Calculation of Emitted Magnetic Field Using Wire Grid Model Considering Dielectric Material of VVF Cable

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***Abstract*— The emissions from the power line communication (PLC) system should be investigated for the influence to the electromagnetic environment. The method of moment (MOM) has been studied to estimate the emitted electric field. However, the MOM is difficult to treat the dielectric material of the cable. This paper proposes the method of creating the wire grid model considering the dielectric material of the power line cable. The radius of the wire was determined from the per unit length inductance of the cable. The admittance is inserted between wires to present the effect of the dielectric material, and the value is determined from the admittance calculated by using the FEM based on the two-dimension model. The other admittance was inserted between each wire and ground and the value was also determined from the FEM results. The appliances were presented by T-type network based on the measurement results. The common mode input impedance and radiated magnetic field were measured and compared with the calculated one, and the evaluation indicated that the well agreement was obtained. A simple model of the indoor power line system was constructed and the radiated magnetic field was calculated. The evaluation was indicated that the calculation results almost agreed with the measured one. These results mean that the wire grid model is effective to estimate the radiated electromagnetic field from PLC system.**

Keywords; PLC; VVF cable; Common mode input impedance; Method of Moment; Radiated Magnetic field

I. INTRODUCTION

Power line communication (PLC) system has been developed to construct the indoor network connecting the appliances such as PC and TV [1]. However, PLC uses the power line cable as the transmission line. This cabling system is not designed for the high-speed signal transmission. Therefore, we should pay attention to the unwanted emissions from the power lines [2].

The studies using the 4-port networks [3] and the method of moment (MOM) [4] have been carried out to estimate the emissions. The method of using 4-port networks has the priorities that the computation time is short and the dielectric material can be consider easily. However, this has the disadvantages that the cable should parallel with the ground plane and place near the ground plane. In addition, this method cannot treat the inductive and capacitive coupling between the lines. The MOM can treat any layout of the line and consider the coupling the between the lines, but this method is difficult to treat the dielectric material of the cable.

Recently, the method of treating the dielectric material has been reported for unshielded twisted pair (UTP) cable [5]. This method presents the effect of the dielectric material by modifying the wire radius, modifying the space between wires, and inserting capacitance between wires. However, this method cannot apply directly to the power line cable because we should consider the loss of the dielectric material and the transmission line constructed with the wires and ground.

This paper proposes the method of creating the wire grid model for the indoor power line system. The first, we describe the method of determining the wire radius and the admittance inserting between wires. The next, we also describe the method of determining the admittance inserting between each wire and ground. Second, the common mode input impedance and the radiated magnetic field is calculated using the wire grid model and the compared with the measure one and the calculation one using the method of 4-port networks. Finally, a simple indoor ac mains system is constructed, and the calculated radiated magnetic field was compared with the measured one and calculation one using the 4-port networks.

II. WIRE GRID MODEL OF POWER LINE CABLE AND HOME APPLIANCE

A. *Wire grid model of power line cable*

The example of power line cable is shown Fig. 1. We selected a PVC-insulated PVC sheathed flat type (VVF) cable for the investigation. The VVF cable is widely used in Japan for indoor power lines. The cable constructed with the insulator (Hereafter, it is called dielectric material) and a pair of conductor. The radius of the conductor is 0.8mm, the material is capper, and the distance between the centers of the conductor is 3.2mm. The width of the cross section of the cable is 4.8mm and the height is 3.2mm. The relative dielectric constant of the dielectric material changes from 3.5 to 3.0 when the frequency changes from 0.3 to 30 MHz and the loss tangent changes from 0.09 to 0.06 in the same frequency rang [3]. The loss tangent value is significant large compared with the value of UTP.

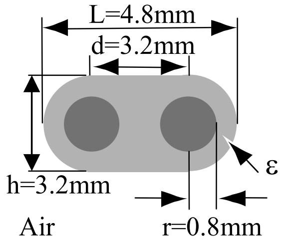

Figure 1. Structure of VVF cable

The wire grid model of the VVF cable is shown in Fig. 2. The wire shown in Fig. 2 presents the conductor of the cable and the admittance, which is constructed with a conductance and a capacitance, presents the effect of the dielectric material. The admittance is inserted between wires and between each conductor and ground. In the case of the UTP cable, we need not insert the conductance because the loss tangent is significant small, but we should consider it in the case of VVF cable.

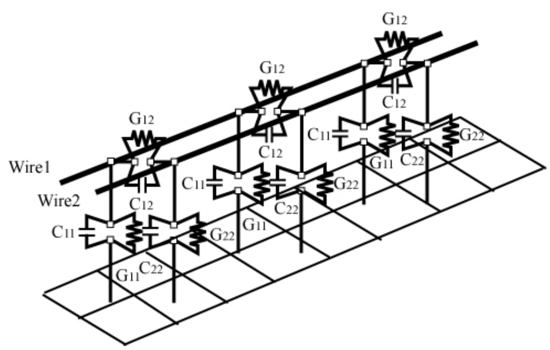

Figure 2. Wire gird model of VVF cable considering with dielectric material

B. Wire grid model between conductors

Figure 3 shows the method of creating the wire grid model of the transmission line constructed with the conductors. The first, we consider the model without the dielectric material as shown in Fig. 3(b) because the dielectric material does not influence to the per unit length inductance. The radius of the wire is determined that the theoretical value using the model in Fig. 3(b) meets the value using the wire grid model shown in Fig. 3(c).

The method of obtaining the per unit length inductance of the wire grid model is illustrated in Fig. 4. The inductance is calculated from the input impedance of the wire grid model when the far end is short and open (Hereafter, it is called the open-short method). The model shown in Fig. 4 is inserted admittance between wires, but the admittance is not inserted when the radius is determined. NEC2 [6] is used for the calculation of the wire grid model in this paper. The determined radius is shown in Fig. 3(c). The radius changes from 0.88mm to 1.01mm caused by the skin effect of the conductor.

Effect of the conductor resistance is not considered in this paper because this value is very small.

The next, the conductance and capacitance inserted between the wires are determined. The per unit length admittance, G_{dFEM} and C_{dFEM} is calculated using the FEM [7] based on the two-dimensional model as shown in Fig. 3(a). The theoretical value of per unit length capacitance, C_d, is calculated based on the model shown in Fig. 3(c). From these values, the inserted conductance and capacitance values are obtained by the following equation.

$$C_{12} = C_{dFRM} - C_d, G_{12} = G_{dFEM} \qquad (1)$$

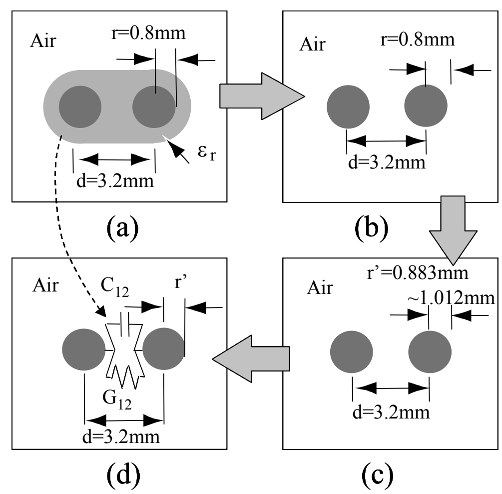

Figure 3. Method of creating wire grid model

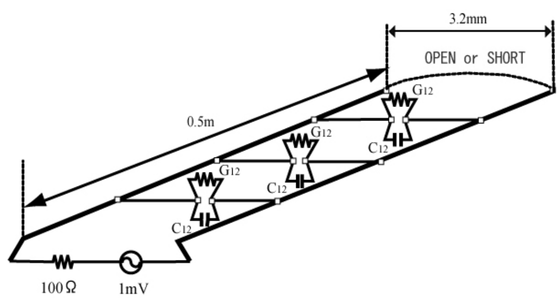

Figure 4. Method of calculating per unit length impedance and admittance of wire grid model

The characteristic impedance and the attenuation constant of the line are shown Fig. 5 and Fig. 6 respectively. These value were calculated from the per unit length impedance and per unit length admittance of the wire grid model. The open-short method shown in Fig. 4 was used to obtain the impedance and the admittance.

In Fig. 5, the dotted line is the theoretical value using the FEM, the solid line is calculated value considering with the dielectric material, the gray line is the calculation value not considering with the dielectric material, and the circles are the measurement value. This shows that that the calculation results based on the model shown in Fig. 3 well agrees with the calculation value using the FEM and the measured values. On the other hand, the calculation value, which does not consider the dielectric material, has large deviation from calculated value using the FEM and the measurement value.

In Fig.6, the solid line is the calculation value based on the wire grid model shown in Fig. 3, and the circles are the measurement value. This shows that the calculation value almost agrees with the measurement one. This results means that the transmission loss is 20 dB at 30 MHz when the cable length is 100m. This is larger than that of UTP cable.

These results mean that the wire grid model in Fig. 3 is effective to model the power line cable.

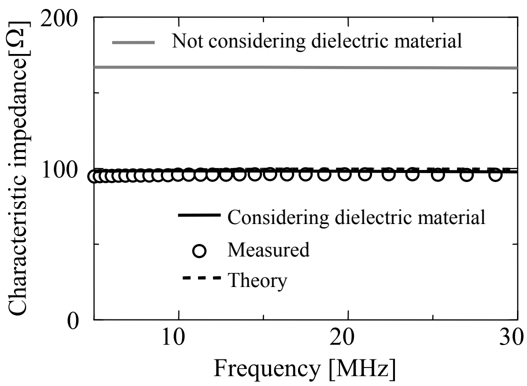

Figure 5. Measured and calculated value of characteristic impedance

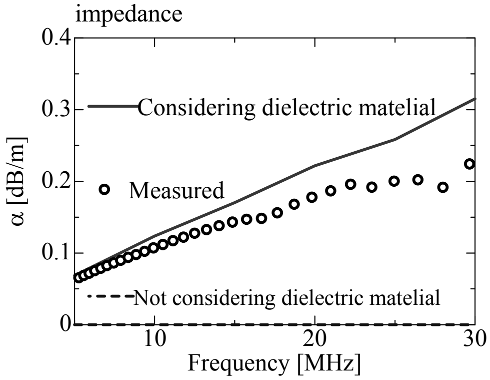

Figure 6. Measured and calculated value of attenuation constant

C. Wire grid model between wire and ground

Figure 7 shows the method of creating the wire grid model of the transmission line constructed with the conductors and ground. The conductance and capacitance values inserted between each wire and ground are determined from the calculation value using the FEM based one the two-dimensional model shown in Fig. 7(a) and the theoretical value based on the model shown in Fig. 7(b). The inserted conductance and capacitance are given by Eq. (2).

$$\left.\begin{aligned} C_{11} &= C_{22} = C_{cFEM} - C_c, \\ G_{11} &= G_{22} = G_{cFEM} \end{aligned}\right\} \qquad (2)$$

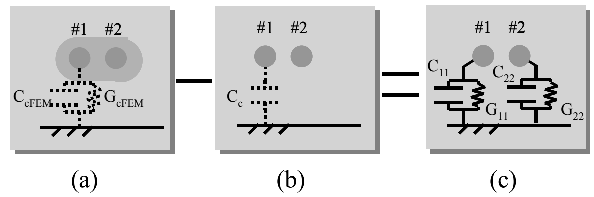

Figure 7. Method of creating admittance inserting between each wire and ground

D. Wire grid model of appliance

The wire grid model of the appliance connected to the indoor power line system is shown in Fig. 8. The appliance is presented by T-type network whose impedances are Z_a, Z_b, and Z_c, and these impedances are directly inserted to the wire grid model as shown in Fig. 8. The impedances of the appliances can be obtained from the measurement [8]. The voltage sources in the figure are removed when the appliance does not a signal source.

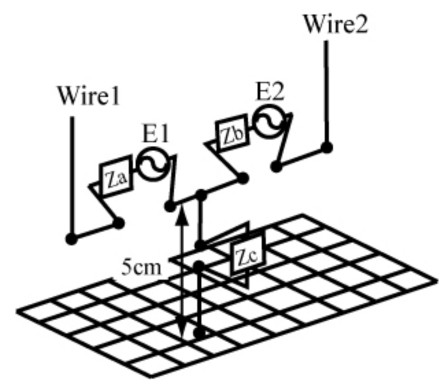

Figure 8 Wire grid model of electrical appliance

III. Evaluation of Wire Gurid Model

The method of creating the wire grid model was evaluated to compare with the measured value and the calculated value using 4-port networks [3].

A. Evaluation of common mode input impedance

The common-mode input impedance was measured and the result was compared with the calculation value using the developed wire grid model. The experimental set-up is shown in Fig. 9. As shown in this figure, 4m long VVF cable was placed in 5cm above the ground plane. At far end, the resistance of 100Ω terminated between conductors, and the resistance of 1kΩ terminated between a conductor and ground. At the near end, the conductors was connected each other and the impedance between conductors and ground was measured using an impedance analyzer.

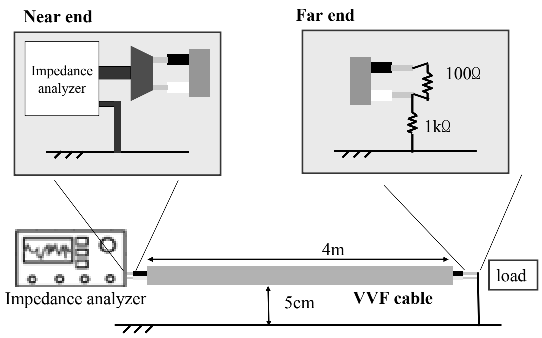

Figure 9. Experimental set-up for measuring common mode input impedance

The wire grid model was created based on the experimental set-up shown in Fig. 9 and the common mode input impedance was calculated from the voltage source value and the current value on the wire. The relationship between the wire length and the calculation results are shown in Fig. 10. The wire length was changed from 1m to 1cm. The wire constructed the wire grid model. The conductance and the capacitance are inserted at each node of wire as shown in Fig. 2. The vertical axis is absolute value of the impedance and the horizontal value is frequency. We calculate the impedance from 0.3 to 30MHz where PLC is used to the signal transmission. This figure shows that the calculation result is converged when the wire length is less than 2cm.

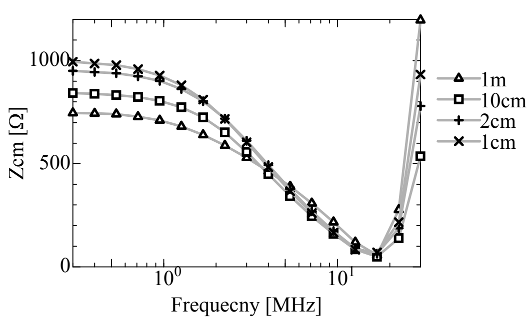

Figure 10. Relationship between wire length and calculation results

Figure 11 shows the calculation and measurement results. In the figure, the circles are the measurement value; the dotted line is the calculation value using the 4-port network [3]; the gray solid line is the calculation value not considering dielectric material; and the black solid line is the calculation value using the model shown in Fig. 2.

This shows that the calculation value using the model in Fig. 2 well agrees with the measurement value and the calculation value. On the other hand, the calculation value using the wire grid model not considering the dielectric material has large deviation from the measurement value. This means that the effect of the dielectric material should be considered to create the wire grid model of the power line cable.

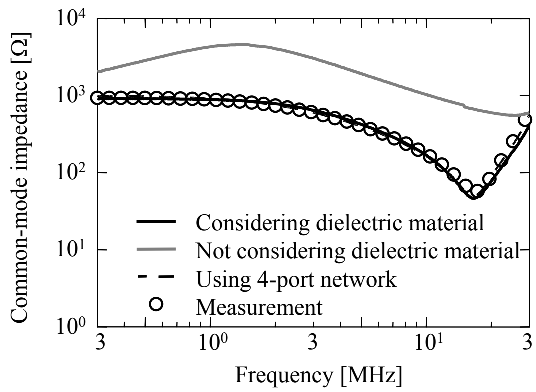

Figure 11. Measured and calculated values of common mode input impedance

B. *Evaluation of radiated magnetic field*

Radiated magnetic field was measured to compare with calculated value. The experimental set-up is shown in Fig. 12.

The straight VVF cable was placed at 5cm above the ground plane, and a balun was connected at both ends of the cable. The loop antenna was arranged at 60cm above ground plane and the distance from the cable is 1m.

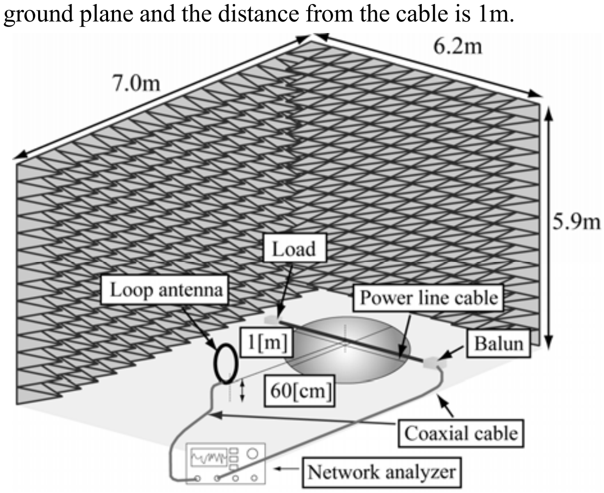

Figure12. Experimental set-up for measuring radiated magnetic field

The primary port of one of the balun was connected to the network analyzer, and the primary port of the other balun was terminated by 50Ω. Therefore the resistance of 100Ω terminated between conductors at far end. The resistance of 150Ω terminated between one conductor and ground plane to present the termination condition shown in Fig. 9.

The output port of the network analyzer is connected to the balun, and the input port was connected to the output port of the antenna. The magnetic field strength for each direction was obtained from the signal level of the network analyzer, P_{in}; the antenna factor of the loop antenna, *AF*; the cable loss, L_{cable}; and the S_{21} from output port to input port. This is given by the following equation.

$$H_{i,i=x,y,z} = P_{in} + S_{21} + L_{cable} + 107 + AF \qquad (3)$$

The total magnetic filed strength was calculated using Eq. (4)

$$H = \sqrt{H_x^{\ 2} + H_y^{\ 2} + H_z^{\ 2}} \qquad (4)$$

The x-component of the magnetic field was not measured. This level was very small because the antenna was placed at the symmetrical position.

Figure 13 shows the measured and calculated values when the input power is 0dBm. On the calculation, the wire grid model was created based on the experimental set-up shown in Fig. 9. The circles are the measurement value, the dotted lien is the calculated value using the method of 4-port network [3], and the solid line is the calculation value using the wire grid model.

This shows that the calculation value using the wire grid model well agree with the measurement one and the calculation one using 4-port networks. This means that the wire grid model shown in Fig. 2 is effective to calculate the radiated electromagnetic field from the indoor power line system.

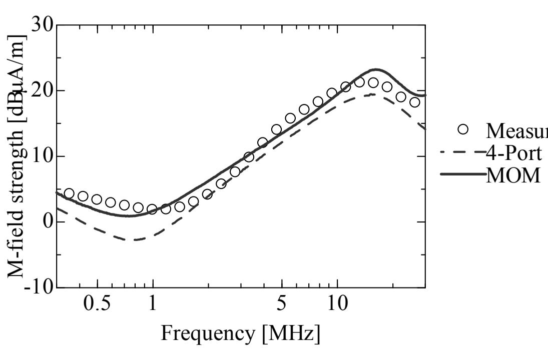

Figure 13. Measured and calculated magnetic field strength radiated from one VVF cable

IV. ANALYSIS OF EMISSION FROM INDOOR POWER LINE SYSTEM

The simple indoor power line system was constructed in the anechoic chamber and the radiated electric field was measured to confirm the validity of the method. The experimental set-up is shown in Fig. 14.

The set-up presents one sub-branch of the indoor power line for a small house. Five appliances, which are a CD player, a rice cooker, a microwave oven, a refrigerator, and an electric fan, were connected to this sub-branch. These appliances were replaced as the equivalent circuit [3] and the public power distribution system was presented using artificial main network (AMN). The signal applied at the AMN position using a balun.

As shown in Fig. 14, the VVF cable was arranged at 5cm above ground. The loop antenna was placed 0.6 m high and the moved for every 1m to x or y direction. S_{21} from the primary port of the balun and the output port of the antenna was measured using a network analyzer. The magnetic field strength was measured calculated using Eqs. (3), and (4).

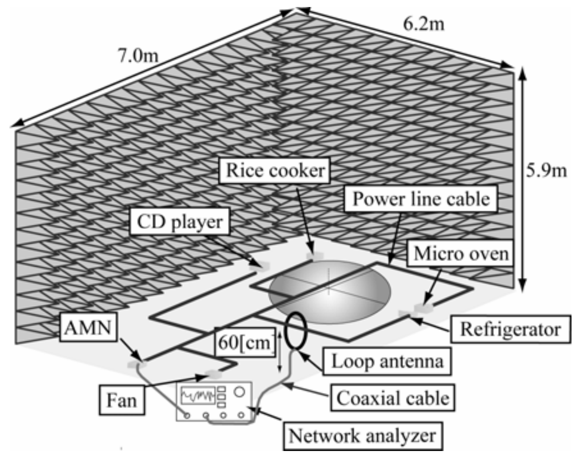

Figure 14. Experimental set-up of indoor power line system for measuring radiated magnetic field

The result of the radiated magnetic field distribution at 20MHz is shown in Fig. 15. Figures 15 (a), (b), and (c) present the calculation value using the model shown in Fig. 2, the measurement value, and the calculation value using the 4-port networks [3] respectively. These results indicated that the calculation value using the wire grid model shown in Fig. 2 almost agree with the measurement value and the calculation value using 4-port networks.

This means that the creation method of the wire grid model proposed in this paper is effective to estimate the radiating electromagnetic field from the power line system because the method can consider the coupling between lines and consider the line that is not parallel to the ground.

V. CONCLUSION

The method of creating the wire grid model was developed to calculate the electromagnetic field strength radiated from the indoor power line system.

A PVC-insulated PVC sheathed flat type (VVF) cable was selected for the investigation as a typical power line cable in Japan. The radius of the wire was determined to meet the theoretical value of the per unit length inductance. The open-short method was used to obtain the per unit length inductance of the wire grid model. The effect of the dielectric material was presented to insert the admittance between wires, and the value was determined from the theoretical value of the wire model without the admittance and the calculation value using the FEM based on the two-dimensional VVF cable model. The evaluation results indicated that the characteristic impedance and the attenuation constant of the wire grid model almost agreed with the calculation value using the FEM.

The common mode input impedance and the radiated magnetic field were calculated and compared with the measured value and the calculated value using the 4-port networks. The results indicated that the calculation value well agreed with the measurement value and the calculation value using the 4-port networks.

The radiated magnetic field from the power line system presenting the sub-branch of the small house was calculated and compared with the measured value and the calculated value using the 4-port networks. The results indicated that the calculated value well agreed with the measured value and the calculated value using the 4-port networks.

These results indicate that the wire grid model is effective to calculate the radiated electromagnetic field. The future problem might to apply this method to an actual house.

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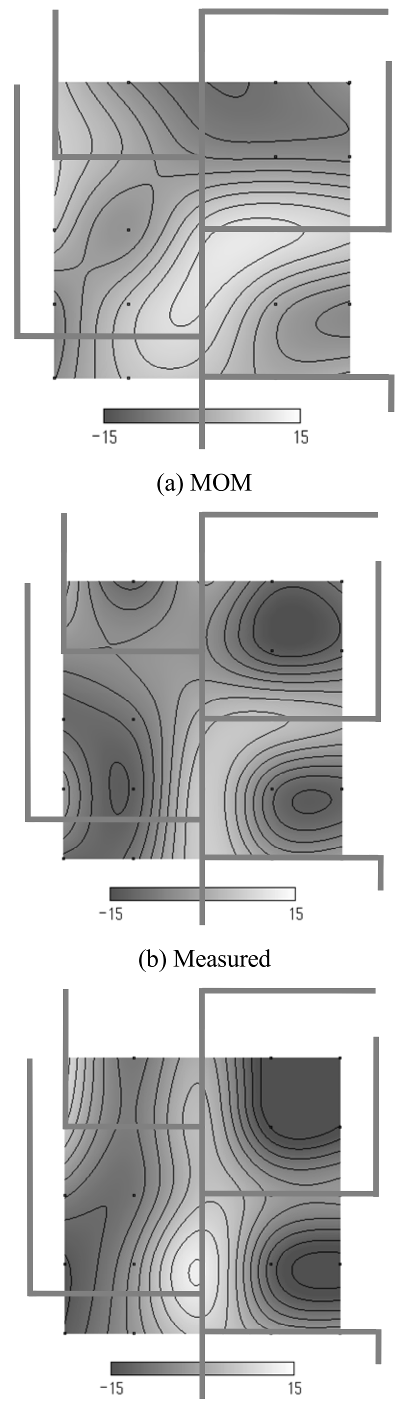

(a) MOM

(b) Measured

(c) 4-Port network

Figure 15. Calculated and measured radiating magnetic field distribution from power line system