Simultaneous and Non-invasive Probe for Measuring Common-mode Voltage and Current

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***Abstract*—Common-mode voltage and current measurements are one of the key issues to solve EMC troubles in the field. Thus, there are several measurement probes have been developed to measure common-mode voltage and current of an electromagnetic disturbance [1]-[4]. However, only separately measuring voltage or current may lead overestimation or under-estimation of phenomena, because voltage and current depend on an impedance. This paper proposes novel non-invasive probe for measuring voltage and current of the electromagnetic disturbance, simultaneously. First, we show configuration of the new probe and describe its principle. Second, characteristics of the probe are presented and evaluated by comparing calculation from equivalent circuit. Finally, we show measured result of impulsive waveform in time domain.**

Keywords—Non-invasive measurement; Common-mode voltage and current; simaltaneous measurement; conducted disturbance;

I. Introduction

Electro-magnetic environment has been complicated since many electro/electronics devices are used in our surroundings. Thus, electro-magnetic compatibility is important to avoid malfunctions or troubles due to electromagnetic disturbances. In the field, it is important to obtain characteristics of the disturbances when troubles occur. In order to solve EMC problems, common-mode voltage and current of the disturbances on cables are usually measured to obtain their characteristics, such as frequency spectrum, peak value, and so on. Several measurement probes have been developed [1][2]. For current measurement, probes that use to electromagnetic induction or hole effect have been developed [1][2]. These probes can measure a disturbance current, non-invasively. On the other hand, voltage measurement by conventional voltage probe usually needs to be contacted with a conductor where disturbance voltage occurs. Therefore, it is difficult to measure the voltage in normal operating conditions, especially in telecommunication field, because it may affect transmitted signals. Thus, non-invasive voltage probe has been developed [3][4] and standardized in the international standard in CISPR [5]. This probe can measure the disturbance voltage without touching a conductor. However, in case of conventional measurement method, these probes should be used separately, thus it is sometimes difficult to measure a voltage and current simultaneously at same point. If the voltage and current can be measured at the same points, we can evaluate a transmission direction of the disturbance by calculating its effective energy [6]. Moreover, only voltage or current measurement may lead misunderstanding of phenomena, because impedance of measured cables is unknown in almost of all the time in the field. Therefore, simultaneous measurement of common-mode voltage and current is important to know the characteristics of disturbances.

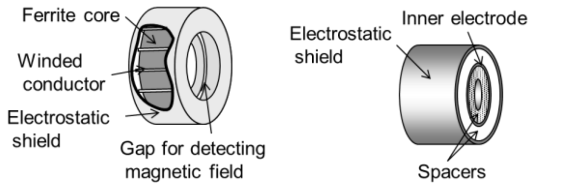
In this paper, we have proposed and studied new method for measuring common-mode voltage and current at same measurement point, simultaneously and non-invasively. First, we propose a new probe that can measure a common-mode voltage and current without contacting to a measured cable and show its equivalent circuit. Second, we made the probe and its frequency characteristic was evaluated, theoretically and experimentally. Finally, we carried out time domain waveform measurements using impulsive wave. To reflects characteristics of the probes into measured data, applied and measured waveforms were evaluated to confirm usefulness of the probe.

II. Configerati and principle of the new probe

A. *Configuration of the conventional probes*

First, let us consider conventional probes that are used for measuring voltage and current on a cable without contact to it. Figure1 shows typical configurations of them. Conventional current probe in Fig 1 (a) is a toroidal structure and is constructed with a ferrite core with winded conductive wire, and metallic cover for shielding electrostatic induction by surroundings [2]. The metallic cover has a small gap to detect a magnetic field produced by current on a measured cable. Non-contact voltage probe as shown in Fig.1 (b) has an inner and outer cylindrical conductor for detecting voltage on the cable and shielding electrostatically by surroundings, respectively [3]-[5]. These probes can detect voltage and current on the cable without touching it. Therefore, these commonly use for measuring a voltage and current on the cable in the field where interference problem occurs.

Comparing structure of these probes, these have similar configuration, i.e. inner conductor and the winded wire can detect electromagnetic field, and outer conductors can work as an electrostatic shield to avoid an influence from surroundings. Thus, we propose new probe that is combined these structures. That is, inner electrode of the voltage probe replaces winded wire in the current probe, and the metallic cover replaces outer electrode of the voltage probe.



(a) Conventional Current probe (b) Conventional voltage probe

Fig. 1. Configuration of Conventional non-invasive probes

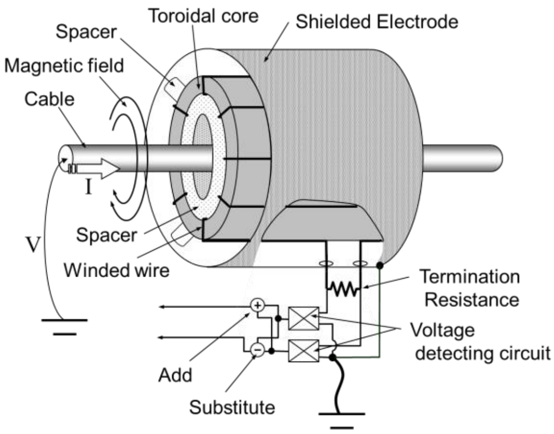


Fig. 2. Configuration of new probe

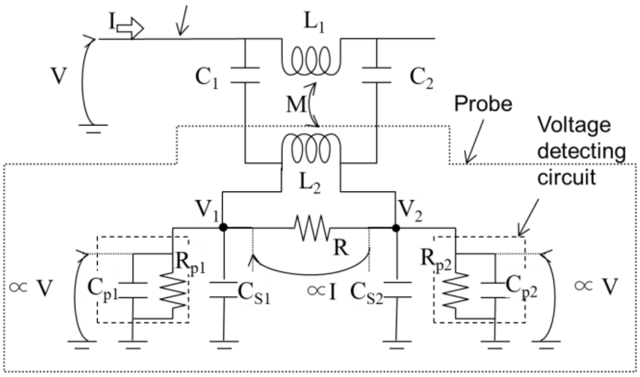
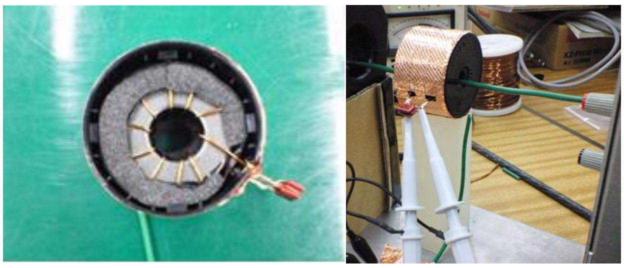


Fig. 3. Equivalent circuit of the new probe



(a) Over view (b) Side-view attaced to a cable

Fig. 4. Outview of new non-invasive voltage and current probe

TABLE I. PARAMETERS OF NEW PROBE

Parameter	Values
Diameter of electrostatic shield	53.4 [mm]
Length of electrostatic shield	33 [mm]
Size of the core	Inner radius 9.5 [mm] Outer radius 19.1 [mm] Thickness 12.7 [mm]
Permiability	3800
Diameter of winded wire	1 [mm]
Termination Resistance	50 [Ω]
Spacer	Formed Ulethen
Voltage detecting circuit	High input imepdance 1 [MΩ]//20[pF]

B. *Configuraion and mechanism of Novel non-contact votage and current probes*

Configuration of novel non-contact voltage and current probe is shown in Fig.2. New probe is similar to conventional current probe. Outside the probe is covered with electrostatic shielded electrode, and inside the probe is constructed with toroidal core with winded wire, i.e. it is toroidal coil, and the wire is terminated by resistance. We replace the inner electrode of the non-contact voltage probe to winded wire and the wire is used as inner conductor and toroidal coil. When measured cable is inserted into the core, electromagnetic induction voltage is appeared on the coil. Moreover, a voltage produced by electrostatic induction is also appeared on the coil.

Equivalent circuit of the proposed probe is shown in Fig 3. In this figure, L_1 and L_2 are the inductance of cable and toroidal coil, respectively, M is the mutual inductance between cable and the coil, C_1 and C_2 are the capacitance between cable and conductor of the coil, C_{s1} and C_{s2} are the capacitance between the conductor and outer shielded electrode, R is the terminated resistance of the coil, and R_{p1}, R_{p2}, C_{p1} and C_{p2} are input resistances and capacitances of the voltage detecting circuits. Parameters of L_1, L_2, C_1 and C_2 are calculated by following equations.

$$L_1 = \frac{\mu L d}{8\pi} + \frac{\mu_0}{2\pi}\left\{L\log_e\left(\frac{L+\sqrt{L^2+a^2}}{a}\right) - \sqrt{L^2+a^2}\right\} \quad (1)$$

$$L_2 = \frac{\mu d N^2}{2\pi}\log_e\left(\frac{c}{b}\right) \quad (2)$$

$$C_1 = C_2 = \frac{2\pi\varepsilon d}{\log_e\left(\frac{b}{a}\right)} \quad (3)$$

$$M = \frac{\mu d N}{2\pi}\log_e\left(\frac{c}{c-b}\right) \quad (4)$$

where a is the radius of the cable, b and c are radius of inner and outer conductors, d is the thickness of the core, L is the length of the conductor, and N is the number of turns.

When $(1/\omega C_1)$ or $(1/\omega C_2)$ is greater than ωL_1 and input impedances of the voltage detecting circuits are sufficiently large, V_1 is proportional to a voltage adding to electrostatic induction voltage and electromagnetic induction voltage, and V_2 is proportional to electrostatic induction voltage. This means that V_1 and V_2 are proportional to common-mode voltage and current on the cable. Thus,

$$Vc_{ommon} \propto (V_1+V_2)/2 \quad (5)$$

$$Ic_{ommon} \propto V_1 - V_2 \quad (6)$$

From these equations, we can obtain common-mode voltage and current, simultaneously by measuring V_1 and V_2.

III. EVALUATION OF NEW PROBE

A. Configuration of new voltage probe

To confirm efficiency of our proposed probe, we made it and carried out measurements. Photo of the probe is shown in Fig.4 and parameters of the probe is given by Table. 1. The probe is cylindrical shape and its size is 33 [mm] long and diameter of 52.4 [mm]. The toroidal core is in the shielded electrode and its size is inner radius of 9.5 [mm], outer radius of 19.1[mm] and thickness of 12.7 [mm]. Relative permeability is 3800, and conducted wire is winded in 10 turns and both ends of the wire are connected to termination resistance of 50 [Ω].

B. Measurement setup for the new probe

Figure 5 shows configuration of measurement setup for evaluating new probe. As shown in this figure, a measured cable was connected to connecters, and placed on a grounded plate. The probe was clamped on the cable and the cable was set on the center of the toroidal coil. One side of the connecter was connected to a signal generator, and the other side was connected to measurement equipment, such as gain-phase analyzer or digital oscilloscope.

When voltage and current appear on the cable, new probe can detect them, and voltages of V_1 and V_2 are induced on the both side of the terminated resistance R. To measure the both voltage by high input impedance voltage detecting circuits, we can obtain V_1 and V_2, and calculate equations (5) and (6), simultaneously.

C. Measurement Results

Fig. 6 shows frequency response both voltage and current measured by the new probe. Fig.6 (a) is the voltage and (b) is the current that are calculated by eq. (1) and (2). The vertical axis on the left in Fig.6 (a) is the gain of voltage calculated by eq. (1), and one in Fig.6 (b) is transfer impedance of the current obtained by eq. (2). The right axes are the phase. As shown in the figures, the probe shows almost flat characteristics in the frequency range of 1 [kHz] to 10 [MHz] for voltage detection and 10 [kHz] to 10 [MHz] for current detection. It is also shown that the phase difference approaches 0 in those frequency range. A comparison of the frequency characteristics between calculated and measured results are shown in Fig. 7. Fig. 7 (a) shows the results of the voltage, and Fig. 7 (b) shows the results of the current. The vertical axes in these figures are the relative value normalized by gain and transfer impedance at 100 [kHz]. From the both figures, the calculation results from the equivalent circuit agree with the measurement results. Therefore, it is confirmed that the characteristics of the probe can be calculated by the equivalent circuit.

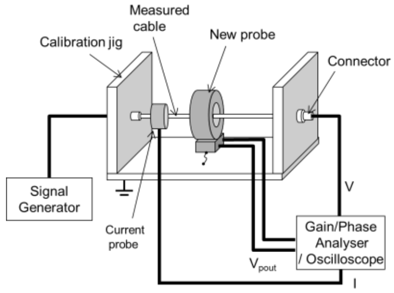
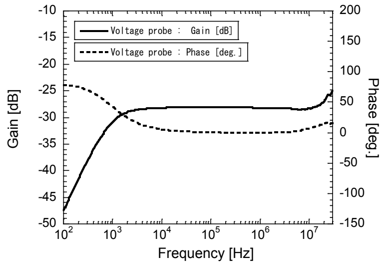
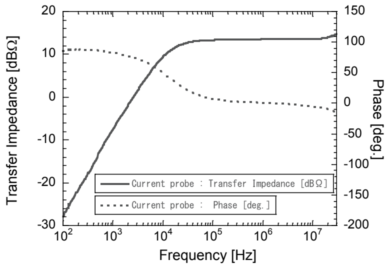


Fig. 5. Configuration of Measurement setup

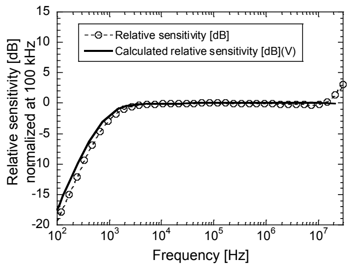


(a) Detected voltage

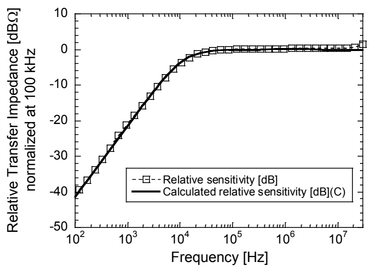


(b) Detected current

Fig. 6. Measurement Results of Frequency Response



(a) Voltage

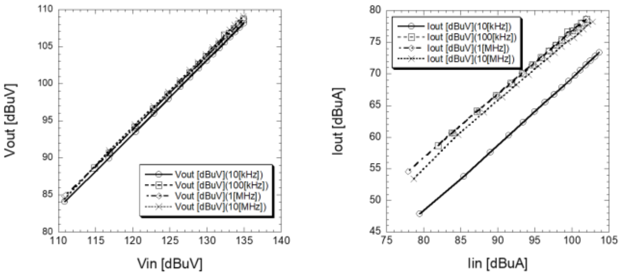


(b) current

Fig. 7. Comparison between measured and calculated results

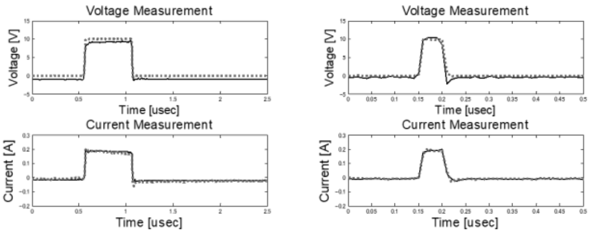
Figure 8 shows sensitivity of the new probe in various frequency. Measurement was carried out by using signal generator and digital oscilloscope. Sensitivity of the voltage detection is shown in Fig.8 (a) and current one is given in Fig.8 (b). From these figures, the probe has good linearity in the frequency range from 10 [kHz] to 10 [MHz].

Finally, time domain measurement was carried out to check feasibility of the probe. We use rectangular pulse signals with these widths of 0.5 [μsec] and 0.05 [μsec], and input level of 10 [$V_{0\text{-}p}$]. Waveform measurements were carried out by using Digital Oscilloscope with sampling rate of 10 [nsec]. Measured waveforms were converted from time domain to frequency domain by Fast Fourier Transform, and calibrated using frequency characteristics in Fig.7. Then, calibrated data was transformed to time domain again, and the calibrated waveform was compared by applied one. The results show in Fig.9. Upper parts of the both figures show the voltage waveforms, and the lowers are the current one. The solid lines are the calibrated measurement waveforms and the dotted lines are the applied pulse waveforms. As shown these figures, measured waveforms are good agreement with applied one. Thus, the pulse waveform with wide frequency range can be measured by proposed probe.



(a) Measured voltage (b) Measured current

Fig. 8. Sensitivity measurements in various frequency



(a) 0.5[μsec] width pulse (b) 0.05[μsec] width pulse

Fig. 9. Measurement results in time domain

IV. 4. Conclusion

In this paper, we investigated a new method to non-invasively and simultaneously measure voltage and current of common-mode disturbances. A new probe for voltage and current measurement, which is a combination of a conventional electromagnetic coupling type current probe and a non-contact voltage probe, was proposed and its basic characteristics were evaluated. As a result, the following points were clarified.

(1) Simultaneous and non-invasive measurement probe for common-mode disturbance voltage and current can be constructed by combining an electromagnetic coupling type current probe and a non-contact voltage probe.

(2) Results calculated by equivalent circuit were good agreement with measured data. Thus, characteristics of the probe can be obtained from the equivalent circuit.

(3) The proposed probe has flat frequency responses in the range of 10 [kHz] to 10 [MHz]. It is wide enough to measure conducted disturbances. Moreover, it has good linearity in the frequency range from 10 [kHz] to 10 [MHz].

(4) As a result of time-domain measurement, this probe can measure the voltage and current of impulsive signal, simultaneously, and waveform can be calibrated by using its frequency characteristics.

Future works will include evaluation of measurement errors and uncertainty, applicability of the probe in the frequency range over 30 [MHz], and establishment of appropriate design method of this probe.

V. References

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