Evaluation of Longitudinal Conversion Loss (LCL) for Indoor AC Mains Line

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Abstract

Influence to electromagnetic environment has been studied for power line communication (PLC). Longitudinal conversion loss (LCL) and input impedance are important parameters to evaluate the influence. Indoor AC mains line is modeled considering with typical conditions of Japanese house. The modeled line and electric equipment are presented with 4-port F-matrixes. The parameters of 4-port F-matrix are determined from calculation and measurement. Using this model, the input impedance and the LCL are calculated. The analysis model is examined by a simple network, and the results show that the calculation values almost agree with the measured values. The input impedance and the LCL are investigated for actual AC mains line, and the measured results almost agree with the calculated value.

Keywords
LCL, PLC, 4-port F-matrix, Common-mode impedance.

1. INTRODUCTION

Recently, progress of telecommunication proposes power line communication (PLC), which uses AC mains line as transmission line. The influence of electromagnetic environment has been studied for PLC signal because AC mains line does not designed to transmit signal [1], [2].

Longitudinal conversion loss (LCL) and input impedance are important parameters to evaluate the influence to electromagnetic environment, and it was evaluated for telecommunication lines [3]. However, it has not been cleared yet for AC mains line.

In this paper, we investigate the calculation method of the LCL and the input impedance for indoor AC mains line. AC mains line is modeled considering with the environment in Japan, and is presented by 4-port networks. Using the networks, the LCL and the impedance values are

calculated. To confirm the validity of the model, the calculation results are compared with measured one for a simple network. Finally, the calculated LCL and impedance using the model are compared with the measured one for actual AC mains line.

2. AC MAINS LINE MODELING

AC mains line in indoor environment should be modeled to calculate the LCL and the input impedance. The model used in this paper is shown in Fig. 1. A statistic in Japan shows that there are 3~6 branches from the panel board and branches have plug sockets and lightings.

In this paper, we make a simple house model, where floor area is about 40m^2 and one or two people live. This topology contains three branches; one of them is for lightings, and rests of them are for plug sockets connected to home appliances.
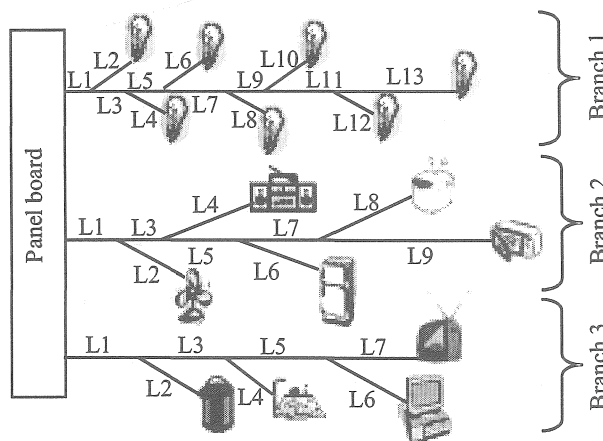

Figure 1. A model of AC mains line

Table 1. Length patterns for modeled topology

Branch 1	Branch 2	Branch 3
L_{11}:0.5	L_{21}:1.0	L_{31}:1.5
L_{12}:1.4	L_{22}:3.0	L_{32}:3.5
L_{13}:0.25	L_{23}:0.5	L_{33}:2.0
L_{14}:2.5	L_{24}:6.0	L_{34}:4.2
L_{15}:0.25	L_{25}:1.5	L_{35}:0.5
L_{16}:3.0	L_{26}:5.0	L_{36}:4.0
L_{17}:0.75	L_{27}:1.0	L_{37}:4.5
L_{18}:1.5	L_{28}:4.0	
L_{19}:0.25	L_{29}:5.0	
L_{1a}:2.0		
L_{1b}:1.1		
L_{1c}:3.0		
L_{1d}:2.0		

Moreover, from the survey, it could be considered that the cable length of each branch is about 10 m. Even the longest branch is not more than few decimeters. In our topology shown in Fig. 1, there are more than 3 sub-branches from each branch. Various electric appliances are connected to the end of the sub-branches. Lengths of cables for each branch are summarized in Table 1. The lengths of the cables are selected considering a real power line wiring of an ordinary house. We also assumed that ten kinds of electric appliances are connected to the power line at the same time at most.

3. ANALYSIS METHOD

3.1 Calculation Method of LCL and Input Impedance

Since, power line is considered as a balanced cable, AC mains line with ground return can be presented by using the 4-port networks as shown in Fig. 2 [3]. In this figure, L_{nm} indicates AC mains cable, Lo_{nm} indicates appliance, and Lo_m presents the input impedance of commercial AC mains line from panel board.
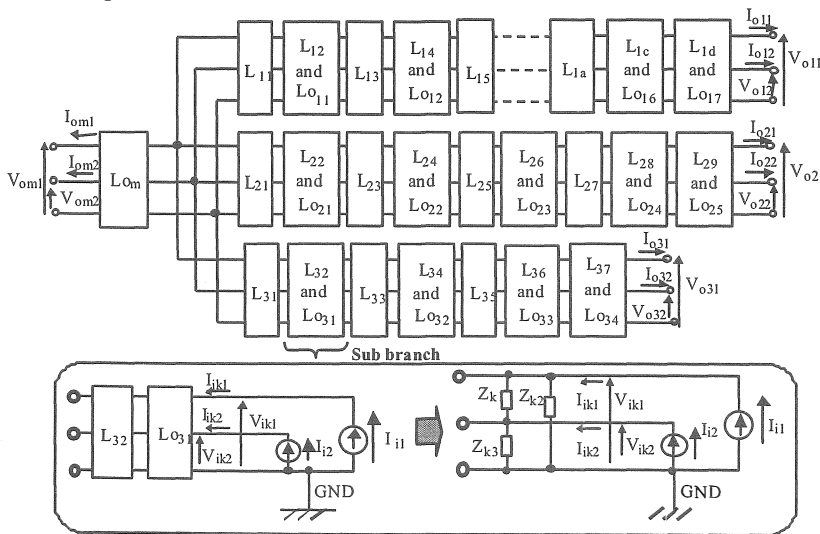

Figure 2. Analysis model of LCL for AC mains line presented by 4-port networks

The parameters of 4-port networks are determined from calculation values for AC mains cable [3], [4] and measured values for appliances. The modeling method of electric home appliance is described in the next section.

The relations between the input voltage and current V_{ik1}, V_{ik2}, I_{ik1}, and I_{ik2} of equipment Lo_k (In case of Fig. 2, Lo_k is Lo_{31}) and the output voltage and current V_{om1}, V_{om2}, I_{om1}, and I_{om2} of Lo_m can be presented in series connection of 4-port F-matrixes, and it is given by

$$\begin{bmatrix} V_{ik1} \\ V_{ik2} \\ I_{ik1} \\ I_{ik2} \end{bmatrix} = [Lo_{31}][L_{32}][B_{3a}][L_{31}][B_2][B_1][Lo_m] \begin{bmatrix} V_{om1} \\ V_{om2} \\ I_{om1} \\ I_{om2} \end{bmatrix} \quad (1)$$

where, $[Lo_{31}]$, $[L_{31}]$, $[Lo_m]$ are the 4-port F-matrixes presenting each line and equipment.$[B_{3a}]$, $[B_2]$, and $[B_1]$ is the 4-port F-matrixes presenting input impedance of each branch. The calculation method is described in appendix.

Eq. (1) can be expressed by 4×4 matrix, which is given by the following equation.

$$\begin{bmatrix} V_{ik1} \\ V_{ik2} \\ I_{ik1} \\ I_{ik2} \end{bmatrix} = \begin{bmatrix} A_{k11} & A_{k12} & B_{k11} & B_{k12} \\ A_{k21} & A_{k22} & B_{k21} & B_{k22} \\ C_{k11} & C_{k12} & D_{k11} & D_{k12} \\ C_{k21} & C_{k22} & D_{k21} & D_{k22} \end{bmatrix} \begin{bmatrix} V_{om1} \\ V_{om2} \\ I_{om1} \\ I_{om2} \end{bmatrix} \quad (2)$$

This matrix can be converted to the impedance matrix, which is presented by

$$\begin{bmatrix} V_{ik1} \\ V_{ik2} \\ V_{om1} \\ V_{om2} \end{bmatrix} = \begin{bmatrix} Z_{k11} & Z_{k12} & Z_{k13} & Z_{k14} \\ Z_{k21} & Z_{k22} & Z_{k23} & Z_{k24} \\ Z_{k31} & Z_{k32} & Z_{k33} & Z_{k34} \\ Z_{k41} & Z_{k42} & Z_{k43} & Z_{k44} \end{bmatrix} \begin{bmatrix} I_{ik1} \\ I_{ik2} \\ I_{om1} \\ I_{om2} \end{bmatrix} \quad (3)$$

From Fig. 2, we can consider

$$I_{om1} = I_{om2} = 0 \quad (4)$$

Then, we get the relation

$$\begin{bmatrix} V_{ik1} \\ V_{ik2} \end{bmatrix} = \begin{bmatrix} Z_{k11} & Z_{k12} \\ Z_{k21} & Z_{k22} \end{bmatrix} \begin{bmatrix} I_{ik1} \\ I_{ik2} \end{bmatrix} \quad (5)$$

Then, we get

$$\begin{bmatrix} I_{ik1} \\ I_{ik2} \end{bmatrix} = \begin{bmatrix} Z_{k11} & Z_{k12} \\ Z_{k21} & Z_{k22} \end{bmatrix}^{-1} \begin{bmatrix} V_{ik1} \\ V_{ik2} \end{bmatrix}$$

$$= \begin{bmatrix} Y_{k11} & Y_{k12} \\ Y_{k21} & Y_{k22} \end{bmatrix} \begin{bmatrix} V_{ik1} \\ V_{ik2} \end{bmatrix} \quad (6)$$

From Eq. (6), Δ-network parameters Z_{k1}, Z_{k2}, and Z_{k3} are given by

$$\frac{1}{Z_{k1}} = -Y_{k12} \quad (7)$$

$$\frac{1}{Z_{k2}} = Y_{k11} + Y_{k12} \quad (8)$$

$$\frac{1}{Z_{k3}} = Y_{22} + Y_{k12} \quad (9)$$

From Δ-network parameters, the T-network parameters, Z_a, Z_b, and Z_c are given by

$$Z_a = \frac{Z_{k3}Z_{k1}}{Z_{k1}+Z_{k2}+Z_{k3}} \qquad (10)$$

$$Z_b = \frac{Z_{k1}Z_{k2}}{Z_{k1}+Z_{k2}+Z_{k3}} \qquad (11)$$

$$Z_c = \frac{Z_{k2}Z_{k3}}{Z_{k1}+Z_{k2}+Z_{k3}} \qquad (12)$$

From T-network parameters, LCL, common-mode impedance, Z_L, and differential-mode impedance, Z_0, can be calculated by the following equation [5].

$$LCL(dB) = 20\log_{10}\left|\frac{-(Z_a-Z_b)^2+2Z_0(2Z_0+4Z_c)}{2Z_0(Z_a-Z_b)}\right| \qquad (13)$$

$$Z_0 = Z_a + Z_b \qquad (14)$$

$$Z_L = \frac{Z_aZ_b}{Z_a+Z_b}+Z_c \qquad (15)$$

2.2 Determining Method of 4-port F-matrix for Appliance

Configuration of electric home appliance connected to power line is shown in Fig. 3. Power line cable contains two leading wires and one ground line that can be modeled as 4-port F-matrix, and it is given by [3], [4]

$$F_{APP} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1/Z_{k1}+1/Z_{k2} & -1/Z_{k1} & 1 & 0 \\ -1/Z_{k1} & 1/Z_{k1}+1/Z_{k3} & 0 & 1 \end{bmatrix} \qquad (16)$$

where, Z_{k1}, Z_{k2}, and Z_{k3} are Δ-network parameters shown in Fig. 2. These values are obtained from measurement.

We can measure input impedance, Z_{m1}, Z_{m2}, and Z_{m3} of appliance as shown in Fig. 3. The relation between Z_{k1}, Z_{k2}, and Z_{k3} and Z_{m1}, Z_{m2}, and Z_{m3} is given by
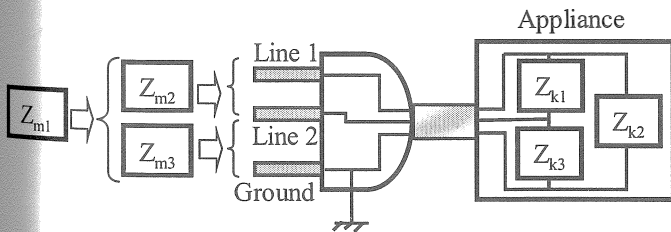
Figure 3. Measurement method of Δ-network parameters for appliance

$$Z_{k1} = \frac{Z_{m3}(1+K)K_1}{K} \qquad (17)$$

$$Z_{k2} = \frac{Z_{m3}(1+K)K_3}{K} \qquad (18)$$

$$Z_{k3} = \frac{Z_{m3}(1+K)}{K} \qquad (19)$$

where,

$$K_1 = \frac{\{(Z_{m1}-Z_{m3})(Z_{m3}-Z_{m2})+Z_{m1}Z_{m2}\}}{Z_{m2}Z_{m3}-Z_{m1}Z_{m3}+Z_{m3}^2}, \qquad (20)$$

$$K_2 = \frac{\{(Z_{m2}-Z_{m1})(Z_{m3}-Z_{m2})+Z_{m1}Z_{m3}\}}{Z_{m2}^2-Z_{m1}Z_{m2}+Z_{m2}Z_{m3}}, \qquad (21)$$

$$K_3 = \frac{K_1}{K_2} \quad \text{and} \quad K = K_1 + K_3 \qquad (22)$$

Fig. 4 shows the example of the impedance characteristics for actual equipment. Microwave oven was selected as the equipment, and the absolute value of the impedance Z_{k1} is shown in this figure. This indicates that the input impedance of the appliance can be presented by an equivalent circuit because the frequency characteristics is simple.

The equivalent circuit of the input impedance for the microwave oven is shown in Fig. 5. The equivalent circuit was determined to meet the frequency characteristics with the actual one, where SPICE software was used to determine the circuit. The frequency characteristics of the equivalent circuit is shown in Fig. 4. This shows that the characteristics of the circuit almost agree with measured one up to 20 MHz. This means that we can use the equivalent circuit to evaluate the LCL and input impedance.
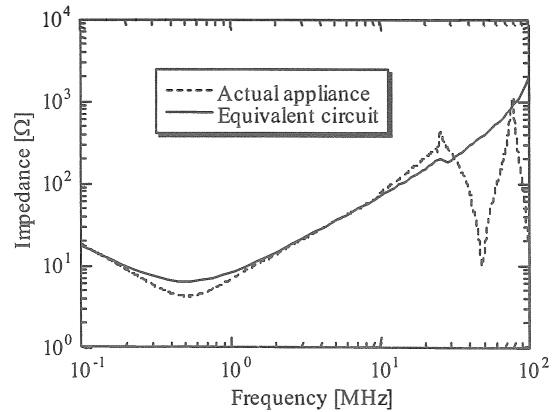
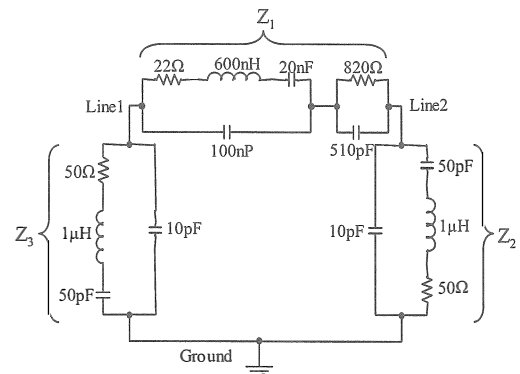Figure 4. Comparison between measured and modeled impedance of appliance

Figure 5. Equivalent circuit for input impedance of microwave oven

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3. EXPERIMENT

3.1 Experimental Set-up

To confirm the validity of the analysis model shown in Fig. 2, the calculated LCL and input impedance values are compared with the measured one for simple network. For the simplicity, we considered only branch 2 of AC mains line model in Fig. 1. The experimental set-up is shown in Fig. 6. AC mains line was constructed on the conductive ground plane. The height of the line was 5 cm. Appliances were presented by their equivalent circuits. The method described in section 2.2 was used to determine the equivalent circuits of appliances connected to this line.

The input impedances between two lines as well as each line and ground were measured by impedance analyzer. These impedances were converted into the impedances of Δ-network (Z_{k1}, Z_{k2}, and Z_{k3}) by the same procedure described in the previous section. Then LCL, differential-mode impedance, and common-mode impedance values were calculated from Z_{k1}, Z_{k2}, and Z_{k3} by using Eq. (13) ~ Eq.(15).
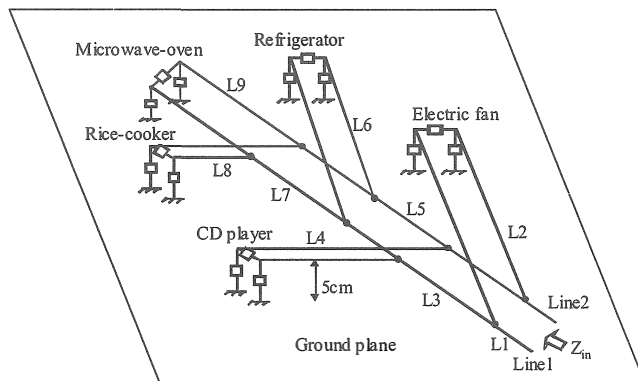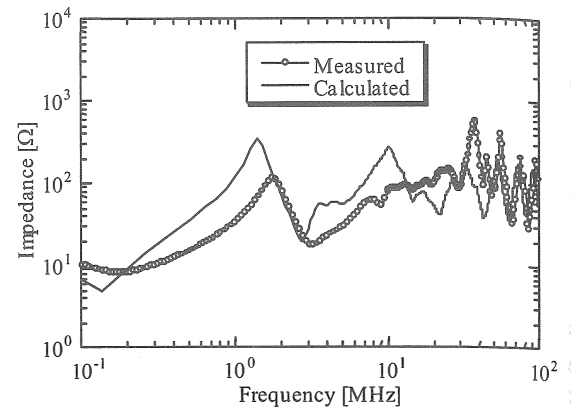

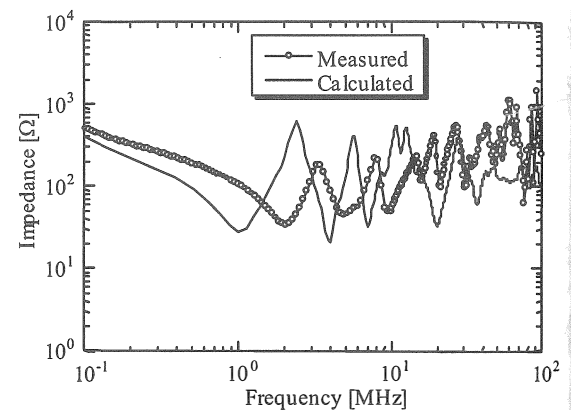**Figure 6. Experimental set-up for measuring LCL and input impedance**

3.2 LCL Measurement Result

Fig. 7 shows the results of measured and calculated impedance frequency characteristics, where Fig. 7(a) presents differential-mode impedance, Z_0 and Fig. 7(b) presents common-mode impedance, Z_L. Solid line and circle indicate calculated and measured values respectively. They indicate that calculated values almost agree with the measured one.

LCL at panel board was obtained by using these input impedances and the measured and calculated LCL are shown in Fig. 8. The solid and circle represent the calculated and measured results respectively. This indicates that calculated value almost agrees with the measured value. These results mean that LCL and input impedance can be calculated by the analysis model shown in Fig. 2.

(a) Differential-mode impedance

(b) Common-mode impedance

Figure 7. Comparison between measured and calculated input impedance characteristics
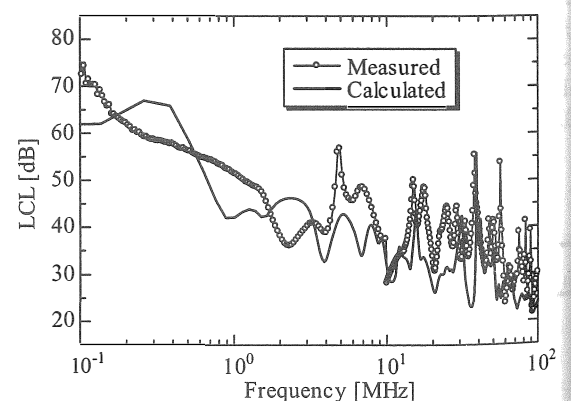

Figure 8. Comparison between measured and calculated LCL

4. LCL ESTIMATION OF ACTUAL AC MAINS LINE

The proposed analysis model was applied to actual AC mains line and the calculated value was compared with measured one. In this chapter, the investigation results are described.

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4.1 Measurement of Input Impedance for Actual AC Mains Line

We measured the input impedances of actual AC mains line at several points at our laboratory building and a home. Fig. 9 shows the measurement points in the laboratory. Four positions in the building were selected. The measurement room in Fig. 9 is the shielding room; the AC mains line in this room is connected to commercial line via filter and transformer, other points are directly connected to commercial line.

Experimental set up for measuring input impedance is shown in Fig. 10. Condenser and transformer were inserted between power source and impedance probe to save the probe from high AC voltage. The influence of the transformer was compensated by the measurement using high frequency resistors. Input impedances Z_{m1}, Z_{m2}, Z_{m3} in Fig. 3 were measured and the differential-mode impedance and common-mode impedance were calculated from measured data.
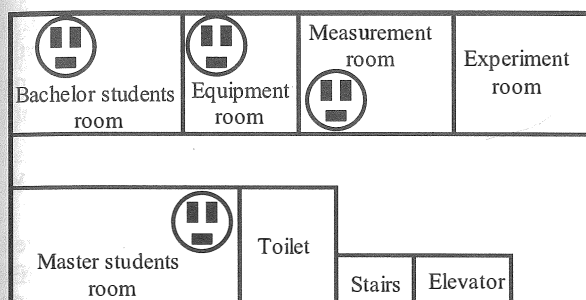
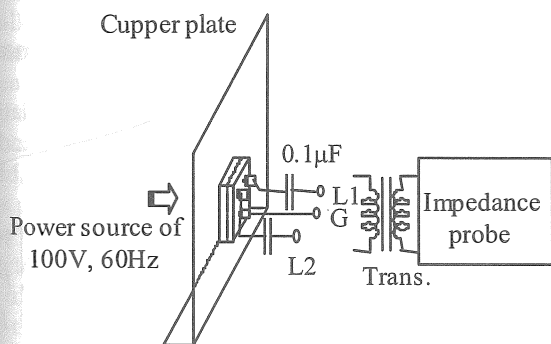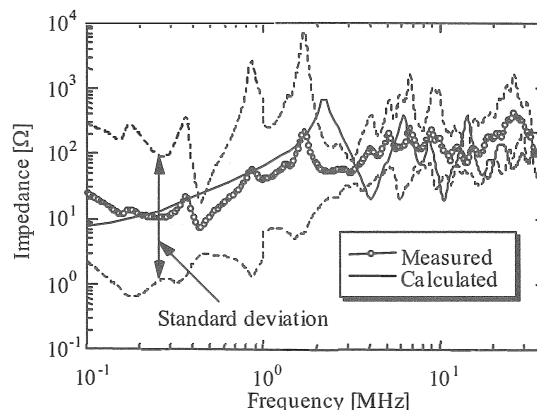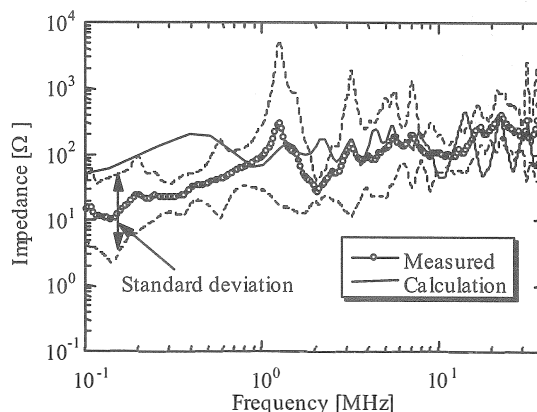Figure 9. Measurement points for input impedance of AC mains line (at laboratory building)

Figure 10. Measurement set up for input impedance of actual AC mains line

Measurement and calculated results of input impedance are shown in Fig. 11. Input impedances were measured at five points, where four points were shown in Fig. 9 and another point was the AC mains port in a home. The average and standard deviation were calculated from those data. Fig. 11(a) shows the frequency characteristics of differential-mode impedance and Fig. 11(b) shows the common-mode impedance. Although, the impedance changes from 1Ω to $10k\Omega$ both for differential and common mode, the variation reduces in more than 1 MHz, and the mean values are around 100Ω in this frequency range.

(a) Differential-mode impedance, Z_0

(b) Common-mode impedance, Z_L

Figure 11. Measured and calculated input impedance of indoor AC mains line

Solid lines in these figures are calculation values. On the calculation, the model in Fig. 2 was used. The 4-port F-matrixes of line, L_{nm}, were obtained from calculation [4], and for the matrixes of equipments, Lo_{nm}, measured values obtained from the method described in section 2.2 were used. The load Lo_m, presenting commercial AC mains line, was simulated by artificial mains network. The input impedance of the network, whose specification meets the requirement of CISPR 22, was measured, and the F-matrix was obtained from the same procedures presented in section 2.2. These figures show that the calculation results almost agree with the measured one in more than 1 MHz.

This means that the model in Fig. 2 is effective to calculate the input impedance of AC mains line.

4.2 Estimation of LCL for Actual AC mains Line

LCL of actual AC mains line can be derived from it's input impedance by using Eq. (13). The LCL values were estimated form the data shown in Fig. 11, and they are shown in Fig. 12

In this figure, solid line indicates the calculation value and the triangle and dotted line indicate measured value for actual AC main lines. The LCL was estimated by measured data at the five points, and average and standard deviation were calculated. This figure shows that the calculation result almost agrees with the measured one in more than 1MHz. It indicates that LCL of AC mains line can be calculated by the analysis model described in this paper.
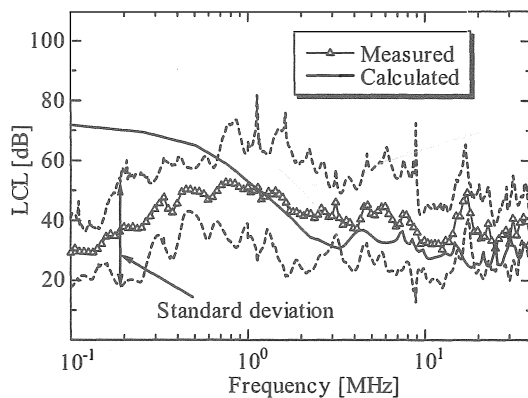

Figure 12. LCL characteristics of AC mains line

Since, high speed PLC system is used in the frequency range of 2 MHz~30 MHz [1], the model in Fig. 2 is effective to evaluate the influence to electromagnetic environment, because the LCL and the common-mode impedance are the important parameters to study it.

5. CONCLUSION

In this paper, longitudinal conversion loss (LCL) and input impedance for indoor AC mains line was investigated. AC mains line in indoor environment was modeled to consider with the wiring system of typical Japanese house. In the analysis, the model was presented in series connection of 4-port F-matrixes. The parameters of F-matrixes were obtained from calculation for the line and measurement for the equipment. The load of the commercial line was simulated by artificial mains network. The LCL, the differential-mode impedance and the common-mode impedance were calculated using this model.

An experiment using simple network was carried out to confirm the validity of the model. The results indicated that the measurement values almost agreed with the calculation one.

The model was applied to calculate the LCL, differential-mode impedance and common-mode impedance for actual environment. The results indicated that the calculation values almost agreed with the measured one in more than 1 MHz. This means that the model presented in this report is effective to evaluate the influence of PLC system for electromagnetic environment, because this system uses the frequency range of 2 MHz~30 MHz.

Future problem is to increase the accuracy of calculation.

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Appendix: Calculation method presenting F-matrix of branch

For example, we consider the case of [B₂]. The relations between the input voltage and current V_{ik1}, V_{ik2}, I_{ik1}, and I_{ik2} of branch 2 and the output voltage and current V_{o21}, V_{o22}, I_{o21}, and I_{o22} can be presented by

$$\begin{bmatrix} V_{ik1} \\ V_{ik2} \\ I_{ik1} \\ I_{ik2} \end{bmatrix} = [L_{21}][B_{22}][L_{23}][B_{24}][L_{25}][B_{26}][L_{27}][B_{28}][B_{29}] \begin{bmatrix} V_{o21} \\ V_{o22} \\ I_{o21} \\ I_{o22} \end{bmatrix}$$

where, $[B_{22}] = [L_{22}] \cdot [Lo_{21}]$, $[B_{24}] = [L_{24}] \cdot [Lo_{22}]$ etc. Using the procedure presenting from Eq. (1) to Eq. (9), we can get Δ-network parameters Z_{k1}, Z_{k2}, and Z_{k3}. Using these parameters, F-matrix can be obtained as the same expression as Eq. (16). For other branches and sub-branches, the same procedure can be applied.