Frequency Response Analysis of IEMI in Different Types of Electrical Networks

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Abstract

In this paper, the frequency responses of the loads in different types of electrical networks subjected to intentional electromagnetic interference (IEMI), are analysed with a method based on the Baum-Liu-Tesche (BLT) equation. The networks can be multi-conductor systems with multiple junctions and branches. To verify the calculation results, a commercial electromagnetic simulator based on electromagnetic topology was used. The calculation results agree well with the numerical simulations.

Keywords: Electrical network, multiple junctions, intentional electromagnetic interference (IEMI), frequency responses.

1 Introduction

Recently, in modern society, intentional electromagnetic interference (IEMI) appears more frequently in threat analyses. Because of the sophistication of electrotechnical and electronic systems the harmfulness of malicious manipulation should be easily understood. Different groups and scholars have contributed in the past to this field (e.g. [1, 2]). Here, in this paper, we investigate the effects on the frequency response characteristics of different loads in networks with different structures as they are subjected to intentional electromagnetic interference (IEMI).

2 The BLT Equation

For a simple electrical network, as shown in Fig. 1, to solve the frequency responses for each load, the BLT approach [3, 4] is applied. In this simple network, we suppose that the length of the transmission line is L, with propagation constant γ and characteristic impedance Z_c. The load impedances are Z_{L1} and Z_{L2}, respectively. The excitation source consists of a lumped voltage (V_s) and current (I_s) source, located x_s from the left load.

The application of BLT equation is described as follows;

$$\begin{bmatrix} V_1^{\text{inc}} \\ V_2^{\text{inc}} \end{bmatrix} = \begin{bmatrix} 0 & e^{-\gamma L} \\ e^{-\gamma L} & 0 \end{bmatrix} \begin{bmatrix} V_1^{\text{ref}} \\ V_2^{\text{ref}} \end{bmatrix} + \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}, \qquad (1)$$

where the excitation vector is

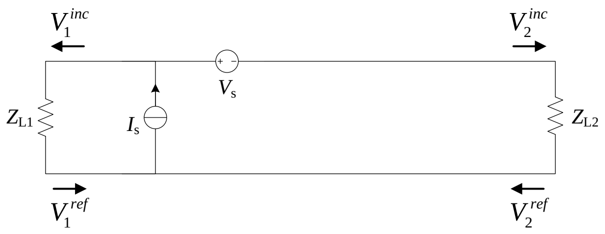


Figure 1. A simple electrical network.

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{2}\left(V_s - Z_c I_s\right) e^{-\gamma x_s} \\ \frac{1}{2}\left(V_s + Z_c I_s\right) e^{-\gamma (L - x_s)} \end{bmatrix}.$$

At the terminals, the reflected voltage can be expressed as

$$\begin{bmatrix} V_1^{\text{ref}} \\ V_2^{\text{ref}} \end{bmatrix} = \begin{bmatrix} \rho_1 & 0 \\ 0 & \rho_2 \end{bmatrix} \cdot \begin{bmatrix} V_1^{\text{inc}} \\ V_2^{\text{inc}} \end{bmatrix}, \qquad (2)$$

where ρ_1 and ρ_2 are the reflection coefficients, defined by

$$\rho_i = \frac{Z_{Li} - Z_c}{Z_{Li} + Z_c}, \ \ (i = 1, 2) .$$

Plugging (2) into (1), we obtain the vector of the incident voltages by

$$\begin{bmatrix} V_1^{\text{inc}} \\ V_2^{\text{inc}} \end{bmatrix} = \left[\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & e^{-\gamma L} \\ e^{-\gamma L} & 0 \end{bmatrix} \cdot \begin{bmatrix} \rho_1 & 0 \\ 0 & \rho_2 \end{bmatrix} \right]^{-1} \cdot \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}. \qquad (3)$$

The frequency response at each load is the superposition of the incident and reflected voltages

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} V_1^{\text{inc}} \\ V_2^{\text{inc}} \end{bmatrix} + \begin{bmatrix} V_1^{\text{ref}} \\ V_2^{\text{ref}} \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 \\ 0 & 1+\rho_2 \end{bmatrix} \cdot \left[\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & e^{-\gamma L} \\ e^{-\gamma L} & 0 \end{bmatrix} \cdot \begin{bmatrix} \rho_1 & 0 \\ 0 & \rho_2 \end{bmatrix} \right]^{-1} \cdot \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}. \qquad (4)$$

In addition, if TEM is the main mode of voltage wave propagation, then for any existing junctions in the electrical network, the reflection coefficients can be calculated according to the transmission line theory. If the transmission line parameters are the same for all branches of a junction (e.g. same type of cables used) and if the load connected to each branch is, electrically, far away from the junction, then the current is equally divided between the branches. For a junction with $N + 1$ branches, the reflection coefficient ρ^* and transmission coefficient T^* are respectively given by [5]

$$\rho^* = \frac{Z_c/N - Z_c}{Z_c/N + Z_c} = -\frac{(N-1)}{(N+1)} \tag{5}$$

$$T^* = 1 + \rho^* = \frac{2}{(N+1)} \tag{6}$$

3 Analysis of different types of network

To some extent, the complexity of an electrical network depends on the number of arbitrarily distributed junctions and branches. Besides, the characteristic impedances of the different transmission lines, branch lengths and load values are also factors. In this paper, we focus on the influence of the number of junctions and branches on the load voltages.

In Fig. 2, we enumerate seven types of electrical networks. In the analysis process, the commercial software EMEC [6] is applied to verify the calculation results. The line lengths, in meter, are given in the subfigures. All the transmission lines studied here were set to have the same characteristic impedance, $Z_c = 45\ \Omega$, but a complex impedance could be given. The values of the load impedances vary from 100 Ω to 600 Ω ascendingly in accordance with the label (#1 ~ #6), and the increment is 100 Ω. The value of the lumped excitation source is chosen to be $V_s = 100$ V, $I_s = 1$A, and we sweep the frequency from 1 Hz to 20 MHz. (Even though the model can handle frequencies between quasi DC and very high frequencies and also more complex input parameters).

For the network shown in Fig. 2a), the calculation results are given in Fig. 3. The results marked with either a circle or a triangle are computed based on the BLT equation, while the solid lines are computed by EMEC. In Fig. 2b) ~ Fig. 2d), the results calculated based on the adapted BLT equation, and by EMEC are given in Fig. 4. Here, the colored red curve, blue curve and black curve represent the frequency responses of load #1, load #2 and load #3, respectively. The value of the curve is the mean value of the results for three networks, and at the same time, we also give the corresponding standard deviation. It is easy to see that, at high frequencies, increasing the number of branches significantly affects the frequency responses of the loads, which are not located on the same branch as the excitation source.

In Fig. 2e) ~ Fig. 2g), we observe the effects of the number of junctions and branches. The calculation results are given in Fig. 5. In this case, the colored cyan curve represents the frequency responses of load #4, while others remain the same meaning (as given above for Fig. 2b) ~ Fig. 2d)). In contrast to the one-junction networks, the overall standard deviation is smaller for the networks with multiple junctions. For load #1 (red curve), the voltage response changes a little after inserting the junction between the two junctions shown in Fig. 2e), while load #2 (blue curve), load #3 (black curve) and load #4 (cyan curve) suffer relatively more in different frequencies. Besides, the extent of the effects they experience relies on the values of the loads, in other words, larger loads are more affected.

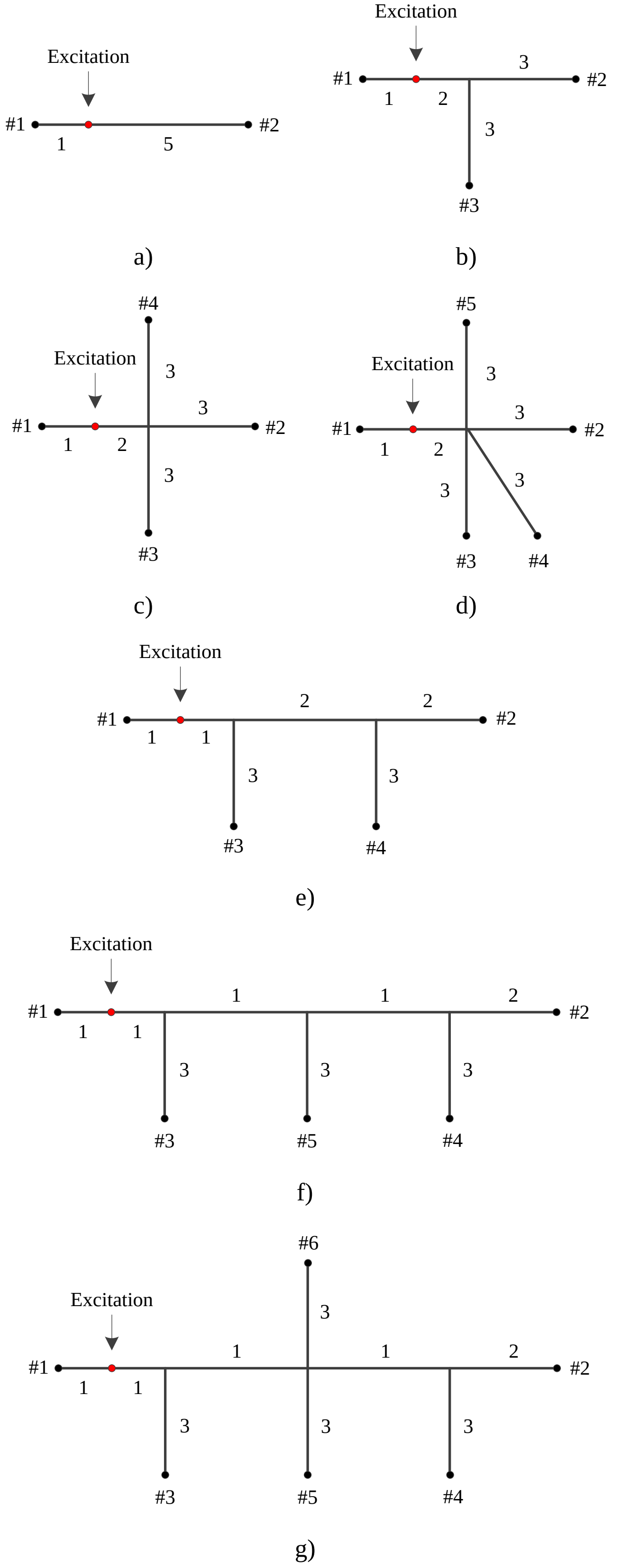


Figure 2. Different types of electrical networks.

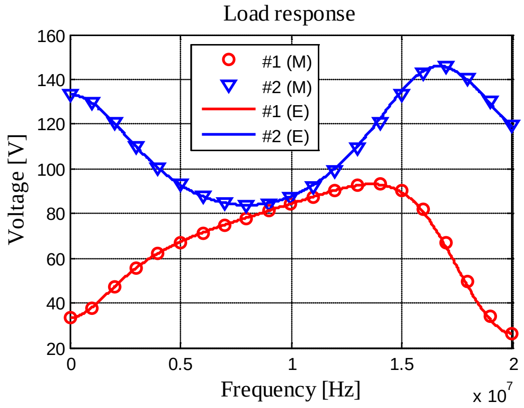
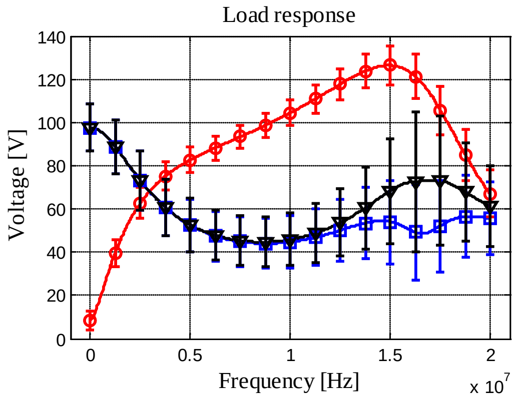
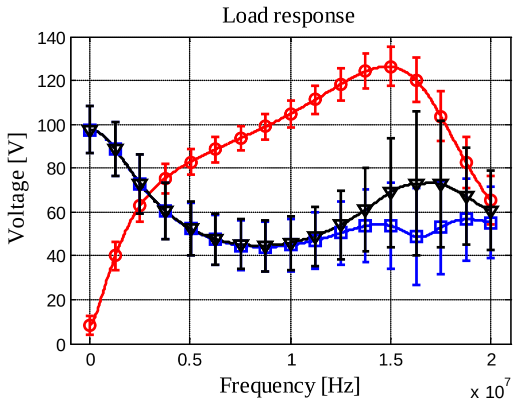


Figure 3. Results of the network shown in Fig. 2a).



a) MATLAB

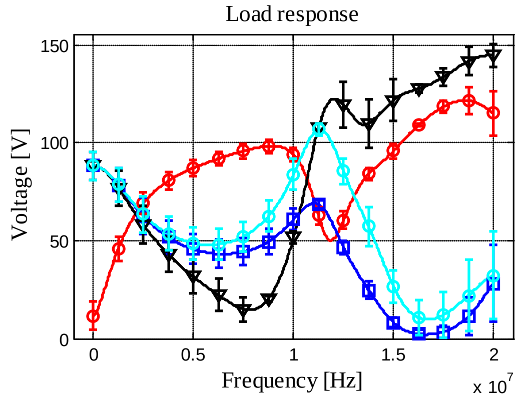


b) EMEC

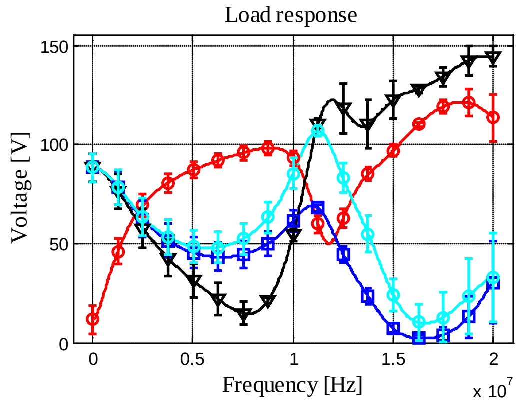
Figure 4. Results of one-junction networks.

4 Conclusions

In this paper, for the electrical networks that may suffer from IEMI attacks, we calculated the frequency responses of several different types of networks, and analyzed the effects of the number of junctions and branches. The results show that, increasing the number of branches at a junction has a great effect on the frequency responses of the loads connected to the different branches, while increasing the number of junctions does not. The calculation results employed in the analysis were verified by the commercial software EMEC, and they agree well with each other.



a) MATLAB



b) EMEC

Figure 5. Results of multi-junction networks.

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