Unsymmetric Voltage of Conducted Noise Measurement System Without Grounding by Estimation of Ground Capacitance

Naruto Arai, *Member, IEEE*, Yohei Toriumi, Ken Okamoto, Jun Kato, Yoshiharu Akiyama, and Ken Sasaki

***Abstract*— Conducted noise originating from power supply equipment disrupts telecommunication networks, causing problems such as telecommunication interruptions and reduction in the speed of communication. Measurement of noise in data transmission lines at a repair site may require additional work to secure the electrical ground level for the measurement, because the data lines are differential pairs and the ground level is not always accessible. A method to estimate the capacitance between the measurement equipment and the ground was developed to allow measurement without access to the ground, i.e., in floating conditions. The method uses an oscillator and multiple electrodes to measure the capacitive coupling with the ground under the floor. A ground-capacitance-estimating device was fabricated and tested. Its accuracy was further improved by incorporating a linear function to express the relationship between the output of the device and the known ground capacitance in the calibration setting. This calibration procedure and the measurement procedure at the repair site are described. The noise voltage was calculated from the estimated ground capacitance and the voltage reading of the floating measurement equipment. The estimated ground capacitance was in the order of several tens of pF. The error of the corrected noise voltage was within 1.6 dB.**

***Index Terms*— Capacitance measurement, conducted noise, unsymmetric voltage, voltage measurement.**

I. Introduction

CONDUCTED noise from several tens of kHz to several tens of MHz is generated at switching circuits in power supply equipment [1]–[3]. The consequent interference with communication devices disrupts telecommunication networks and degrades equipment performance and transmission quality [4]. Although communication equipment is designed to tolerate a certain level of conducted noise, the noise level may exceed the design specification. For example, aged equipment with deteriorated capacitors generates high levels of noise [5]. When a communication problem occurs and conducted noise is suspected, the conducted noise is measured at the site. The common mode current and unsymmetric voltage of conducted noise are measured with equipment such as an oscilloscope. The problem is usually solved by using a noise suppressor that matches the frequency band of the conducted noise or by replacing the equipment that is emitting the conducted noise.

Some studies have tried to improve the efficiency of these operations. For example, a probe that can measure the current and voltage of conducted noise simultaneously has been developed [6]. Measurement at a site becomes an onerous task when an electrical ground needs to be secured to measure the unsymmetric voltage of the conducted noise. In some cases, it is necessary to drive a grounding rod into the earth to obtain the ground for the measurement. If the conducted noise can be measured without requiring the equipment to be grounded, the work at the site will be much easier.

Several studies have reported asymmetric digital subscriber line (ADSL) systems that were affected by conducted noise [7]–[11]. The ADSL is a communication method that operates on frequencies of 25.875 kHz to 1.104 MHz and uses twisted pair cables for high-speed data transmission [12]. In this study, a method for measuring the unsymmetric voltage of the conducted noise in the frequency band of ADSL using the floating measuring equipment was investigated.

When the floating measurement equipment is used, the measured voltage is not reliable because there is no direct connection between the ground of the measurement equipment and the ground of the data communication equipment and noise source. The ground of the data communication equipment and the noise source are usually electrically connected to conductive materials under the floor or behind the wall, such as metal parts used for the floor, structural elements of the building, pipes, or conduits. In this article, we will refer to this electrical ground as the "ground plane," and the capacitance between the measurement equipment and the ground plane as the "ground capacitance."

Manuscript received January 5, 2021; accepted January 11, 2021. Date of publication January 25, 2021; date of current version February 11, 2021. This article is a technically extended version of the conference paper [18], which was presented at the International Instrumentation and Measurement Technology Conference (I2MTC) 2020. The Associate Editor coordinating the review process was Dr. Dimitrios Georgakopoulos. *(Corresponding author: Naruto Arai.)*

Naruto Arai is with the Space Environment and Energy Laboratories, Nippon Telegraph and Telephone Corporation, Tokyo 180-8585, Japan, and also with the Graduate School of Frontier Sciences, The University of Tokyo, Tokyo 277-8563, Japan (e-mail: naruto.arai.ud@hco.ntt.co.jp).

Yohei Toriumi and Jun Kato are with the Space Environment and Energy Laboratories, Nippon Telegraph and Telephone Corporation, Tokyo 180-8585, Japan (e-mail: youhei.toriumi.fv@hco.ntt.co.jp, jun.katou.en@hco.ntt.co.jp).

Ken Okamoto is with the Information Network Laboratory Group, Nippon Telegraph and Telephone Corporation, Tokyo 180-8585, Japan (e-mail: ken.okamoto.ag@hco.ntt.co.jp).

Yoshiharu Akiyama is with the Environmental Business Unit, NTT Advanced Technology Corporation, Tokyo 180-8585, Japan (e-mail: yoshiharu.akiyama@ntt-at.co.jp).

Ken Sasaki is with the Graduate School of Frontier Sciences, The University of Tokyo, Tokyo 277-8563, Japan (e-mail: ksasaki@edu.k.u-tokyo.ac.jp).

Digital Object Identifier 10.1109/TIM.2021.3053986

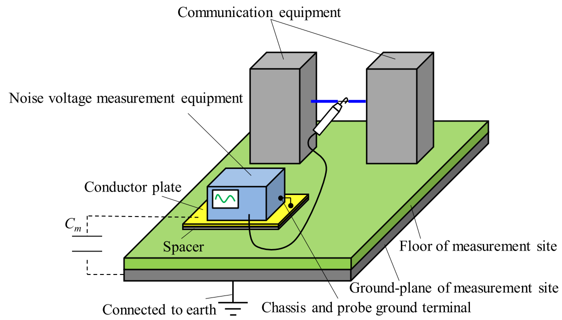

Fig. 1. Schematic of the measurement setup at the work site.

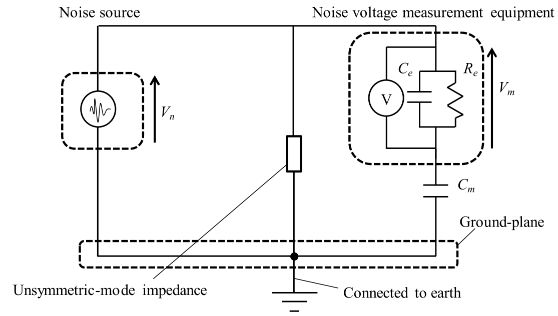

Fig. 2. Equivalent circuit of conducted noise measurement without grounding.

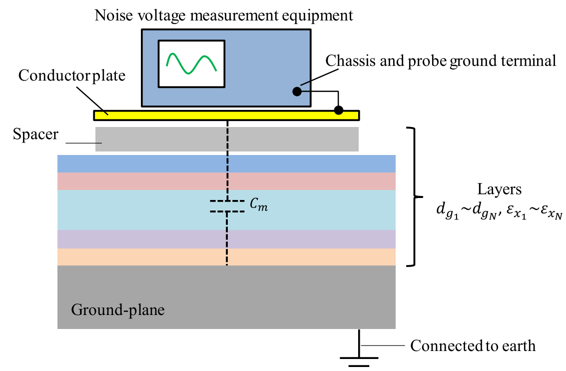

Fig. 3. Model of ground capacitance C_m.

If we can measure the ground capacitance, we can correct the voltage reading of floating measurement equipment and estimate the noise voltage. A common approach for measuring capacitance is to attach probes to the two sides that form the capacitance [13]–[16]. However, the ground plane is not accessible in the present case. We have therefore developed a ground-capacitance-estimating device consisting of a local oscillator and multiple electrodes. This device is placed on the floor of an inspection site, and the ground capacitance is then estimated by applying a sinusoidal signal to one of the electrodes and measuring the voltage at another electrode [17]. The unsymmetric voltage and the waveform of the conducted noise are obtained by correcting the voltage reading of the floating measurement equipment using the estimated ground capacitance [18], [19]. This method is based on an equivalent circuit consisting of multiple capacitors, some with known capacitances and some with capacitances related to the ground capacitance. One major drawback of this method is that the errors in the capacitances used in the estimation lead to an error in the estimation of the ground capacitance. Furthermore, capacitance errors arise due to the simple parallel plate capacitor model that does not consider electrical flux lines spreading out at the edges of the electrodes [20]. In this article, we propose a method to improve the accuracy of ground-capacitance estimation by obtaining the relationship between the output of the estimating device and the actual ground capacitance in a controlled experimental environment. The obtained relationship can be applied at the inspection site to estimate the ground capacitance more accurately.

In Sections II–IV, the unsymmetric voltage measuring system that uses the ground-capacitance-estimating device and the method for estimating the ground capacitance is first described. This part is mainly taken from [18]. Next, the method for improving the accuracy is proposed and verified by experiments in Section V. Conclusion is given in Section VI.

II. Unsymmetric Noise Voltage Measurement Using Floating Equipment

A schematic of the measurement setup at the work site is shown in Fig. 1. The probe of the noise voltage measurement equipment is attached to the data transmission line between the communication equipment. The ground of the probe (typically a short wire with an alligator clip) is left open, because the ground of the signal is not accessible. Instead, the ground of the equipment is connected to a conductor plate that is placed under the equipment. This conductor plate and the ground plane under the floor form the ground capacitance C_m. The purpose of the conductor plate is to increase and stabilize the capacitive coupling.

Fig. 2 shows the equivalent circuit of the setup shown in Fig. 1. We assumed that the unsymmetric-mode impedance, which mainly consists of the input impedance of the communication equipment, was sufficiently smaller than the input impedance of the noise voltage measurement equipment, and that it did not affect the voltage measurement. The ground plane is connected to the so-called earth ground; however, this connection is not relevant in the present discussion because it is not part of the noise path. R_e and C_e are the input resistance and capacitance of the voltage measurement equipment, respectively. The relationship between the measured voltage V_m and the unsymmetric voltage V_n of the conducted noise is given by

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

where ω_n is the angular frequency of the conducted noise and j is $(-1)^{0.5}$. With the obtained ground capacitance C_m, the unsymmetric voltage of the conducted noise V_n is estimated by (1).

Figure 3 shows the model of the ground capacitance C_m. We assumed that there are multiple layers of insulators between the conductor plate and the ground plane. The thicknesses are denoted by $d_{g1} - d_{gN}$, and the relative values of permittivity are denoted by $\varepsilon_{x1} - \varepsilon_{xN}$. The spacer under the conductor plate is for protection of the plate and is part of the

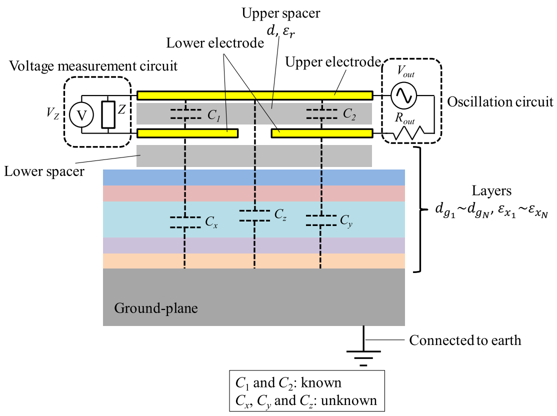

Fig. 4. Configuration of the ground-capacitance-estimating device.

layer. The actual floor construction does not necessarily consist of layers of different materials and may be more complex.

III. Ground-Capacitance-Estimating Device

A. Method for Estimating Ground Capacitance

This section describes the ground-capacitance-estimating method reported in [18]. The configuration of the ground-capacitance-estimating device is shown in Fig. 4. This device consists of one upper electrode, two lower electrodes, an oscillation circuit, and a voltage measurement circuit. The thickness and the material of the lower spacer are the same as the spacer under the conductor plate. The capacitances C_x and C_y are the ground capacitances of the lower electrodes, and C_z is the ground capacitance of the upper electrode. C_1 and C_2 are the capacitances between the upper electrode and the lower electrodes. The oscillation circuit is connected to the upper electrode and one of the lower electrodes. The voltage measurement circuit is connected to the upper electrode and the other lower electrode. V_{out} is the output voltage of the oscillation circuit, R_{out} is the output resistance of the oscillation circuit, Z is the input impedance of the voltage measurement circuit, and V_z is the voltage measured by the voltage measurement circuit. The basic idea of the ground-capacitance estimation is to measure the voltage V_z, which is related to the capacitances C_x, C_y, and C_z, and obtain a parameter that represents the ground capacitance.

The capacitances C_x, C_y, C_z, C_1, and C_2 are given by

$$C_x = \frac{\varepsilon_0 S_1}{\delta} \tag{2}$$

$$C_y = \frac{\varepsilon_0 S_2}{\delta} \tag{3}$$

$$C_z = \frac{\varepsilon_0 (S_3 - S_1 - S_2)}{\frac{d}{\varepsilon_r} + \delta} \tag{4}$$

$$C_1 = \varepsilon_0 \varepsilon_r \frac{S_1}{d} \tag{5}$$

$$C_2 = \varepsilon_0 \varepsilon_r \frac{S_2}{d} \tag{6}$$

where ε_0 is the electric constant, ε_r is the relative permittivity of the upper spacer, S_1 and S_2 are the surface areas of the lower electrodes, S_3 is the surface area of the upper electrode, d is the thickness of the upper spacer, and δ is an equivalent thickness of the layers above the ground plane, which is expressed by

$$\delta = \sum_{k=1}^{N} \frac{d_{gk}}{\varepsilon_{xk}}. \tag{7}$$

Here we assumed a simple parallel plate capacitor model where straight electrical flux lines perpendicular to the electrodes are considered and electrical flux lines spreading out at the edges of the electrodes are not considered.

When we replace the ground-capacitance-estimating device with a conductor plate of area S_m, the ground capacitance C_m between the conductor plate and the ground plane is given by

$$C_m = \frac{\varepsilon_0 S_m}{\delta}. \tag{8}$$

This equation requires the value of δ from the measured voltage V_z. In (2)–(6), C_1 and C_2 are constant values that can be calculated or measured. C_x, C_y, and C_z are unknown but are expressed by the same parameter δ. Although it is possible to obtain δ from V_z by solving the circuit equation of Fig. 4, we used a circuit simulator to obtain the value of δ that gave the voltage V_z closest to the measured V_z. This search procedure was straightforward because the relationship between δ and V_z was monotonic.

B. Construction of Ground-Capacitance-Estimating Device

The fabricated ground-capacitance-estimating device is as follows. The upper and lower electrodes were printed with a silver ink printer on polyethylene terephthalate (PET) film. A $250 \times 120 \times 10$ mm^2 acrylic plate was used for the lower spacer. A $250 \times 120 \times 10$ mm^3 hollow box made of cardboard with a relative permittivity of approximately 1 was used as an upper spacer. The dimensions of the lower electrodes and the upper electrode were 100×120 and 250×120 mm^2, respectively. The output resistance of the oscillation circuit R_{out} was set to 50 Ω and the input resistance R_Z and capacitance C_Z of the voltage measurement circuit for V_z were 1 MΩ and 24 pF, respectively. A battery-powered laptop controls the oscillation circuit and displays the measured V_Z through a universal serial bus (USB) interface. The output signal from the oscillation circuit was a 5-V$_{\text{p-p}}$ sinusoidal signal. The setup of this device at the work site is shown in Fig. 5.

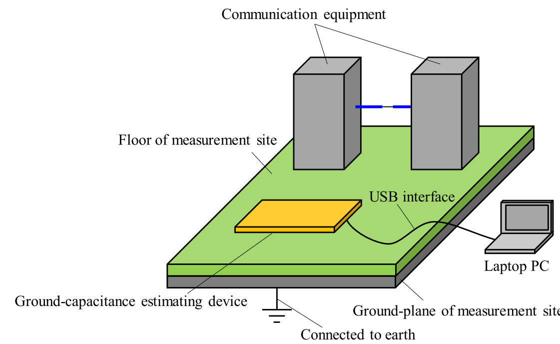

Fig. 5. Setup of the ground-capacitance-estimating device at the work site.

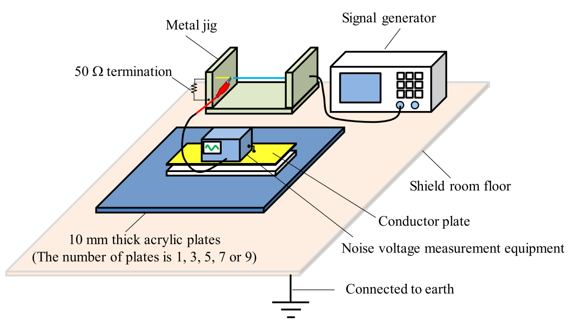

Fig. 6. Experimental setup to measure the ground capacitance in shield room.

IV. Evaluation of Ground-Capacitance-Estimating Device

A. Preparation of Ground Capacitance in Experimental Setting

The ground-capacitance-estimating device was evaluated by measuring the ground capacitance in an experimental setting. Experiments were conducted in a shielded room with a conductive floor, regarded as the ground plane. The ground capacitance for evaluation was prepared by stacking 10-mm-thick acrylic plates on the floor. The ground-capacitance-estimating device, or the set of conductor plate and the noise voltage measurement equipment (3144 Noise Search Tester; HIOKI E.E. CORPORATION, Nagano, Japan), was placed on top of the stacked acrylic plates. The ground capacitance was varied by changing the number of acrylic plates.

We needed to know the effective ground capacitance of this setting in order to evaluate the performance of the ground-capacitance-estimating device. We measured the capacitance by using a signal generator, conductor plate, and the noise voltage measurement equipment, as shown in Fig. 6. The method for obtaining the capacitance is as follows.

Solving (1) for C_m we get

$$C_m = \frac{C_e}{\left(\sqrt{\frac{1}{\omega_n^2 R_e^2 C_e^2}\left(\frac{|V_n|^2}{|V_m|^2}-1\right)+\frac{|V_n|^2}{|V_m|^2}}-1\right)\left(\frac{1}{1+\frac{1}{\omega_n^2 R_e^2 C_e^2}}\right)} \quad (9)$$

where V_n is the noise source voltage, which is the amplitude of the continuous sinusoidal signal at a frequency of ω_n from the signal generator, V_m is the voltage reading of the noise voltage measurement equipment, and R_e and C_e are the input resistance and capacitance of the voltage measurement equipment, respectively.

The number of acrylic plates was changed to 1, 3, 5, 7, and 9. Adding the thickness of the lower spacer of 10 mm, the total distance between the lower electrode and the ground plane was 20, 40, 60, 80, and 100 mm. A 3-V_{p-p} sinusoidal signal from the signal generator was connected to a bare wire suspended across a metal jig, and the probe of the noise voltage measurement device was attached to this line. The noise voltage measurement equipment was placed on a 250 × 120 × 10 mm^3 acrylic plate whose top side was covered with a thin electrode that acted as the conductor plate. The ground of the equipment was connected to this plate. The dimension of the conductor plate was the same as the dimension of the upper electrode of the ground-capacitance-estimating device.

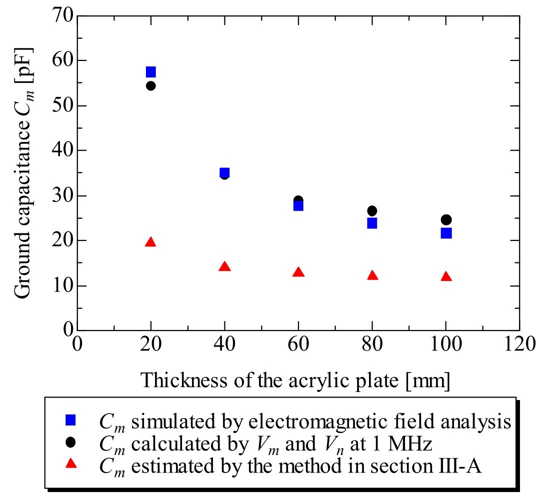

Fig. 7. Relationship between thickness of acrylic plate and ground capacitance C_m.

R_e and C_e were 1 MΩ and 177 pF. C_e includes the capacitance of the coaxial cable of the probe.

The effective noise source voltage $|V_n|$ was measured by connecting the ground of the noise voltage measurement equipment directly to the ground plane, i.e., the floor of the shielded room, to form a closed loop without C_m. The average ground capacitance C_m calculated from the measured voltage $|V_m|$ and $|V_n|$ using (9) at frequencies from 10 kHz to 2 MHz was 56.4, 35.8, 29.8, 27.3, and 25.3 pF for total plate thicknesses of 20, 40, 60, 80, and 100 mm, respectively. The capacitances at 1 MHz are depicted in Fig. 7 by black circles. These capacitances will be used as references in the evaluation of the ground-capacitance-estimating device.

B. Numerical Analysis of Ground Capacitance in an Experimental Setting

We also conducted a numerical analysis of the capacitance of the experimental setting described in Section IV-A. The analysis model was as follows. The ground plane was modeled by a conductor plate of 750 × 360 mm^2. These dimensions were determined so that it was sufficiently larger than the upper conductor plate, which was 250 × 120 mm^2. A large acrylic plate with dimensions of 750 × 360 mm^2 and with a thickness of 10, 30, 50, 70, and 90 mm, a small acrylic plate of dimensions 250 × 120 × 10 mm^2, and the upper conductor plate, were stacked on the ground plane. The total distance between the two conductor plates was 20, 40, 60, 80, and 100 mm. The relative permittivity of the acrylic plate was set to be 3.5. We used electromagnetic field analysis software that uses the finite element method (Femtet, Murata Software Co., Ltd., Tokyo, Japan). The results are 57.5, 35.1, 27.7, 23.9, and 21.6 pF and are shown by blue squares in Fig. 7. The capacitances agree with the measured values in Section IV-A, with errors in the order of a few pF.

C. Evaluation Result of Ground Capacitance Estimating Device

The noise voltage measurement device and the conductor plate in Fig. 6 were replaced by the ground-

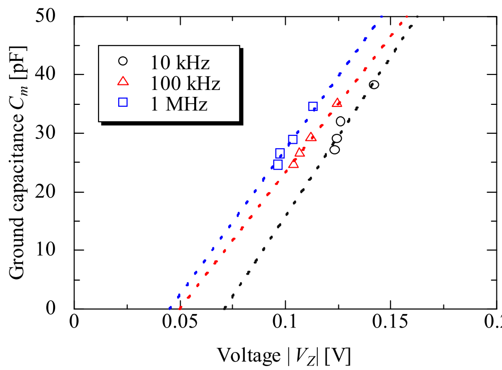

Fig. 8. Relationship between measured voltage $|V_Z|$ and the ground capacitance C_m.

capacitance-estimating device to evaluate its estimation accuracy. The effective voltage $|V_Z|$ was measured and δ was obtained by a circuit simulator. C_m was estimated by substituting δ and the conductor plate area S_m into (8). The results at 1 MHz are shown by red triangles in Fig. 7. The estimated ground capacitances were approximately half of the capacitances measured and calculated in Sections IV-A and IV-B, respectively. We presume that this estimation error was mainly due to the simple capacitor model used in derivation of (2)–(6). Nonetheless, the result shown in Fig. 7 suggests that the measurement output of the ground-capacitance-estimating device represents the capacitive characteristic of the floor at the site.

V. Additional Calibration Method and Evaluation of Unsymmetric Conducted Noise Measurement

A. Additional Calibration Method

As suggested in Section IV-C, the estimation accuracy can be improved by finding a relationship between the output of the ground-capacitance-estimating device and the actual ground capacitance. Instead of finding the relationship between the two capacitances indicated by red triangles and black circles in Fig. 7, we investigated the relationship between the voltage $|V_Z|$ measured by the ground-capacitance-estimating device and the capacitance indicated by black circles. In this way, we can eliminate the process of obtaining δ in calculating the capacitance indicated by red triangles.

The results at frequencies of 10 kHz, 100 kHz, and 1 MHz are shown in Fig. 8. These results indicate that the relationship can be approximated by a linear function. The linear function was obtained by the least square method. The approximate functions for other frequencies are given in Table I.

This process for obtaining the approximate functions can be performed in an experimental environment, such as a shielded room, prior to inspection and repair work at the site. It should be noted that the approximate functions are obtained for particular conductor plate dimensions. Therefore, the same conductor plate must be used at the site. The procedure at the work site will be as follows.

Step 1: Place the ground-capacitance-estimating device on the floor and measure $|V_Z|$.

TABLE I
FUNCTIONS FOR CONVERTING MEASURED VOLTAGE $|V_Z|$ TO GROUND CAPACITANCE C_m

Frequency	Ground-Capacitance C_m [pF]
10 kHz	$C_m = 545\|V_Z\| - 38.7$
20 kHz	$C_m = 473\|V_Z\| - 26.0$
50 kHz	$C_m = 464\|V_Z\| - 23.2$
100 kHz	$C_m = 465\|V_Z\| - 23.1$
200 kHz	$C_m = 467\|V_Z\| - 21.9$
500 kHz	$C_m = 463\|V_Z\| - 19.9$
1 MHz	$C_m = 497\|V_Z\| - 22.4$
2 MHz	$C_m = 548\|V_Z\| - 25.5$

Step 2: Obtain the ground capacitance C_m by substituting $|V_Z|$ into the linear approximate function of the frequency used in Step 1.

Step 3: Place conductor plate and noise voltage measurement device on the floor, connect the ground of the equipment to the conductor plate, and attach the probe to the line to be inspected.

Step 4: Read $|V_m|$ measured by the noise voltage measurement equipment and obtain the noise voltage $|V_n|$ by substituting $|V_m|$ into (1).

B. Evaluation of Unsymmetric Voltage Measurement System

The unsymmetric voltage measurement method described in Section V-A was evaluated in a shielded room and in a typical office room. In the shielded room, the ground capacitance was changed by using medium-density fiberboard (MDF) plates instead of acrylic plates. The relative permittivity of the MDF plate was unknown. The thickness of the MDF plate was 9 mm, and the number of plates was changed to 1, 2, and 3. The floor of the office room had carpet (with rubber on the bottom side) spread over metal panels. This is a typical office floor construction to allow easy routing of computer and power cables. We did not use additional plates to change the ground capacitance in the office room.

First, the ground-capacitance estimating device was placed, and $|V_Z|$ was measured at frequencies from 10 kHz to 2 MHz. The average $|V_Z|$ was 0.165, 0.144, and 0.124 V for MDF plate of thicknesses of 9, 18, and 27 mm, respectively, in the shielded room, and 0.184 V in the office room. The ground capacitances C_m calculated by the function shown in Table I using the voltage $|V_Z|$ are shown in Fig. 9.

Next a 3-V_{p-p} sinusoidal signal at frequencies of 10 kHz to 2 MHz was supplied from the signal generator as the noise signal and was measured by the noise voltage measurement equipment, whose ground was connected to the conductor plate. This setup is the same as that shown in Fig. 6. In the office room, the signal generator was placed on the floor, and the ground of the signal generator was not connected to anything. The power supply from the outlet was the only direct connection with the environment.

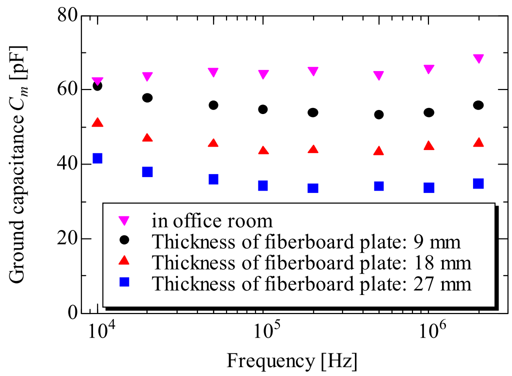

Fig. 9. Calculated ground capacitance Cm.

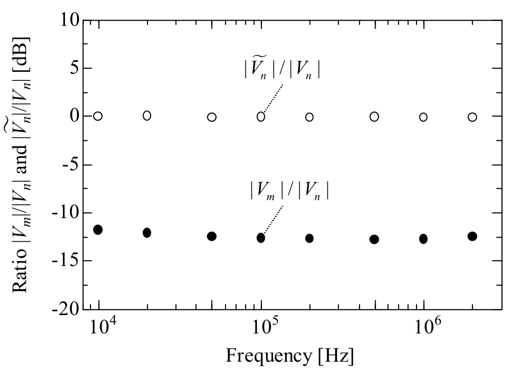

Fig. 10. Measurement and correction result with 9 mm thickness fiberboard plate.

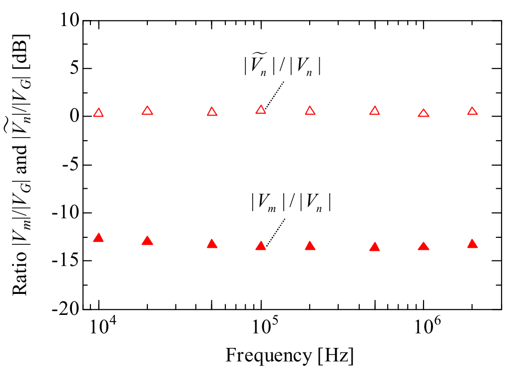

Fig. 11. Measurement and correction result with 18 mm thickness fiberboard plate.

The effective value of the measured voltage $|V_m|$ was corrected to the effective value of the unsymmetric voltage $|\widetilde{V}_n|$ by (1) using the ground capacitance C_m shown in Fig. 9. The ratios between $|V_m|$ and $|V_n|$ and between $|\widetilde{V}_n|$ and $|V_n|$ are shown in Figs. 10–13. The ratios are expressed in dB. Zero dB means that the measured or estimated voltage is equal to the source voltage. The ratios of $|V_m|/|V_n|$ were 11 dB or more, while the ratios of $|\widetilde{V}_n|/|V_n|$ were 1.6 dB or less, indicating that the noise voltage V_n was successfully estimated from the voltage V_m, which was measured by the noise voltage measurement equipment.

The result in the office room is of particular importance, because it indicates that the ground capacitance estimated by the proposed method was the dominant impedance in the noise measurement loop. In other words, although the signal generator's ground was not connected to anything, other impedances in the ground-plane path were sufficiently smaller

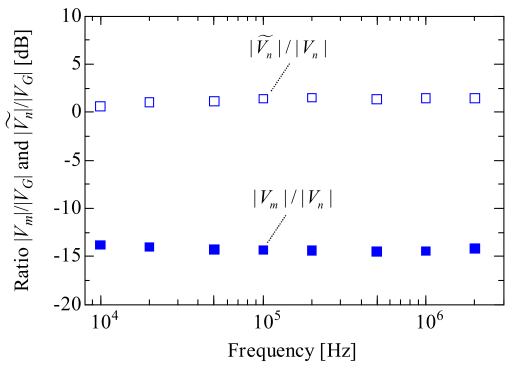

Fig. 12. Measurement and correction result with 27 mm thickness fiberboard plate.

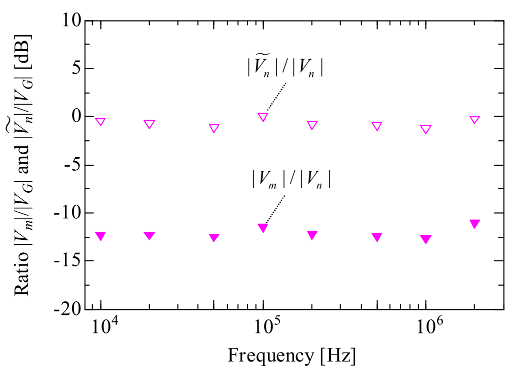

Fig. 13. Measurement and correction result in the office room.

than the impedance of the ground capacitance just beneath the conductor plate of the measurement equipment. This suggests that we only need to estimate the ground capacitance at the point on the floor where the measurement equipment is placed.

VI. Conclusion

Methods for measuring the unsymmetric voltage of conducted noise without connecting the ground of the measurement equipment were proposed and evaluated by experiments. A device consisting of an oscillator and electrodes was designed and fabricated to measure the capacitive coupling between the electrodes and the ground. The ground capacitance was estimated by solving the equivalent circuit model of the device. The estimated capacitances were approximately half of the capacitances that were verified in an experimental setting. The error was mainly due to the simple capacitor model used for calculating the capacitances of the device. The relationship between the voltage measured in the capacitance estimating device and the ground capacitance of the experimental setting was expressed by linear equations. These equations improved the accuracy of the capacitance estimation. Experiments in a shielded room and in an office room showed that the measurement error of the unsymmetric voltage of the conducted noise was 1.6 dB or less.

References

[1] N. Bondarenko *et al.*, "A measurement-based model of the electromagnetic emissions from a power inverter," *IEEE Trans. Power Electron.*, vol. 30, no. 10, pp. 5522–5531, Oct. 2015.

[2] F. Mahmood, K. Okamoto, and K. Takaya, "A study on conducted disturbance below 150 kHz from commercial power-conditioning system," in *Proc. IEEE Int. Telecommun. Energy Conf. (INTELEC)*, Osaka, Japan, Oct. 2015, pp. 1–3.

[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, Nov. 1995.
[4] *Method for Measuring Radio-Frequency Induced Noise on Telecommunications Pairs*, document ITU-T Rec. K. 24, 1988.
[5] F. Ishiyama and Y. Toriumi, "Live line aging estimation of AC adapters," in *Proc. IEEE Int. Symp. Signal Process. Inf. Technol. (ISSPIT)*, Louisville, KY, USA, Dec. 2018, pp. 175–178.
[6] R. Kobayashi, A. Nagao, H. Ito, and N. Hirasawa, "Simultaneous and non-invasive probe for measuring common-mode voltage and current," in *Proc. Joint Int. Symp. Electromagn. Compat., Sapporo Asia–Pacific Int. Symp. Electromagn. Compat. (EMC Sapporo/APEMC)*, Sapporo, Japan, Jun. 2019, pp. 645–648.
[7] W. R. W. Abdullah, A. N. Z. Abidin, M. Z. M. Jenu, and T. C. Chuah, "Measurement and verification of the impact of electromagnetic interference from household appliances on digital subscriber loop systems," *IET Sci., Meas. Technol.*, vol. 3, no. 6, pp. 384–394, Nov. 2009.
[8] A. N. Z. Abidin, W. R. W. Abdullah, A. Ramli, and M. Z. M. Jenu, "Interference limit proposal for ADSL2+ using APD methodology," in *Proc. IEEE Asia–Pacific Conf. Appl. Electromagn. (APACE)*, Port Dickson, Malaysia, Nov. 2010, pp. 1–4.
[9] W. R. W. Abdullah, F. Mahtar, A. N. Z. Abidin, M. Z. M. Jenu, and A. Ramli, "The effects of electrical fast transient (EFT)/burst on ADSL background noise," in *Proc. Asia–Pacific Symp. Electromagn. Compat., 19th Int. Zurich Symp. Electromagn. Compat.*, Singapore, May 2008, pp. 84–87.
[10] W. Yu, D. Toumpakaris, J. M. Cioffi, D. Gardan, and F. Gauthier, "Performance of asymmetric digital subscriber lines in an impulse noise environment," *IEEE Trans. Commun.*, vol. 51, no. 10, pp. 1653–1657, Oct. 2003.
[11] K. Murakawa, N. Hirasawa, H. Ito, and Y. Ogura, "Electromagnetic interference examples of telecommunications system in the frequency range from 2 kHz to 150 kHz," in *Proc. IEEE Int. Symp. Electomagn. Compat.*, Tokyo, Japan, May 2014, pp. 581–584.
[12] *Asymmetric Digital Subscriber Line (ADSL) Transceivers*, document ITU-T Rec. G. 992. 1, 1999.
[13] N. Hagiwara and T. Saegusa, "An RC discharge digital capacitance meter," *IEEE Trans. Instrum. Meas.*, vol. IM-32, no. 2, pp. 316–321, Jun. 1983.
[14] W. Ahmad, "A new simple technique for capacitance measurement," *IEEE Trans. Instrum. Meas.*, vol. IM-35, no. 4, pp. 640–642, Dec. 1986.
[15] S. S. Awad, "Capacitance measurement based on an operational amplifier circuit: Error determination and reduction," *IEEE Trans. Instrum. Meas.*, vol. IM-37, no. 3, pp. 379–382, Sep. 1988.
[16] A. D. Koffman, S. Avramov-Zamurovic, B. C. Waltrip, and N. M. Oldham, "Uncertainty analysis for four terminal-pair capacitance and dissipation factor characterization at 1 and 10 MHz," *IEEE Trans. Instrum. Meas.*, vol. 49, no. 2, pp. 346–348, Apr. 2000.
[17] N. Arai, K. Okamoto, and J. Kato, "Development of ground capacitance estimating method for simplified grounding," in *Proc. Joint Int. Symp. Electromagn. Compat., Sapporo Asia–Pacific Int. Symp. Electromagn. Compat. (EMC Sapporo/APEMC)*, Sapporo, Japan, Jun. 2019, p. 278.
[18] N. Arai, K. Okamoto, and J. Kato, "Conducted noise measuring system using floating voltage measurement equipment," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC)*, Dubrovnik, Croatia, May 2020, pp. 1–5.
[19] N. Arai, K. Okamoto, J. Kato, and Y. Akiyama, "Method of measuring conducted noise voltage with a floating measurement system to ground," *IEICE Trans. Commun.*, vol. E103.B, no. 9, pp. 903–910, Sep. 2020.
[20] R. F. Harrington, "Electrostatic fields," in *Field Computation by Moment Methods*. Hoboken, NJ, USA: Wiley, 1993, pp. 22–40.

Naruto Arai (Member, IEEE) received the B.S. degree in precision engineering and the M.S. degree in human and engineered environmental studies from The University of Tokyo, Tokyo, Japan, in 2015 and 2017, respectively, where he is currently pursuing the Ph.D. degree with the Department of Human and Engineered Environmental Studies, Graduate School of Frontier Sciences.

He then joined NTT Network Laboratories, Tokyo, and is currently researching EMC technologies for telecommunication systems in NTT Space Environment and Energy Laboratories.

Yohei Toriumi received the B.E. and M.E. degrees in electrical and electronics engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2003 and 2005, respectively.

In 2005, he joined the NTT Energy and Environment Systems Laboratories, Tokyo. He is currently a Senior Research Engineer at the Planning Department, NTT Space Environment and Energy Laboratories, Tokyo.

Ken Okamoto received the B.S. and M.S. degrees in science from Nagoya University, Nagoya, Japan, in 2004 and 2006, respectively.

He joined NTT Energy and Environment Systems Laboratories, Tokyo, Japan, in 2006. He is currently studying EMC technology for telecommunication systems with the NTT Information Network Laboratory Group.

Jun Kato received the B.E. degree from Shizuoka University, Shizuoka, Japan, in 1992.

He joined the Telecommunication Networks Laboratory, Nippon Telegraph and Telephone Corporation (NTT), Tokyo, Japan, in 1992, and is currently a Project Manager at NTT Space Environment and Energy Laboratories. He was engaged in research and development of EMC protection for telecommunication systems.

Yoshiharu Akiyama received the B.E. and D.E. degrees from the University of Electro Communications, Chofu, Japan, in 1990 and 2010, respectively.

After joining NTT, Tokyo, Japan, in 1990, he has been researching methods of testing and measuring for electromagnetic compatibility (EMC) on wireless communication and broadband communication systems and engaged in international standardization of them. He is currently a Manager of Environmental Business Unite with NTT Advanced Technology Corporation.

Ken Sasaki received the B.S., M.S., and Ph.D. degrees in precision engineering from The University of Tokyo, Tokyo, Japan, in 1980, 1982, and 1987, respectively.

Since 1987, he has been an Associate Professor with the Department of Precision Engineering, Faculty of Engineering, The University of Tokyo. He is currently a Professor with the Department of Human and Engineered Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo. His research fields are mechatronics, signal processing, and human interface.