Nuclear Instruments and Methods in Physics Research A 844 (2017) 19–23

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Configuration of three distributed lines for reducing noise due to the coupling of the common and normal modes

Souma Jinno[a,b], Hiroshi Toki[a,*], Masayoshi Abe[a,b]

[a] Science and Technology Entrepreneurship Laboratory (e-square), Osaka University, Suita, Osaka 565-0871, Japan
[b] Science Engineering, Osaka University, Toyonaka, Osaka, 560-8531, JapanCon guration of Three Distributed Lines for Reducing

ARTICLE INFO

Keywords:
Normal mode
Common mode
Mode coupling
Noise

ABSTRACT

In this study, the coupling between the common and normal modes in distributed lines and the resulting electromagnetic noise were considered. The telegraph equations of three distributed lines with the boundary conditions of a lumped circuit reveal the presence of mode-coupling noise. To reduce the coupling noise, the geometrically and electrically symmetric configuration of the three distributed lines is proposed. The simulation results show that the proposed configuration can decrease the mode-coupling noise by a factor of 1×10^{-8} in comparison with that of asymmetric configurations.

1. Introduction

Common-mode noise, also known as an electromagnetic noise, is troublesome in electrical and electronic equipment. Because electromagnetic noise is a phenomenon intricately intertwined, noise identification and reduction are extremely difficult. Various approaches to describing electromagnetic noise have been proposed and applied. Because of the complexity of electromagnetic noise, it has been described using phenomenological models in past studies [1–6]. To clarify the source of electromagnetic noise, another approach based on Maxwell's theory [7] has been investigated. As an application of this approach, the differential signal and symmetry arrangement were used with the Heavy-Ion Medical Accelerator in Chiba (HIMAC), which has extremely low electromagnetic noise, and stable operation was realized [8]. Two geometrically symmetric signal lines with a grounded line centered between them enabled the reduction of electromagnetic noise. Because two symmetric signal sources are required when applying this approach to HIMAC, the application of this symmetric configuration to other fields may be limited.

In this study, a single signal source was simulated to reduce the electromagnetic noise induced by the coupling of the common and normal modes. The main ring synchrotron of the Japan Proton Accelerator Research Complex (JPARC/MR) uses a single signal source for its noise filter and magnet system, resulting stable operation with a medium noise level [9]. In electrical and electronic equipment, the use of only a single signal source is commonplace, and it is important to know how to reduce common-mode noise. Previously obtained simulation results based on the theory of signal propagation for multiple distributed lines [10] are consistent with the present theories regarding the common and normal modes.

In Section 2, the present theory regarding the common and the normal modes is briefly discussed, and telegraph equations describing the voltage and current of the common and normal modes are given. The simulation circuits considered in this study, in which multiple distributed lines and lumped electronics are combined, are presented in Section 3. In Section 4, the simulations of three distributed lines performed in this study are described. Electromagnetic noise due to mode coupling was found to be present under asymmetric configurations, and a noise-reducing configuration is proposed. A symmetric configuration containing resistors with parasitic capacitances is also presented, and its applicability is discussed.

2. Theory of common and normal modes for three distributed lines

The third line discussed in this paper represents the conducting materials surrounding the circuit, such as a chassis, a ground plane, or an enclosure. These finite-sized conducting materials are simplified to a straight line to mathematically treat the common mode in a simple and transparent manner. The effective coefficients of the potential and inductance were used to include the effects of the finite size of the materials [10]. With this third line included, a three-conductor transmission line theory for the coupling of the normal and common modes was developed.

To understand the three distributed lines, it is important to first develop a theory for the common and normal modes and their

* Corresponding author.
E-mail addresses: soumajinno117@s.ee.es.osaka-u.ac.jp (S. Jinno), toki@rcnp.osaka-u.ac.jp (H. Toki), abe@stec.es.osaka-u.ac.jp (M. Abe).

http://dx.doi.org/10.1016/j.nima.2016.11.017
Received 10 October 2016; Received in revised form 1 November 2016; Accepted 8 November 2016
Available online 12 November 2016
0168-9002/

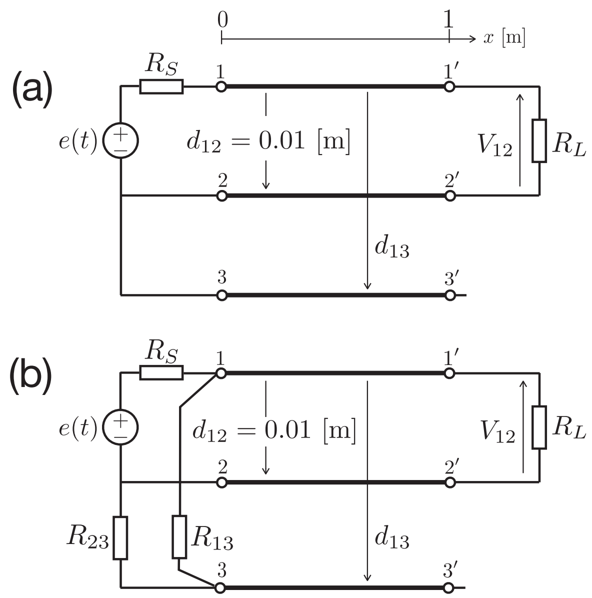

Fig. 1. Simulation circuits combining lumped circuits and distributed lines. Thick and thin lines represent distributed lines and lumped circuits, respectively. Line 3–3′ is regarded as a ground plane, or an enclosure in the circuit. The left edge of line 3–3′ is connected (a) directly to node 2 ($U_2(0, t)$) or (b) to nodes 1 and 2 through resistors R_{13} and R_{23}.

relationship. A previously developed theory for three distributed lines based on the multiple distributed lines theory [10] is summarized here. The details of this approach have been previously described by Toki et al. [7,11]. This theory considers three distributed lines with potentials and currents of $U_k(x, t)$ and $I_k(x, t)$, respectively, where k (=1, 2, 3) is the line number and x and t are the position of the distributed line and the time, respectively (see Fig. 1). A signal propagates through lines 1–1′ and 2–2′ , and line 3–3′ is a simplified model of the conducting material surrounding the circuit [12]. The observable normal-mode voltage $V_n(x, t)$ and current $I_n(x, t)$ are respectively given by

$$V_n(x, t) = U_1(x, t) - U_2(x, t) \tag{1}$$

$$I_n(x, t) = \frac{1}{2}(I_1(x, t) - I_2(x, t)). \tag{2}$$

And we define common mode voltage $V_c(x, t)$ and current $I_c(x, t)$ referring to the potential $U_3(x, t)$ and the current $I_3(x, t)$. The third distributed line 3 – 3′ is the reference of this circuit and called “common” for the first and second distributed lines.

$$V_c(x, t) = \frac{1}{2}(U_1(x, t) + U_2(x, t)) - U_3(x, t) \tag{3}$$

$$I_c(x, t) = \frac{1}{2}(I_1(x, t) + I_2(x, t) - I_3(x, t)). \tag{4}$$

Substituting (1)–(4) into the telegraph equation for the multiple distributed lines [10] yields the following deformed telegraph equations as functions of V_n, I_n, V_c, and I_c:

$$\frac{\partial V_n(x, t)}{\partial t} = -P_n \frac{\partial I_n(x, t)}{\partial x} - P_{nc} \frac{\partial I_c(x, t)}{\partial x} \tag{5}$$

$$\frac{\partial V_c(x, t)}{\partial t} = -P_{cn} \frac{\partial I_n(x, t)}{\partial x} - P_c \frac{\partial I_c(x, t)}{\partial x} \tag{6}$$

$$\frac{\partial V_n(x, t)}{\partial x} = -L_n \frac{\partial I_n(x, t)}{\partial x} - L_{nc} \frac{\partial I_c(x, t)}{\partial t} \tag{7}$$

$$\frac{\partial V_c(x, t)}{\partial x} = -L_{cn} \frac{\partial I_n(x, t)}{\partial t} - L_c \frac{\partial I_c(x, t)}{\partial t}. \tag{8}$$

The variable definitions for these equations can be found in the work by Toki et al. [7]. Under the condition $P_{nc} = P_{cn} = 0$ and $L_{nc} = L_{cn} = 0$, the coupling of the normal and common modes can be eliminated. Thus, one of the conditions is to maintain the geometric symmetry of the circuit [9].

3. Simulation models and methods

To perform simulations for less noise structure, the circuit configurations shown in Fig. 1(a) and (b) were considered. Three distributed lines of 1 m in length, represented by thick lines in Fig. 1, are connected to the lumped circuits. In Fig. 1(a), distributed line 3–3′ is connected directly to the left edge ($x = 0$) of line 2–2′ . This configuration represents the conducting material surrounding the circuit (line 3–3′) connected to the lumped circuit and distributed lines 1–1′ and 2–2′ . Calculations were also performed for the circuit shown in Fig. 1(b), which contains additional resistors R_{13} and $R_{23}(=R_{13})$ that balance the electrical symmetry [13]. The calculations of the distributed lines were performed using the finite-difference time-domain (FDTD) method [10]. To solve the conditions at the boundaries between the distributed lines and the lumped circuits, the algorithm for multiple distributed lines was used [11].

A voltage pulse $e(t)$ with a height of 1.0 V and a width of 1.0 ns was applied, and it propagated through distributed lines 1–1′ and 2–2′ . In both cases of Figs. 1(a) and (b), we have calculated the time-variation of the element voltage $V_{12} = U_1(1, t) - U_2(1, t)(=V_n(1, t))$ at R_L. The distance d_{13} between lines 1–1′ and 3–3′ was changed while the distance d_{12} between lines 1–1′ and 2–2′ remained fixed at $d_{12} = 0.01$ m. During the simulations, R_S and R_L were set equal to the characteristic impedance between lines 1–1′ and 2–2′, which depends on the positions of the three distributed lines. The relative dielectric constant was set to 2, and the signal propagation speed was calculated to be 2.1×10^8 m/s.

4. Results and discussions

Fig. 2(a) and (b) shows the simulation results for the circuit in Fig. 1(a) at line 3–3′ positions of $d_{13} = 0.02$ and 0.005 m, respectively. One see pulse trains in all graphs. Because the pulsed signal $e(t)$ was

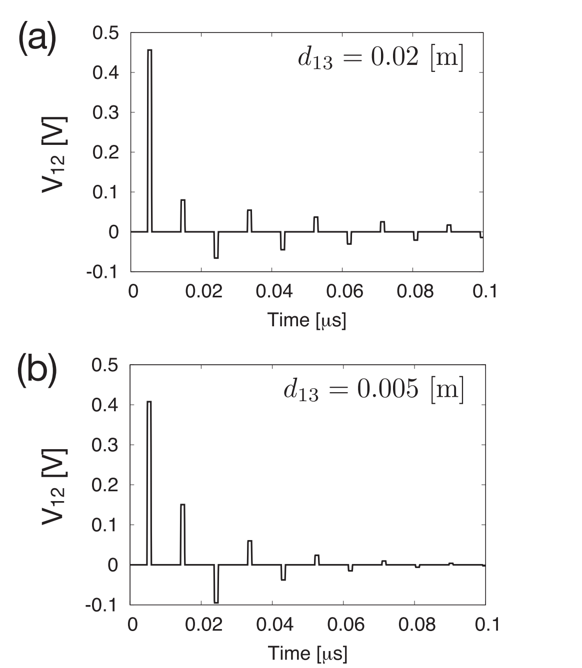

Fig. 2. Time variation of the simulated voltage V_{12} of the circuit shown in Fig. 1(a). The position of line 3–3′ was set to (a) $d_{13} = 0.02$ m and (b) $d_{13} = 0.005$ m. The resistances R_S and R_L were adjusted to match the characteristic impedance, which depends on d_{13}.