of the lower electrodes, S_3 is the surface area of the upper electrode and d is the distance between the upper electrode and the lower electrodes.

From the equivalent circuit in Fig. 5, the generated voltage V_R at measurement resistance R is given by

$$\begin{aligned}
V_R &= V_{output}\frac{\alpha}{\alpha+\dfrac{1}{j\omega C_1}}\frac{\beta}{\beta+\dfrac{1}{j\omega C_2}}\frac{\gamma}{\gamma+R_{out}}\\
\alpha &= \frac{R\dfrac{1}{j\omega C_4}}{R+\dfrac{1}{j\omega C_4}}\\
\beta &= \frac{\dfrac{1}{j\omega C_3}\left(\alpha+\dfrac{1}{j\omega C_1}\right)}{\dfrac{1}{j\omega C_3}+\alpha+\dfrac{1}{j\omega C_1}}\\
\gamma &= \frac{\dfrac{1}{j\omega C_5}\left(\beta+\dfrac{1}{j\omega C_2}\right)}{\dfrac{1}{j\omega C_5}+\beta+\dfrac{1}{j\omega C_2}}
\end{aligned} \tag{4}$$

where j is $(-1)^{0.5}$ and ω is the angular frequency of the oscillated signal.

It is shown in Eq. (3) that C_1, C_2 and C_3 can be expressed by the same parameter δ. And the output voltage of the oscillation circuit V_{output}, the output resistance R_{out} and the measurement resistance R are determined by the selected elements. Thus, only one parameter δ is needed to represent the right side of Eq. (4), so measuring V_R makes it possible to estimate δ. In other words, Eq. (1) can be solved for δ using V_R, which is a measurable value. The capacitances C_m, C_1, C_2 and C_3 can be calculated using Eqs. (2) and (3) by δ. Using this method, the capacitance between the measurement instrument and the ground plane can be estimated even if the distance and relative permittivity of the space are unknown.

3. Evaluation of the Proposed Method

This section describes the developed measuring system and offers an evaluation of it.

3.1 Ground Capacitance Estimation

The experimental setup of the ground capacitance estimating device is shown in Fig. 7. The authors inserted a 10 mm thick acrylic plate, with a relative permittivity of 4.0, as a spacer between an upper electrode and two lower electrodes. The size of the upper electrode was 250 × 120 mm, and the two lower electrodes had the same total area being 100 × 120 mm and spaced 50 mm apart. To precisely calculate capacitance using Eq. (3), the size of the electrodes ideally has to be sufficiently larger than the distance between them. Increasing the size of the upper electrode has advantages in terms of reducing leakage through the electric flux line between electrodes, and increasing the shielding effectiveness of the upper electrode, which both affect the level of error in the calculated capacitance values. Thus, in actual conditions, the size of the electrodes has to be as large as possible because the distance between the lower electrodes and ground is unknown. However, this is not practicable. In this paper therefore, the size of the electrodes is determined based on considerations of portability. Also, it is advantageous to make the lower electrode as large as possible so as to enlarge the capacitances C_1 and C_2. As a result of this, V_R is enlarged, facilitating ease of measurement. On the other hand, if the lower electrodes are too close to each other, stray capacitance undesirable for the proposed method is formed between the electrodes. Therefore, in this experiment, the size and configuration of the electrodes was decided as stated above. The electrodes were 1 mm thick copper plates. Sinusoidal waves of 5 $V_{\text{p-p}}$ from 10 kHz to 5 MHz were applied from a battery powered signal generator with an output impedance of 50 Ω. The voltage generated at a resistance of 10 kΩ was measured with an oscilloscope using a differential probe with the distance between the lower electrodes and the shield room floor set to 10 mm, 30 mm, 50 mm, 70 mm and 90 mm using 10 mm thick acrylic plates. Changing the distance between the device and the floor of the shield room in this way simulates the change in materials and distance to ground at actual troubleshooting sites.

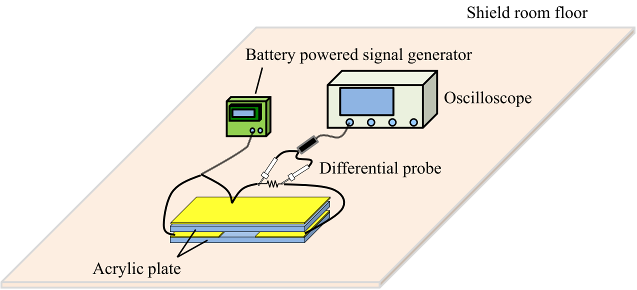

Fig. 7 Experimental setup of ground capacitance estimating device.

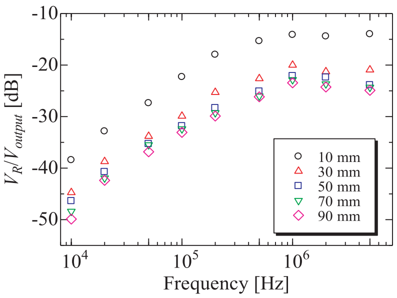

Fig. 8 Measurement result of V_R/V_{output}.

The result is shown in Fig. 8. It is shown that the ratio between the generated voltage at a resistance of 10 kΩ and the output voltage of the signal generator V_R/V_{output} gets smaller as the distance between the device and the floor of the shield room increases, that is, the ground capacitance decreases. The theoretical value of δ can be obtained because the thickness and relative permittivity of the spacer inserted under the lower electrodes are known in the setup shown in Fig. 7. However, in the actual environment, the material and thickness are unknown, so δ is determined as an unknown parameter from V_R/V_{output}. The experimen-

Table 1 Estimated values obtained using the ground capacitance estimating device.

Spacer [mm]	C_1,C_2 [pF]	C_3 [pF]	δ [m] estimated	δ [m] theoretical
10	27.2	8.3	3.9×10^{-3}	2.5×10^{-3}
30	11.3	4.5	9.4×10^{-3}	7.5×10^{-3}
50	8.7	3.6	12.2×10^{-3}	12.5×10^{-3}
70	7.8	3.3	13.6×10^{-3}	17.5×10^{-3}
90	7.4	3.1	14.4×10^{-3}	22.5×10^{-3}

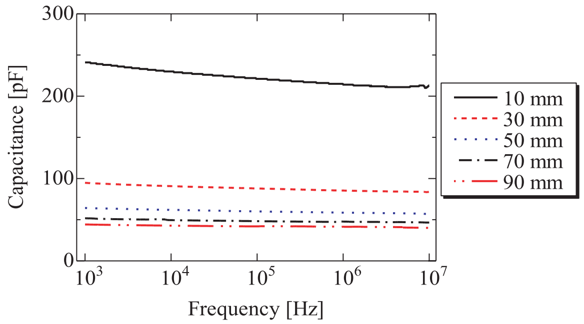

Fig. 9 Capacitance measured with an impedance analyzer.

Table 2 Estimated ground capacitance C_m.

Spacer [mm]	C_m [pF] Impedance analyzer	C_m [pF] Proposed method
10	225	182
30	87.5	75.4
50	60.5	58.1
70	48.1	52.1
90	41.9	49.2

tal setup in Fig. 7 includes impedances other than the capacitance of C_1 to C_5 shown in Fig. 5, such as cable resistance and inductance. In order to minimize the effect of the measurement error caused by these impedances, the least squares method is used to estimate δ in order to minimize the difference between the theoretical frequency characteristic of V_R/V_{output} and the measured frequency characteristic of V_R/V_{output}. The estimated values for δ and C_1, C_2 and C_3, which are calculated by Eq. (3), and the theoretical values of δ, which are calculated by Eq. (2), along with the relative permittivity and thickness of the acrylic plates, are all shown in Table 1. It was found that the estimated value of δ was in error by less than 60% of the theoretical value. In order to evaluate this result, the ground capacitance C_m measured by an impedance analyzer was compared with C_m obtained from Table 1 and Eq. (2). The size of the conductor plate on which the voltage measuring device is installed was set to 400 × 200 mm to match the area of the copper plate actually used in the next chapter. The resulting measurements taken by the impedance analyzer are shown in Fig. 9. Table 2 shows the C_m obtained by the approximation of the least square method using Fig. 9 and the C_m obtained from Table 1 and Eq. (2). It was found that the ground capacitance obtained by the proposed method can be estimated within 25% of the measurement results obtained using an impedance analyzer.

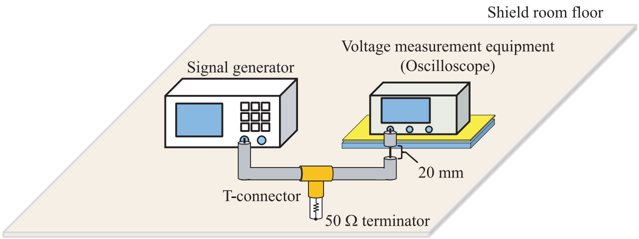

Fig. 10 Experimental setup of unsymmetric voltage measurement.

3.2 Unsymmetric Voltage Measurement

The setup for unsymmetric voltage measurement with floating voltage measurement equipment is shown in Fig. 10. The signal is output from the signal generator to a coaxial cable and the coaxial cable is connected to a T-connector, which is connected to a 50 Ω terminator. The applied signal passes through the 50 Ω terminator and reaches the floor of the shield room because the ground of the signal generator is connected to the floor of the shield room. This signal flow simulates the conducted noise flow at an actual troubleshooting site. In order to measure the generated voltage at the 50 Ω terminator with the floating oscilloscope, a coaxial cable is connected to the T-connector and the floating oscilloscope. At this time, in order to avoid a connection between the oscilloscope ground and the shield room floor through the outer conductor of the coaxial cable and the T-shaped connector, about 20 mm of the outer conductor of the coaxial cable is removed 10 mm ahead from its connection with the oscilloscope. The oscilloscope is placed on the 400 × 200 mm copper plate and the ground of the oscilloscope is connected to this copper plate. The copper plate under the voltage measurement equipment is placed horizontally at a height of 10, 30, 50, 70 and 90 mm from the floor of the shield room using layers of 10 mm acrylic plates. The output impedance of the signal generator is 50 Ω and the input impedance of the oscilloscope is 1 MΩ in parallel with 13 pF. The equivalent circuit is shown in Fig. 11. There is stray capacitance between the inner conductor and the outer conductor at the point where the outer conductor of the coaxial cable is removed, and this stray capacitance could affect the input voltage to the oscilloscope. However, considering the experimental setup shown in Fig. 10, the stray capacitance is considered to be negligibly small compared to that between the ground plate under the oscilloscope and the shield room floor, which is what we wish to estimate. This is because the size of the ground plate under the oscilloscope is much larger than the size of the cross section of the coaxial cable, and the distance between the bottom of the oscilloscope and the shielded room floor is comparable to 20 mm.

For the unsymmetric voltage correction, it is necessary that both amplitude and phase correction are performed. In order to observe the phase change between the applied signal and the signal measured with the oscilloscope, it is

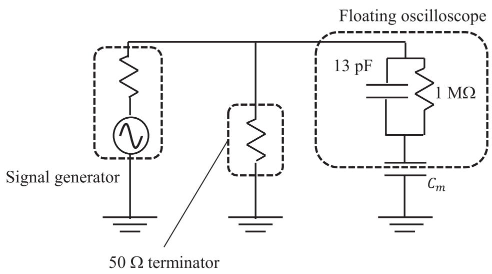

Fig. 11 Equivalent circuit of measurement.

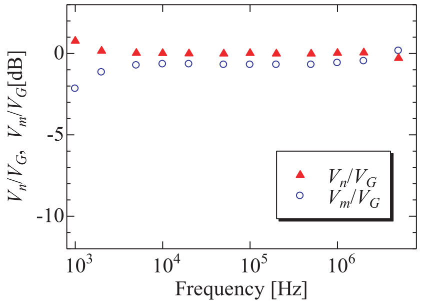

Fig. 12 Measurement result for 10 mm spacer.

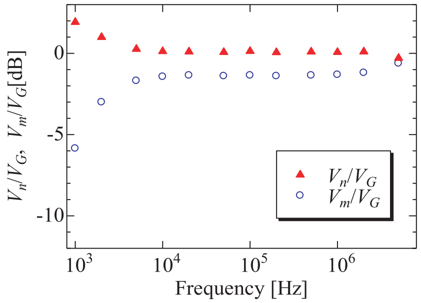

Fig. 13 Measurement result for 30 mm spacer.

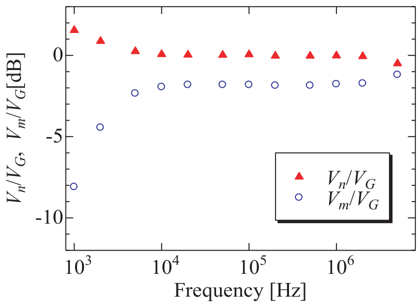

Fig. 14 Measurement result for 50 mm spacer.

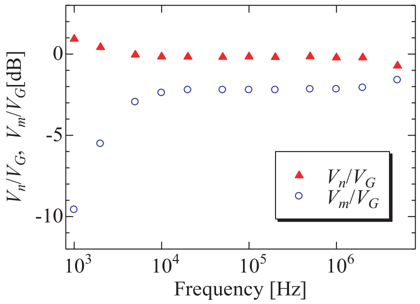

Fig. 15 Measurement result for 70 mm spacer.

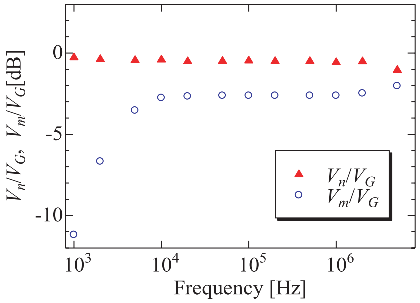

Fig. 16 Measurement result for 90 mm spacer.

necessary to connect the signal generator and oscilloscope, and synchronize them. However, connecting these devices changes the experimental setup. Therefore, we first show that the amplitude can be corrected using sinusoidal waves with frequency of 1 kHz to 5 MHz. Next, it is shown that the phase can be corrected by a rectangular wave correction. A rectangular wave displays sag when there is a capacitance on the signal path; if the proposed correction eliminates this sag, it means that the phase can be corrected.

First, a sinusoidal wave with frequency of 1 kHz to 5 MHz, amplitude 1 $V_{\text{p-p}}$ was applied from the signal generator. The unsymmetric voltage can be corrected by Eq. (1). The ratio between the voltage before the correction by Eq. (1) V_m and the unsymmetric voltage obtained with grounded voltage measurement equipment V_G and the ratio between the voltage after the correction by Eq. (1) V_n and V_G are calculated. The correction results for each height are shown in Figs. 12 to 16 and the correction results for 1 kHz, 10 kHz, 100 kHz and 1 MHz are shown in Figs. 17 to 20. These results show that the corrected voltage is in good agreement with the measured voltage when the measurement equipment is grounded. All correction results V_n are within 2 dB of the difference from grounded voltage measurement equipment V_G and the arithmetic mean of the absolute value of the discrepancy is 0.12 dB when the height is 10 mm, 0.35 dB when the height is 30 mm, 0.29 dB when the height is 50 mm, 0.30 dB when the height is 70 mm and 0.51 dB when the height is 90 mm. In this evaluation, we regarded the signal generator with output impedance of 50 Ω as a noise source and the 50 Ω terminator as unsymmetric-mode impedance. Under real-life conditions, the internal impedance of the noise source and the unsymmetric-mode impedance of the conducted noise are not always 50 Ω, but they are generally sufficiently small compared to the input impedance of the measuring instrument using on-site measurement. Therefore, the results show that the amplitude can be corrected by the proposed method.

Next, a rectangular wave with frequency 20 kHz, amplitude 1 $V_{\text{p-p}}$, pulse width 25 µs and edge time 10 µs, was

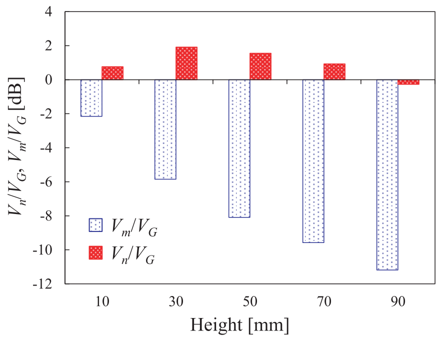

Fig. 17 Measurement result for 1 kHz.

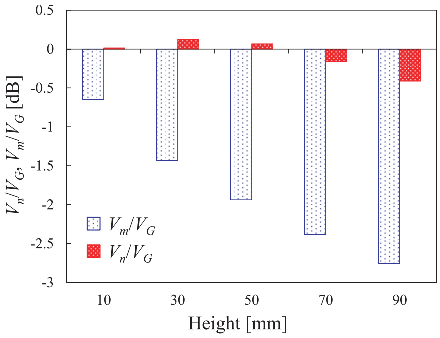

Fig. 18 Measurement result for 10 kHz.

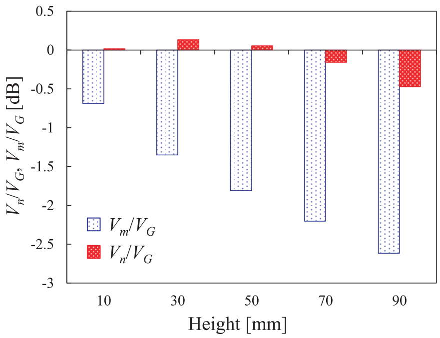

Fig. 19 Measurement result for 100 kHz.

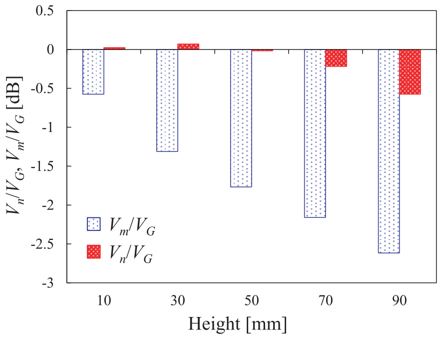

Fig. 20 Measurement result for 1 MHz.

generated from the signal generator, and an oscilloscope was installed on a copper plate raised 50 mm from the shield room floor with acrylic plates. After Fourier transform of the measured waveform, correction was conducted using Eq. (1), and the waveform was reconstructed by inverse Fourier transform of the corrected result. The measurement results and correction results are shown in Fig. 21 and Fig. 22. In the uncorrected waveform, a 14% sag occurs due to the ground capacitance between the copper plate and the shield room floor, however the sag is eliminated by the correction. This indicates that the phase can be corrected by the proposed method.

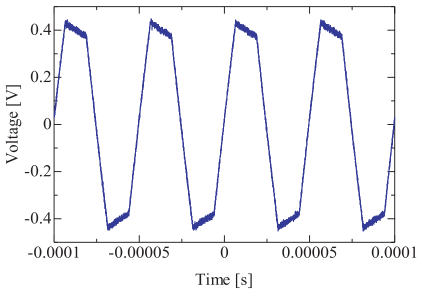

Fig. 21 Measured waveform.

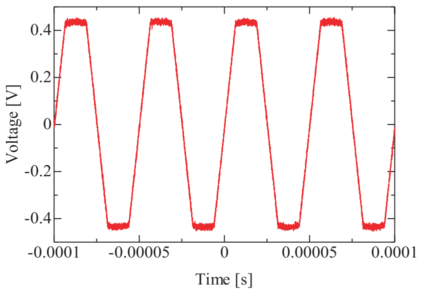

Fig. 22 Corrected waveform.

4. Conclusion

In this paper, a method of measuring conducted noise voltage with floating measurement system is proposed. This system consists of methods of estimating the stray capacitance between the measurement instrument and the ground plane and of correcting measured voltages to match the unsymmetric voltage of the conducted noise by using an estimate of capacitance. And this method is intended to be applicable to on-site noise voltage measurement such as in telecommunications centers, where the voltage reference point or ground plane is relatively close to the measurement instrument.

The capacitance was estimated within 25% error even if the distance and the relative permittivity were unknown. From the experiments, it was shown that the amplitude of the unsymmetric voltage can be corrected to within an error of 2 dB or less in the frequency range from 1 kHz to 5 MHz. And it is also shown that the sag of a rectangular wave caused by the ground capacitance can be eliminated as a result of this correction. This means that the phase of the unsymmetric voltage can be corrected with the proposed method.

References

[1] A. Kempski and R. Smolenski, "Decomposition of EMI noise into common and differential modes in PWM inverter drive system," Electrical Power Quality and Utilization Journal, vol.12, no.1, pp.53–57, 2006.

[2] N. Bondarenko, L. Zhai, B. Xu, G. Li, T. Makharashvili, D. Loken, P. Berger, T.P. Van Doren, and D.G. Beetner, "A measurement-based model of the electromagnetic emissions from a power Inverter," IEEE Trans. Power Electron., vol.30, no.10, pp.5522–5531, 2015.

[3] E. Zhong and T.A. Lipo, "Improvements in EMC performance of inverter-fed motor drives," IEEE Trans. Ind. Appl., vol.31, no.6, pp.1247–1256, 1995.

[4] F. Mahmood, K. Okamoto, and K. Takaya, "A study on conducted disturbance below 150 kHz from commercial power-conditioning system," Proc. IEEE 37th International Telecommunications Energy Conference (INTELEC 2015), pp.1–3, 2015.

[5] ITU-T Rec. K.24, "Method for Measuring Radio-frequency Induced Noise on Telecommunication Pairs."

[6] T. Magesacher, P. Odling, T. Lunberg, M. Isaksson, and P.O. Borjesson, "An adaptive mixed-signal narrowband interference canceller for wireline transmission systems," Proc. 2001 IEEE International Symposium on Circuits and Systems (ISCAS 2001), pp.450–453, 2001.

[7] L. De Clercq, M. Peeters, S. Schelstraete, and T. Pollet, "Mitigation of radio interference in xDSL transmission," IEEE Commun. Mag., vol.38, no.3, pp.168–173, 2000.

[8] P. Odling, O. Borjesson, T. Magesacher, and T. Nordstrom, "An approach to analog mitigation of RFI," IEEE J. Sel. Areas Commun., vol.20, no.5, pp.974–986, 2002.

[9] R. Kobayashi, A. Nagao, H. Ito, and N. Hirasawa, "Simultaneous and non-invasive probe for measuring common-mode voltage and current," Proc. EMC Sapporo & APEMC 2019, pp.645–648, 2019.

[10] R. Kobayashi, Y. Hiroshima, H. Ito, H. Furuya, M. Hattori, and Y. Tada, "A novel non-contact capacitive probe for common-mode voltage measurement," IEICE Trans. Commun., vol.E90-B, no.6, pp.1329–1337, June 2007.

[11] H. Takahashi, N. Kuwabara, F. Amemiya, and M. Hattori, "Method of measuring voltage without cable correction by loading capacitance changeable CVP," Proc. 18th Int. Zurich Symposium on EMC, pp.481–484, 2007.

[12] CISPR Publication 16-1-2, "Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-2: Radio disturbance and immunity measuring apparatus – Ancillary equipment – Conducted disturbance."

[13] CISPR/TR Publication 16-2-5, "Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-5: In situ measurements for disturbing emissions produced by physically large equipment."

[14] N. Arai, K. Okamoto, and J. Kato, "Development of ground capacitance estimating method for simplified grounding," Proc. EMC Sapporo & APEMC 2019, p.278, 2019.

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