Chinese Journal of Physics 55 (2017) 904–915

Contents lists available at ScienceDirect

Chinese Journal of Physics

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

Mechanism of common-mode noise and heat generation in an electric circuit with grounding using multiconductor transmission-line theory

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ARTICLE INFO

Article history:
Received 24 December 2016
Revised 25 February 2017
Accepted 10 March 2017
Available online 21 March 2017

Keywords:
Three-line circuit
Normal and common modes
New circuit theory
Electromagnetic noise
Heat generation

ABSTRACT

The experimental measurements clearly show electromagnetic noise patterns in a three-line circuit, which represents a two-line circuit with grounding. A new three-line circuit theory reproduces the noise patterns of an electric circuit with grounding, allowing the origin of the noise of the three-line circuit to be understood. In addition, comparing the theoretical calculations of a three-line circuit to the experimental results reveals that electric power is converted to heat over time due to the resistance in the third line. The results demonstrate the importance of reducing the common-mode noise to avoid heat generation in an electric circuit.

1. Introduction

It is important to understand the source of electromagnetic noise to ensure a quality performance of an electric circuit. In recent years, theoretical studies on electromagnetic noise have been conducted by deriving a multiconductor transmission line (MTL) theory starting from Maxwell's equations [1–3]. These theoretical studies have demonstrated the significance of a symmetrized three-line circuit to reduce the noise in the common mode, which couples to the normal mode of the circuit when the symmetry is broken. The MTL theory has allowed the performance of an electric circuit to be calculated and the origin of electromagnetic noise to be elucidated.

The transmission-line theory was introduced by Heaviside phenomenologically more than a century ago [4]. There were many theoretical studies to derive the MTL theory from Maxwell's equations [5,6]. These studies are limited to derive the MTL theory for the TEM mode as an approximation to the full MTL theory, which should include the non-local terms for the electromagnetic fields in terms of the charge and current in conductors and the antenna terms for electromagnetic radiation. The derivation of the MTL theory for the TEM mode from Maxwell's equations and its application to various phenomena are described in the book of Paul [7]. For the full description of electromagnetic noise, however, we need all the terms as the non-local terms and the antenna terms to quantify these effects.

There are various sources of electromagnetic noise in an electric circuit. Most of these sources are understood as coming from electric elements in the circuit. However, one source of noise called common-mode noise is not clearly understood,

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http://dx.doi.org/10.1016/j.cjph.2017.03.002

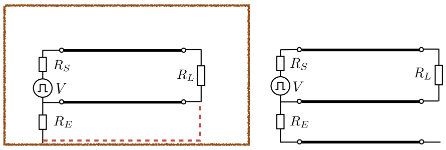

Fig. 1. A two-line circuit is equipped with a power supply V, a source resistance R_S, and the load resistance R_L, which are connected by two-transmission lines as shown in the left hand figure. This circuit is placed in an enclosure shown by brown square, which contains conducting materials and is connected by a grounding line with a resistance R_E. The common-mode current goes through the two-line circuit as a whole and then through the surrounding materials with parasitic capacitor as indicated by red line. In this paper, we simplify the surrounding conducting materials by the third line connected by the grounding line, which is shown in the right hand figure, to describe the common mode explicitly. It is important to note that the end of the third line is not connected to the two-line circuit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

since the common-mode noise is considered as due to the summed-current in the two lines going through conducting materials surrounding the circuit. In addition, there is an electromagnetic radiation from the circuit. Hence, there are many experimental and theoretical efforts to measure the electromagnetic noise in the circuit and radiation around the circuit [8–11]. In all these studies, PCB is used with simple circuit configurations and the noise signals are measured in the frequency domain. Since the circuit configurations cannot be described in the MTL theory with the TEM approximation, several models are introduced to understand the experimental results. However, the mechanism of electromagnetic noise is still not clear and we do not have yet a convincing view on the electromagnetic noise.

In this paper, we study a simple two-line circuit with grounding by the following simple arrangement. We arrange the conducting materials around the circuit simply by introducing the third line, connected through the grounding line by the circuit. The resulting circuit is a three-line circuit, where we are able to define the normal mode and common mode explicitly. In addition, we take circuits with long conducting lines so that we are able to observe the noise signals in the time domain. In this arrangement, we can clearly see the common-mode noise and its origin as coming from the construction of the circuit with grounding to the surrounding conducting materials. The purpose of this paper is to understand the performance of a two-line circuit with grounding by introducing the third line to represent the surrounding conducting materials. Using this simplified system, we want to understand the role of the third (ground) line and its influence on the two-line circuit using the three-conductor transmission-lines both experimentally and theoretically. Recently, Kitora et al. theoretically demonstrated the patterns of electromagnetic noise in a three-line circuit where two lines are used as a circuit and the third line is used as the surrounding conductors [12]. Strong noise patterns are observed in the common mode by the ringing phenomenon due to the fact that the impedance matching is never fulfilled in the common mode.

The simplification of a two-line circuit with grounding and the recent theoretical study motivated us to construct a three-line circuit and to measure its electromagnetic voltages experimentally. We used a simple arrangement for the three-line circuit with a pulse generator and an oscilloscope. We calculated the electromagnetic voltages in both the normal and common modes using a new three-line circuit theory and compared results to the experimental data to elucidate the connection between the common-mode noise and heat generation using the circuit theory.

This paper is arranged as follows. Section 2 briefly describes the theoretical formulas used to calculate the electromagnetic voltages and defines the normal and common modes for a three-line circuit. Section 3 discusses the details of the experimental arrangement and the results. Section 4 presents the theoretical results and compares them to the experimental data. In addition, we show that the heat generation is caused by the common-mode noise in a three-line circuit. Section 5 is devoted to the summary of the present study.

2. Two-line circuit with grounding

We shall discuss the common-mode noise and its coupling to the normal mode in an ordinary two-line circuit surrounded by conducting materials in this paper. Usually a two-line circuit is placed in an enclosure, which consists of conducting materials, and the circuit is connected to the surrounding conducting materials through the grounding line as shown in Fig. 1. The normal-mode current goes through the two-line circuit as the differential mode. On the other hand, the common-mode current goes through the circuit as a whole and then goes through the surrounding conducting materials as shown by the dashed line in Fig. 1. Here, it is assumed that a parasitic capacitor exists between the circuit and the enclosure. Since it is difficult to treat this situation, we introduce the third line to represent the surrounding conducting materials for simplification, which is shown in the right hand figure in Fig. 1. It is very important to note that the end of the third line is not connected to the circuit. This arrangement causes a ringing pattern in the common mode, and a common-mode wave goes through the third line. In this section, we briefly describe this particular three-line circuit for a two-line circuit with surrounding conducting materials. In this case, we can define the common mode in addition to the normal mode. We shall discuss also electric powers in the normal and common modes in connection with heat generation.