Method of implementing radiation resistance to analysis model for radiated emission using chain parameter matrix

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Abstract: The analysis method using the chain parameter matrix (F-matrix) has been proposed for calculating radiated emission from the cable used by power line communication (PLC). In this paper, the radiation resistance was implemented to the F-matrix as the load of the common mode current which was converted from the differential mode PLC signal by the unbalance of the transmission system and was considered as the emission source. The calculated result for the simple cable model was compared to the measurement value and to the calculation value of which the radiation resistance was not considered. The investigation result indicated that the influence of radiation resistance appeared at the frequency where the high radiated emission was observed.

Keywords: EMC, emission, power line communication, power cable, chain parameter matrix

Classification: Electromagnetic Compatibility (EMC)

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1 Introduction

The radiated emissions from the cable used for the transmission line of power line communication (PLC) were calculated by the method of using the multi-wire transmission line (MTL) theory [1] and the method of moment (MoM) [2]. In the case of the method of using MTL theory, the common mode (CM) current which is converted from the differential mode (DM) current of PLC signal by the unbalance of the transmission system is considered as the disturbance source of radiated emission, and the CM current is calculated independently from the radiated energy. As shown by the antenna theory, the radiated electromagnetic energy is presented by the radiation resistance as the load [3], and the MoM can calculate the current considering with the radiated energy [2]. Therefore, the hybrid MoM-MTL method was proposed for calculating radiated emission from MTL on the printed circuit board [4]. However, the method was very complicated because two numerical methods were used for obtaining an interaction solution. The radiation resistance acts as a load of CM current because the radiated energy is expended from the propagating energy. However, the method of implementing the radiation resistance to the transmission line as the load has not been studied. This paper describes the method of implementing the radiation resistance as a load of CM current, and the influence is estimated by comparing to the result to the calculation result of which the radiation resistance is not considered.

2 Method of implementing radiation resistance to MTL method

2.1 Method of calculating radiated emission by MTL method

Figure 1 shows the method of implementing the radiation resistance to the analysis method of using MTL theory (MTL method) [1]. In MTL method, when the length of segment is sufficiently short from the wavelength, the short part of the transmission line (Segment) can be presented by the lumped constant circuit as shown in the left part circuit of Fig. 1. In this circuit, $R_{11}$ and $R_{22}$ are the resistance of cable conductor, $L_{11}$ and $L_{22}$ are the self-inductance of the conductor, $L_{12}$ is the mutual inductance between conductor and ground plane.
mutual-inductance between conductors, \( G_{11} \) and \( G_{22} \) are the conductance between conductor and ground, \( G_{12} \) is the conductance between conductors, \( C_{11} \) and \( C_{22} \) are the capacitance between conductor and ground, and \( C_{12} \) is the capacitance between conductors. These elements are determined from the per-unit-length parameters of the transmission line [1].

Using the circuit presenting the left side in Fig. 1, the chain parameter matrix (F-matrix) is obtained, and the transmission line is represented by the chain of F-matrices. The termination devices at the end of the transmission line are also presented by the F-matrix, and the CM current is obtained by solving the F-matrices problem. And then, the radiated emission is calculated from the CM current. The detailed processes for the calculation are described in the paper [1].

2.2 Method of implementing radiation resistance

From the antenna theory, the radiated energy from the antenna is represented by the radiation resistance [3]. This means that the influence of the radiated energy from the cable appears by the resistance load against the CM current because the CM current is the source of radiation. The right part circuit in Fig. 1 is the circuit for implementing the radiation resistance to the F-matrix. A transformer is used for implementing the radiation resistance as the load of only CM current because the influence of radiation resistance to the DM current is sufficiently small by the balance of cable. In this circuit, \( L_{t11} \), \( L_{t22} \), and \( L_{t33} \) are the self-inductance of transformer winding, and \( L_{t12} \), \( L_{t23} \), and \( L_{t31} \) are the mutual inductance. The radiation resistance influences to only the CM current by setting the transformer winding to the same direction. Using the circuit theory, the F-matrix is given by Eq. (1).

\[
[F_{rad}] = \begin{bmatrix}
1 & 0 & j\omega L_{t11} + \frac{\omega^2 L_{t31}^2}{R_r + j\omega L_{t33}} & j\omega L_{t12} + \frac{\omega^2 L_{t31} L_{t23}}{R_r + j\omega L_{t33}} \\
1 & 0 & j\omega L_{t12} + \frac{\omega^2 L_{t31} L_{t23}}{R_r + j\omega L_{t33}} & j\omega L_{t22} + \frac{\omega^2 L_{t23}^2}{R_r + j\omega L_{t33}} \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (1)

In Eq. (1), we can assume \( L_{t11} = L_{t22} = L_{t33} = L_{t12} = L_{t23} = L_{t31} = L \) and \( R_r \ll \omega L \) because the transformer in Fig. 1 is an ideal transformer whose impedance ratio is 1. Therefore, Eq. (1) can be rewritten as a simple form shown in Eq. (2).

\[
[F_{rad}] = \begin{bmatrix}
1 & 0 & R_r & R_r \\
1 & 0 & R_r & R_r \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (2)

In the above equation, \( R_r \) is the radiation resistance which is defined by the current source and the average Poynting vector at far field, and this is given by the second part of Eq. (3). In this paper, the radiation resistance of short electric dipole
is employed because the segment length is sufficiently small from the wavelength, and this is given by the last part in Eq. (3) [3].

\[ R_r = \frac{1}{|I_c|^2 / 2} \int S \frac{1}{2} Re(E_\theta H_\phi^*)dS = 80\pi^2 \left( \frac{\Delta s}{\lambda} \right)^2 \]  

In Eq. (3), \( I_c \) is the amplitude of CM current and this is the source current of the dipole. \( E_\theta \) is the electric field component of far field, \( H_\phi \) is the magnetic field component, and \( \lambda \) is the wavelength. \( \Delta s \) is the length of dipole elements and this is the segment length shown in Fig. 1. The F-matrix is modified according to the model in Fig. 1, and is given by Eq. (4).

\[ [F_{sg}] = [F_{sg}'] [F_{rad}] \]  

In Eq. (4), \([F_{sg}']\) is the F-matrix of the circuit shown on the left side in Fig. 1. Using the method described in the paper [1], the CM current is calculated by solving the F-matrices problem, and the radiated emission is calculated from the CM current.

3 Influence of radiation resistance

The radiated magnetic field was calculated in order to investigate the influence of radiation resistance. The investigation model is illustrated in Fig. 2. The experimental model where two-wire VVF cable (PVC insulated and PVC sheathed flat type cable) was placed on the formed polystyrene supporter [1] was used for the investigation. The measurement result was used for comparing to the calculation results. In addition, the previous calculation result where the radiation resistance was not considered was also used for comparing to the new calculation results. The cable height, the horizontal cable length, the circuit of the signal source, the circuit of termination device, the cable conductor diameter, the cable conductor space, and the observation positions of magnetic field strength were determined according to the experimental model [1]. The current source value was determined from the condition that the voltage at the primary port of the balun used for signal source was 1 V at impedance matching condition.

The maximum \( S_{21} \) from the primary port of balun to the output port of the loop antenna which was used for the measurement of the radiated emission was calculated.
by the method presenting in the paper [1]. The segment length of 0.01 m was used as the condition where the sufficient convergence solution was obtained.

The calculation and measurement results are shown in Fig. 3. In this figure, the vertical axis is the absolute value of the maximum $S_{21}$, the solid line is measurement value [1], the triangles are the previous calculation (Pr. cal.) value where the radiation resistance was not considered, and the circles are the new calculation (New cal.) value where the radiation resistance was implemented. As shown in this figure, the new calculation result is a bit low comparing to the previous results at the frequency where the higher radiated emission peak appears, and the new calculation value is nearer to the measurement value than the previous calculation value. This is because the influence of radiation resistance increases in proportion to the increase in radiation efficiency. This means that the calculation accuracy using the MTL method is improved by implementing the radiation resistance.

![Fig. 3. Investigation result for influence of radiation resistance.](image)

4 Conclusion

The radiation resistance was implemented in the analysis model using F-matrix. The calculation results indicated that the calculation accuracy using the MTL method is improved by implementing the radiation resistance.