University of Missouri-Rolla
Electromagnetic Compatibility Laboratory

Title:

A Common Problem with Printed Circuit Board Radiation Models

Report Number: TR93-3-011P

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Date: February 15, 1993

Abstract - Two-dimensional, lumped element, or transmission line modeling techniques are often applied to printed circuit board configurations in order to model the propagation of high-speed signals. These techniques can be used to calculate the currents in a circuit with a high degree of accuracy. Under the assumption that an accurate calculation of the signal currents is necessary (or at least sufficient) to ensure an accurate determination of the radiated fields, several researchers have attempted to model the radiated electromagnetic emissions from printed circuit board configurations using these same techniques. This paper uses a few simple examples to illustrate the common-mode current problem and demonstrate why only full-wave, three-dimensional techniques should be used to model the radiation from printed circuit board configurations.

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Two-dimensional, lumped element, or transmission line modeling techniques are often applied to printed circuit board configurations in order to model the propagation of high-speed signals. These techniques can be used to calculate the currents in a circuit with a high degree of accuracy. Under the assumption that an accurate calculation of the signal currents is necessary (or at least sufficient) to ensure an accurate determination of the radiated fields, several researchers have attempted to model the radiated electromagnetic emissions from printed circuit board configurations using these same techniques. This paper uses a few simple examples to illustrate the *common-mode* current problem and demonstrate why only full-wave, three-dimensional techniques should be used to model the radiation from printed circuit board configurations.

Introduction

There is a growing amount of interest in modeling the radiation from printed circuit boards using numerical techniques. Unintentional electromagnetic radiation from high-speed circuitry on printed circuit boards can interfere with licensed radio receivers or other electronic devices. Reducing the unintentional radiation by using a thoughtful and sensible board design is much more effective than trying to shield or filter a poor design. Numerical models can potentially help printed circuit board designers to determine which design options to choose in different situations in order to minimize the radiated fields.

Numerical electromagnetic modeling techniques are already an important and widely-used tool for modeling and predicting the behavior of signals that propagate on printed circuit boards. Computer modeling can tell a board designer whether a particular design will meet criteria for signal quality, propagation delay, crosstalk, and other specifications. A variety of numerical techniques are being applied to printed circuit board configurations including 2-dimensional and 3-dimensional methods, quasi-static and time-varying methods, time and frequency domain methods, and lumped-element, distributed-element, and full-wave methods.

Although several researchers have applied 3-dimensional, full wave models to simplified configurations resembling printed circuit boards, most practical circuit board configurations are too complex to be analyzed with existing full-wave techniques [1]. In the meantime, given the lack of efficient full-wave models, a number of 2-dimensional, quasi-static, lumped element, and/or transmission line modeling approaches have been proposed. Approaches that have been successfully used to calculate signal currents on printed circuit boards have been modified to calculate radiated electromagnetic interference. The basic philosophy of these codes is that if the signal currents can be calculated to within a reasonable accuracy, then the radiated fields can be calculated with a similar accuracy. This would be true if the radiated fields were directly related to the signal currents. Unfortunately, this is usually not the case.

Example

Consider the simple circuit illustrated in Figure 1. A 1-volt, 100-MHz ideal voltage source drives a 50-ohm load through a 10-cm x 1-cm wire transmission line. The currents on the wire and subsequently the radiated fields can be calculated using a full-wave method-of-moment approach. In this case, the Numerical Electromagnetics Code, NEC, [2] was used and the 30-meter radiated electric field strength is plotted in Figure 2.

A much simpler and computationally more efficient approach is to use transmission line theory to calculate the currents first. Once the currents are obtained, the radiated fields can be readily calculated and there is no need to resort to a full-wave solution of any kind.

The circuit in Figure 3 illustrates this idea. It is similar to the circuit in Figure 1 except that all lumped elements have been removed and each segment of the circuit is driven by it's own current source. We can use simple transmission line theory to calculate the amplitudes of these current sources and then find the radiated field strength by summing the fields due to each simple current element. This approach avoids the necessity of solving a complex system of equations. Results are obtained much more efficiently, and as Figure 2 indicates, they are within a few dB of the 3D full-wave solution.

A Second Example

Examples like the one above are often used to validate printed circuit board radiation models that do not employ full-wave 3D EM modeling techniques. Unfortunately, balanced circuits with perfect symmetry are non-existent in real applications. Radiation from the vast majority of printed circuit board configurations is primarily due to unintentional *common-mode* currents [3-5].

For example, consider the configuration in Figure 4. It is similar to the circuit in Figure 1 except that like most real circuits, both *sides* of the circuit are not identical. In this case, one side of the circuit (which we will arbitrarily call *ground*) has a 50-cm wire extending from it. Since this wire is attached at only one end, there are no signal currents flowing in it. In fact, a full-wave NEC analysis of this configuration reveals that the peak current induced on this wire is less than 0.5 mA. This is an apparently negligible level of current when compared with the 11 mA of current flowing in the circuit.

A plot of the electric field strength (Figure 5) however, reveals that this current is far from negligible. The peak field strength of the circuit with the 50-cm wire attached is 51.6 dB(μV/m). This is significantly higher than the 38.6 dB(μV/m) due to the signal currents alone.

A Third Example

The magnitude of the signal current on each segment calculated by NEC for the circuits in both Figure 1 and Figure 4 is listed in Table 1. Since the currents in the circuit part of the configuration (segments 1-26) agree to within less than 1 dB, it appears at least plausible that a significant amount of computation could be eliminated by using transmission line theory to calculate the currents in the circuit. The currents on the wire could then be calculated using a full-wave approach.

This idea is illustrated in Figure 6. The currents calculated using transmission line theory are used as the source terms for a full-wave analysis. Because there are fewer unconstrained segments, the amount of computation required to find a solution is significantly reduced.

Although this approach is widely used, it makes the erroneous assumption that the signal currents are the only currents of any consequence in the circuit. The results of a combination transmission-line/full-wave analysis are compared to the full-wave results in Figure 7. Even though the signal currents have been modeled to within 1 dB, the error in the peak calculated field strength is greater than 10 dB.

Conclusions

Perhaps the most intuitive way to view these examples and radiation from printed circuit cards in general, is to recognize that the total current in each circuit can be decomposed into two components. There is a differential mode (also called the signal mode or symmetric mode) current, which flows out on one side of the circuit and returns on the other side. There is also a common mode (or asymmetric mode), which is the rest of the current flowing in the configuration. Figure 8 illustrates the common-mode and differential-mode currents for the example above. In printed circuit boards that are reasonably well designed, the differential-mode currents do not contribute significantly to the radiated field strength. Effective calculation of the radiated fields therefore requires an accurate common-mode current calculation. Two-dimensional models, circuit models, and transmission line models can only solve for differential currents.

The model in Figure 6 forced the common-mode current on the circuit to be zero by making the circuit currents differential. Although it is the current on the longer attached wired that is primarily responsible for the radiated emissions, the current on the attached wire must equal the common-mode component of the current in the circuit at the attachment point. Neglecting to account for the small common-mode component of current in the circuit therefore, caused the entire solution to be in error.

The simple examples presented here do not represent an unlikely or random phenomenon. The circuits on well designed, high-speed printed circuit boards rarely radiate significant amounts of electromagnetic energy directly. They radiate by inducing common-mode currents on attached or nearby cables and enclosures.

Transmission line modeling techniques and 2-dimensional techniques are only capable of calculating differential-mode currents by definition. Although the common-mode component of the current may be small, it generally cannot be neglected even in parts of the configuration where it is overwhelmed by the differential mode currents. Therefore transmission line and 2-dimensional modeling techniques should not be used to make printed circuit board radiation calculations. Accurate printed circuit board radiation modeling requires a full-wave, 3D modeling technique.

References

[1] T. H. Hubing, "Numerical techniques for EMI source modeling: a review of progress," *Proceedings of the Eighth Annual Review of Progress in Applied Computational Electromagnetics*, Monterey, CA, pp. 413-417, Mar. 1992.

[2] G. J. Burke and A. J. Poggio, "Numerical Electromagnetic Code (NEC) - method of moments," Naval Ocean Syst. Center, San Diego, CA, *NOSC Tech. Document 116*, Jan. 1981.

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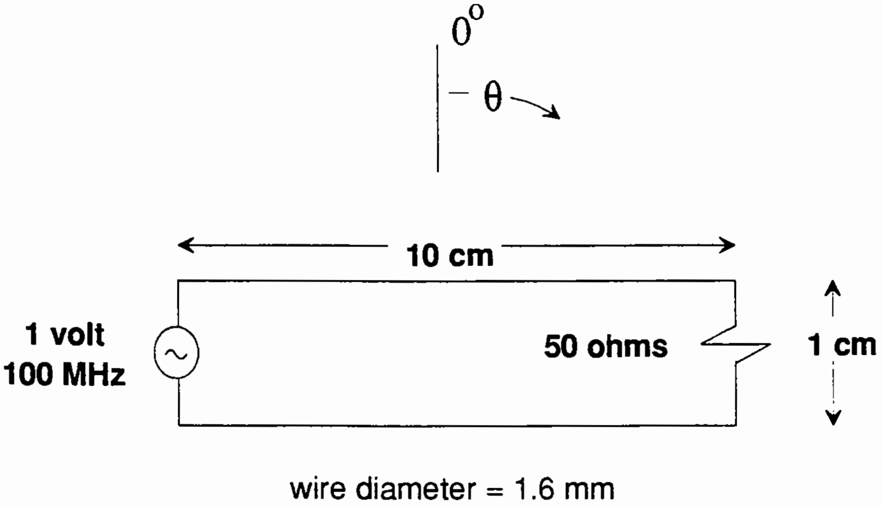

Figure 1: Simple circuit example

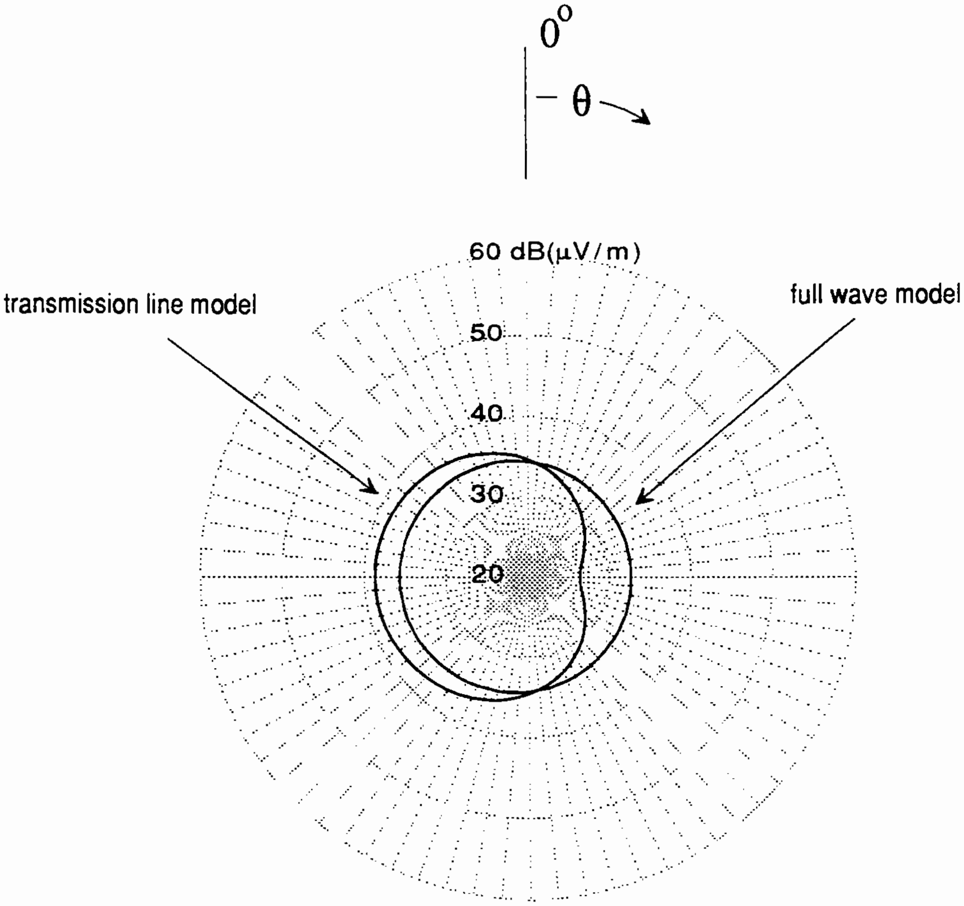

Figure 2: 30-meter electric field strength

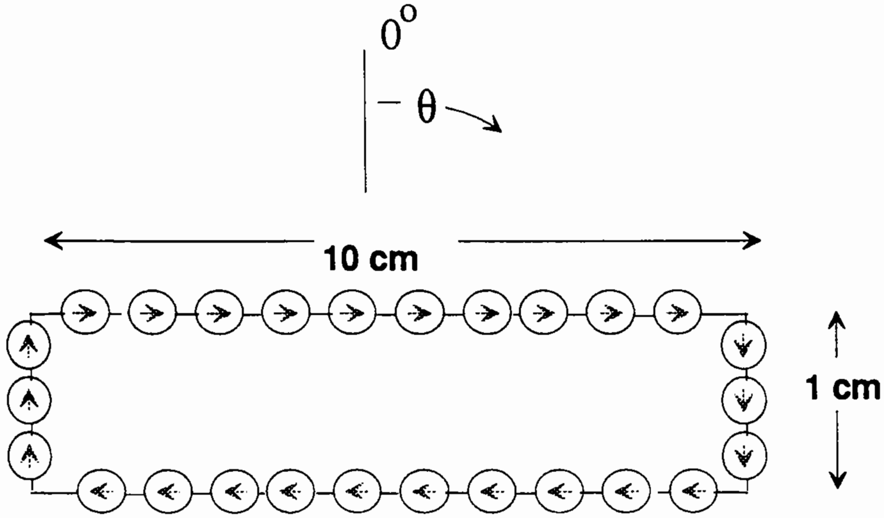

Figure 3: Circuit with current on each segment constrained

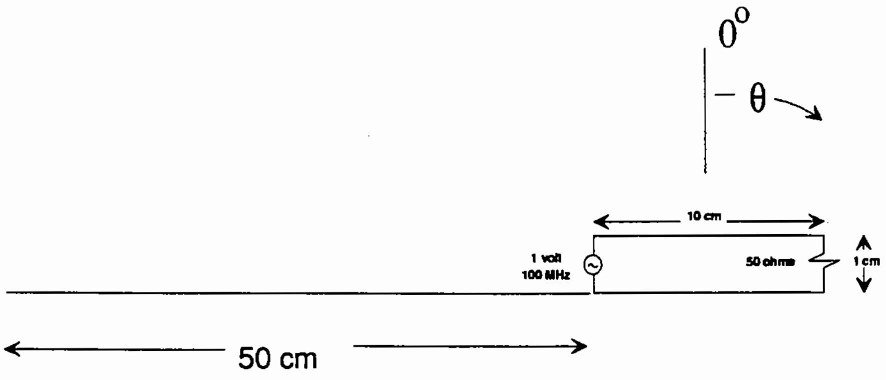

Figure 4: Another circuit example

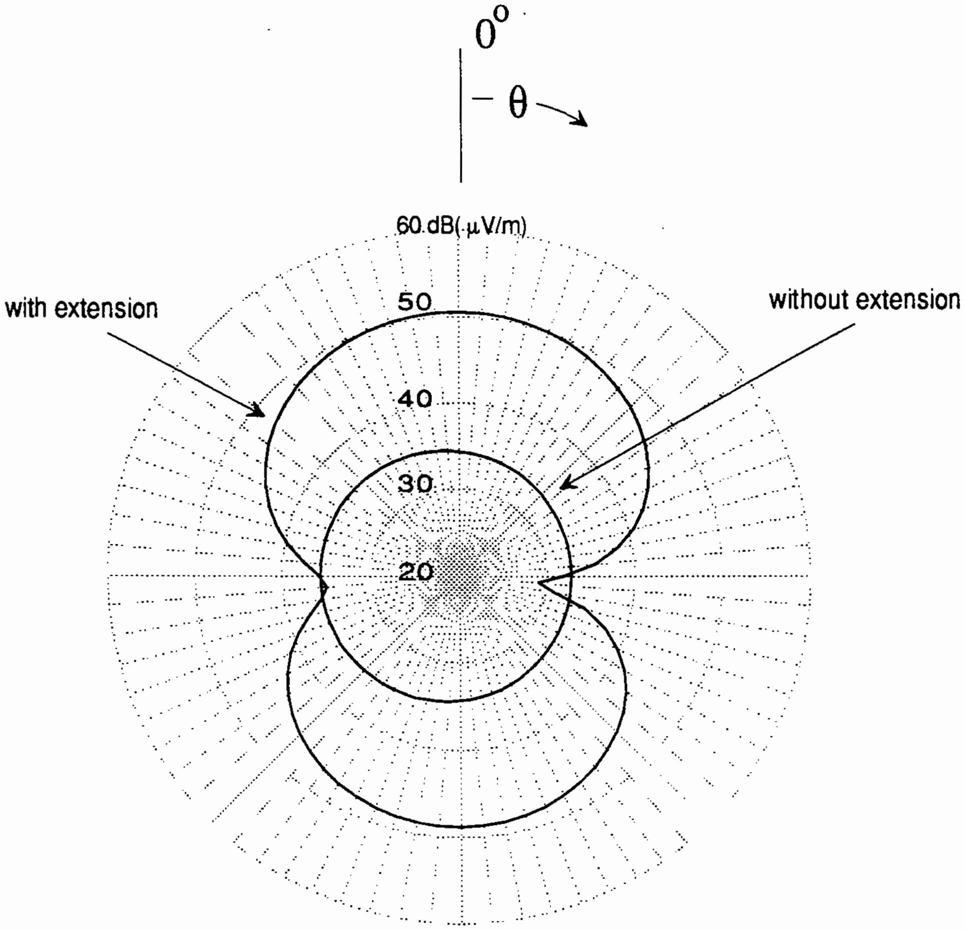

Figure 5: 30-meter field strength for second example

Table 1: Calculated currents on each segment

segment #	**circuit with extension** (magnitude in mA)	**circuit without extension** (magnitude in mA)
1	10.93	11.63
2	10.91	11.61
3	10.95	11.63
4	10.99	11.67
5	11.06	11.72
6	11.11	11.76
7	11.17	11.80
8	11.21	11.83
9	11.25	11.85
10	11.29	11.88
11	11.32	11.89
12	11.35	11.90
13	11.37	11.91
14	11.39	11.91
15	11.39	11.91
16	11.40	11.91
17	11.41	11.91
18	11.42	11.90
19	11.43	11.89
20	11.43	11.88
21	11.42	11.85
22	11.41	11.83
23	11.40	11.80
24	11.38	11.76
25	11.35	11.72
26	11.33	11.67
27	0.47	
28	0.45	
29	0.44	
30	0.43	
31	0.42	
.	.	
.	.	
.	.	
69	0.09	
70	0.08	
71	0.07	
72	0.06	
73	0.05	
74	0.03	
75	0.02	
76	0.01	

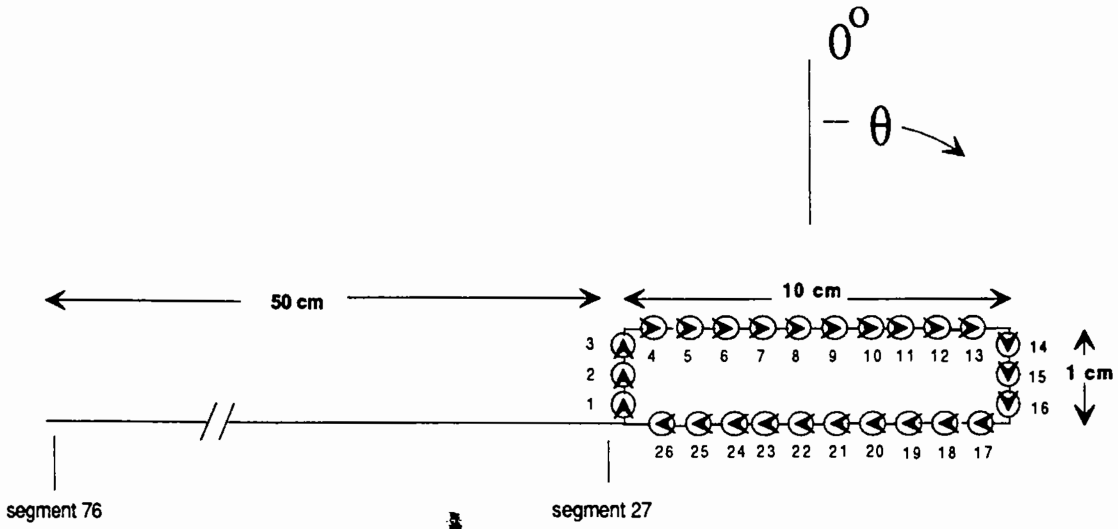

Figure 6: Using TL model to simplify a full-wave calculation

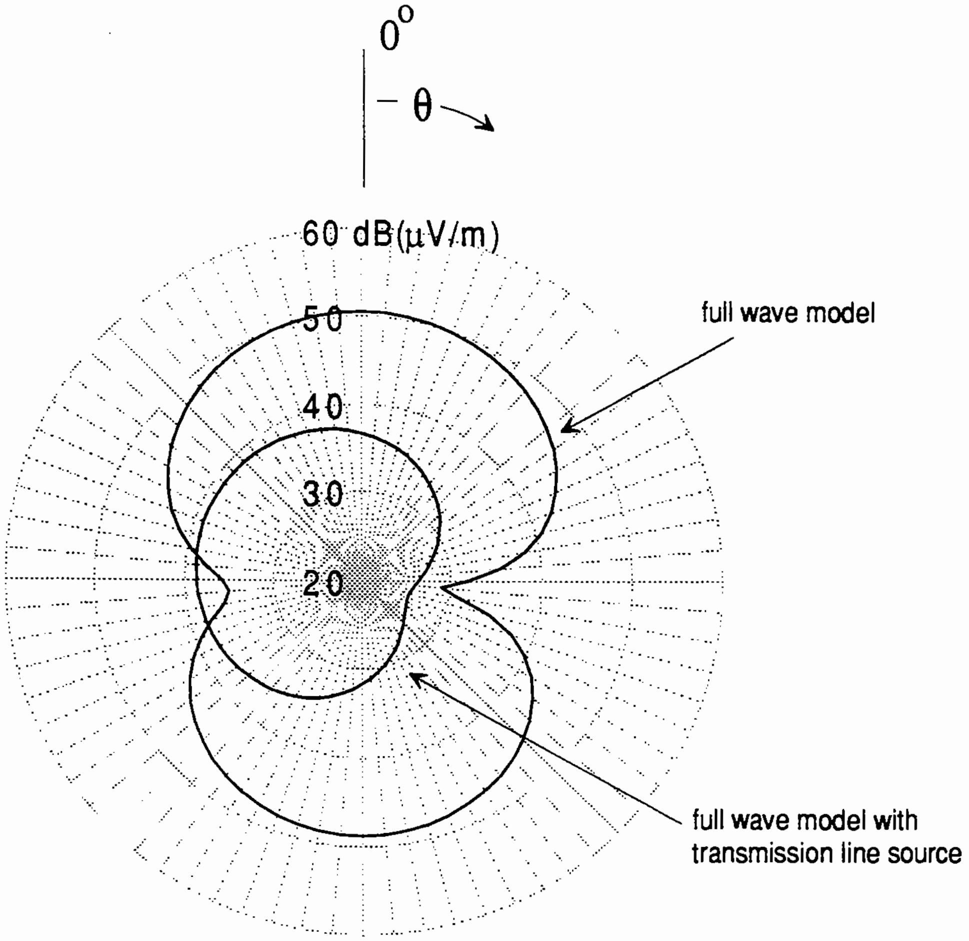

Figure 7: Field strength due to circuit in Figure 6

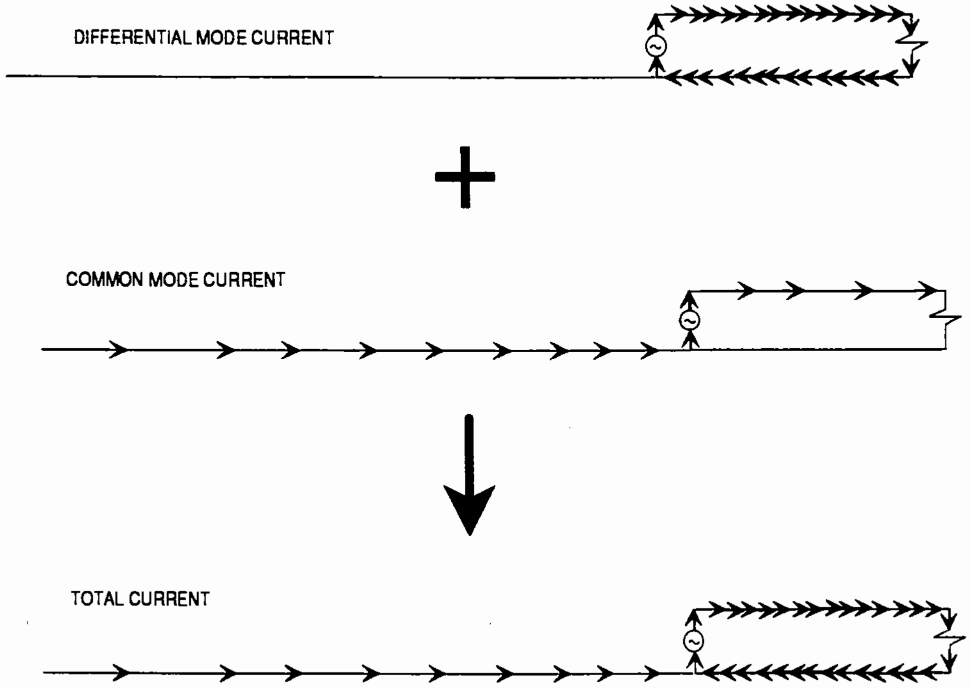

Figure 8: Common and differential mode current components