Guiding Conductive Strip for Electromagnetic Interference Mitigation

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1. Introduction

In modern nuclear power plants, various digital equipment has been introduced to enhance functionality related to safety and operation. Small modular reactors (SMRs), which have recently gained significant attention, are expected to incorporate numerous digital instrumentation and control systems, including wireless communication technologies. However, digital-based SMRs, composed of multiple module-type reactors, are susceptible to electromagnetic (EM) interference due to the proximity of digital equipment within confined spaces. Since safety-related digital systems in SMRs must function reliably to ensure operational safety during design-based events and accidents, the mitigation of the EM interference (EMI) problems is crucial. Therefore, appropriate countermeasures are required to minimize the risk of EMI adversely affecting adjacent digital equipment within SMRs.

To build precaution against EMI problems in digital-based SMRs, we propose the implementation of a guiding conductive strip (GCS) to collect and confine electric fields that adversely affect nearby objects. To elucidate the operating principle and determine the optimal geometrical parameters of the GCS, we employ the mode-matching method as an analytical approach. In order to facilitate readers' understanding of the proposed method, we first describe the configuration of the target object, including the guiding conductive strip. Subsequently, we introduce a mode-matching formulation for the analytical interpretation of the electromagnetic problem. Finally, we examine the positive effects of the guiding conductive strip on EMI mitigation based on the results of the mode-matching analysis.

2. Mode Matching Formulation

Fig. 1 shows the target environment where the GCS is placed in the middle of the influencing and victim objects. We assume that the ceiling and the bottom floor are made of the grounded conductor (0 V) and the influencing object, the GCS, and victim object are composed of a conductor with potentials V_1, V_2, and V_3, respectively. In addition, we assume that every object illustrated in Fig. 1 is infinitely long along the z-axis.

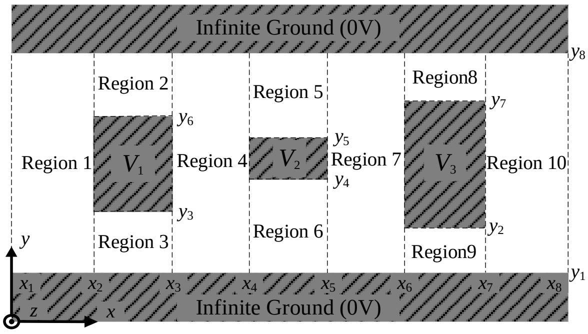

Fig. 1. Target structure for a mode-matching analysis.

First, we divide the analyzed space in Fig. 1 into regions 1 to 10, then we apply the Laplace equation to each region in conjunction with the superposition principle to obtain an expression for the potential of each region [1, 2]. The potentials of regions 1 to 4 are expressed as (1) – (4) and the other potential expressions for the other regions are analogously derived by Laplace equation [3]. Note that the explanation of the derivation of potentials expression is described in detail in [4].

$$\Phi_1 = \sum_{m_1=1}^{\infty} (B_{m_1} e^{\frac{m_1\pi}{y_8-y_1}x}) \sin\frac{m_1\pi}{y_8-y_1}(y-y_1) \tag{1}$$

$$\begin{aligned}\Phi_2 = &\sum_{m_2=1}^{\infty} (C_{m_2} e^{-\frac{m_2\pi}{y_8-y_6}x} + D_{m_2} e^{\frac{m_2\pi}{y_8-y_6}x}) \sin\frac{m_2\pi}{y_8-y_6}(y-y_6) \\ &+ \frac{V_1}{y_6-y_8}(y-y_8)\end{aligned} \tag{2}$$

$$\begin{aligned}\Phi_3 = &\sum_{m_3=1}^{\infty} (E_{m_3} e^{-\frac{m_3\pi}{y_3-y_1}x} + F_{m_3} e^{\frac{m_3\pi}{y_3-y_1}x}) \sin\frac{m_3\pi}{y_3-y_1}(y-y_1) \\ &+ \frac{V_1}{y_3-y_1}(y-y_1)\end{aligned} \tag{3}$$

$$\Phi_4 = \sum_{m_4=1}^{\infty} (G_{m_4} e^{-\frac{m_4\pi}{y_8-y_1}x} + H_{m_4} e^{\frac{m_4\pi}{y_8-y_1}x}) \sin\frac{m_4\pi}{y_8-y_1}(y-y_1) \tag{4}$$

As the potential expressions (1) – (4) contain unknown modal coefficients (B_{m1}, C_{m2}, D_{m2}, E_{m3}, F_{m3}, G_{m4}, and H_{m4}), there are a total of 18 unknown modal coefficients across all regions. To obtain the exact electromagnetic solution for this application, these modal coefficients must be determined by applying appropriate boundary conditions. Specifically, we impose 6 Dirichlet boundary conditions (ensuring continuity of potentials) and 12 Neumann boundary conditions (ensuring continuity of electric fields) at the interfaces located at $x = x_2$, x_3, x_4, x_5, x_6, and x_7. As a representative example, the Dirichlet and Neumann boundary conditions at the interface $x = x_2$ are explicitly provided in (5) and (6) – (7), respectively.

$$\Phi_1(x,y)\big|_{x=x_2} = \begin{cases} \Phi_2(x,y)\big|_{x=x_2} & , y_6 \le y < y_8 \\ V_1 & , y_3 \le y < y_6 \\ \Phi_3(x,y)\big|_{x=x_2} & , y_1 \le y < y_3 \end{cases} \quad (5)$$

$$\left.\frac{\partial \Phi_1(x,y)}{\partial x}\right|_{x=x_2} = \left.\frac{\partial \Phi_2(x,y)}{\partial x}\right|_{x=x_2} \quad , y_6 < y < y_8 \quad (6)$$

$$\left.\frac{\partial \Phi_1(x,y)}{\partial x}\right|_{x=x_2} = \left.\frac{\partial \Phi_3(x,y)}{\partial x}\right|_{x=x_2} \quad , y_1 < y < y_3 \quad (7)$$

Analogously, boundary conditions at the remaining interfaces can be established similarly. Consequently, a set of simultaneous equations can be formulated based on these boundary conditions, enabling efficient computation of the modal coefficients through appropriate truncation of the infinite series in the simultaneous equations.

3. Mode Matching Results

After validating our mode-matching analysis, we applied it to the investigation of the capacitance matrix to check the capability of the GCS to confine the influencing electric fields from interfering object to the victim object [4]. Fig. 2 illustrates the investigated C_{13}, which means the variation of electromagnetic coupling between the interfering and victim objects, when the GCS is located in the ranges of -0.2 m ≤ x ≤ 0.2 m and -0.4 m ≤ y ≤ 0.4 m.

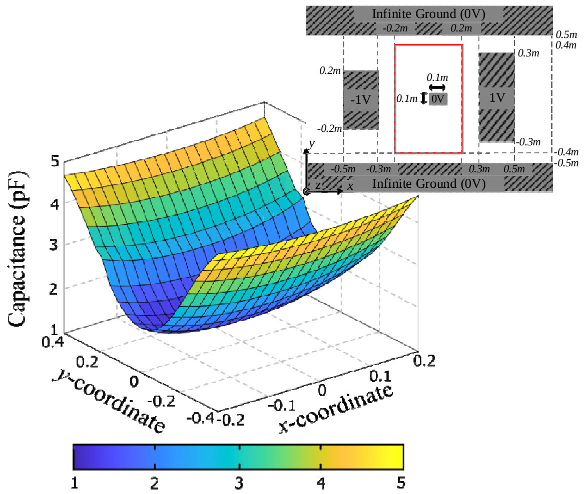

Fig. 2. The variation in C_{13} of a capacitance matrix while the location of the GCS varies.

In Fig. 2, we set the sizes and locations of the interfering and victim objects as fixed, and the voltages V_1, V_2, and V_3 are –1 V, 0 V, and 1 V, respectively. The result of Fig. 2 reveals that C_{13} decreases when the GCS is placed between the interfering and victim objects. This result is because the GCS collects and confines the electric fields influencing the victim object adversely.

4. Conclusions

In this study, we utilized a mode-matching method to analyze the EMI mitigation of GCS between the influencing and victim objects. Based on Laplace equations and the superposition principle, we derived potential expressions for the inner space of the target structure. We then enforced the Dirichlet and Neumann boundary conditions to constitute a set of simultaneous equations for modal coefficients. To investigate the capability of the GCS to confine the influencing electric fields, we examined the capacitance matrix while varying the location of the GCS. The result of this investigation provides us with useful information to mitigate EMI for the modernized nuclear power plants, such as a small modular reactor.

5. Acknowledgement

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