System Electromagnetic Compatibility Analysis Method Based on Cascaded Multi-Port Networks

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***Abstract*—To address the challenges in efficiently modeling and simulating Electromagnetic Compatibility (EMC) for complex electrical and electronic systems, a system-level EMC analysis method based on cascaded multi-port network theory is proposed. According to the topological structure of the system, this method decomposes the complex system into multiple cascaded multi-port network modules, where electromagnetic energy transmission and coupling occur via ports. In this method, the Electromagnetic Interference (EMI) transfer characteristics of each module are described by the impedance matrix of its internal circuitry. The voltage and current coupling relationships at system ports are calculated using the cascaded impedance matrix of the multi-stage network combined with specific boundary conditions, thereby significantly simplifying the modeling and simulation process. Numerical validation performed on a three-stage cascaded system across the 10–100 MHz frequency band demonstrates that the proposed method achieves high fidelity. Compared with full-wave simulations, the maximum absolute error for the current response is limited to 0.7 mA (occurring at 10 MHz), and for the voltage response is merely 0.037 V, with the average current error maintained at approximately 0.1 mA. The relative error for both responses at critical ports consistently remains within 0.2%. Furthermore, both modeling complexity and calculation time are substantially reduced, providing a feasible technical approach for the EMC modeling and simulation of complex systems.**

Keywords-System-Level EMC; Multi-Port Network; Cascaded Network; Impedance Matrix; Electromagnetic Port; Electromagnetic Coupling

I. INTRODUCTION

With the increasing integration and complexity of modern electrical and electronic systems, the internal electromagnetic environment continues to deteriorate, leading to more intricate coupling paths. Wei Jixiang. and Wang Biao. investigated the anti-interference optimization and emission characteristics of smart cockpit electronic systems and AMT controllers in complex environments, respectively. Their work further confirms that implementing EMC forward design to eliminate potential electromagnetic interference (EMI) hazards during the design phase has become crucial for ensuring system reliability and safety.

System-level simulation is a critical approach for EMC forward design; however, constructing practical simulation models presents severe challenges. Since modern systems typically exhibit characteristics such as wide frequency bands and multi-scale features, directly applying electromagnetic computational methods to discretize and solve the entire system results in a drastic increase in the number of computational meshes. Liu Xingjiang, when simulating transmission lines combined with multiple vias, pointed out that the presence of fine structures imposes extremely high demands on modeling accuracy and computational resources. Therefore, exploring modeling methods that reduce model complexity without compromising accuracy has been a focal point of research for scholars worldwide.

In today's complex electronic systems, cables not only connect various devices but also serve as significant channels for electromagnetic interference propagation. However, system cables are often long and follow complex, irregular paths. When using traditional three-dimensional full-wave electromagnetic simulation software (such as HFSS or CST) for modeling, a significant scale disparity arises: the physical dimensions of cables often reach the meter scale, while the characteristic dimensions of other system structures are mostly at the millimeter scale or smaller. This disparity creates substantial difficulties for mesh generation. To ensure computational accuracy, fine meshing of cable regions is usually required, which significantly expands the calculation scale, drastically increases computation time and memory consumption, and may even lead to insufficient computational resources. Consequently, in practical system-level simulations, engineers often simplify cables—for instance, by ignoring their actual routing or equivalenting them as straight-line models. While such simplifications reduce simulation complexity, they often lead to significant deviations between simulation results and actual conditions.

Commercial equipment, widely used in engineering systems, typically exists in the form of a "black box." Suppliers usually provide only port S-parameters or simple functional models, without offering internal circuit diagrams. Under these circumstances, establishing a complete physical model is impossible. Therefore, it is necessary to adopt a method that can directly utilize port test data (such as Z-parameters or S-parameters) for modeling. This approach does not rely on the internal structural information of the device; instead, it characterizes electromagnetic properties by describing the voltage and current relationships at the ports, making it well-suited for analyzing complex systems composed of various "black box" modules.

To address the challenges of complex system modeling, Baum et al established the theoretical framework of Electromagnetic Topology (EMT). By employing a topological approach that divides complex systems into different shielding levels and sub-regions, they proposed the BLT equation. However, as the system scale expands, the dimension of the super-matrix in the traditional BLT equation increases exponentially, leading to difficulties in matrix inversion. Although scholars such as Sun Dongyang, Dai Hanzhe, and Zhang Xi have extended electromagnetic topology to three dimensions by combining it with numerical algorithms like FDTD, they still face issues of massive resource consumption and complex interface handling when dealing with multi-level, multi-subsystem heterogeneous models. Feng Bolun. systematically summarized the application of Kron's method in the EMC field, pointing out that this method can effectively reduce the dimensions of system-level calculations through tensor transformation. However, the physical significance of Kron's method is not intuitive, which limits its general applicability in engineering.

In recent years, multi-port networks have garnered significant attention due to their standardized parameter description capabilities. Sekine T et al. proposed using scattering parameters (S-parameters) to characterize coupling properties, achieving decoupling analysis through S/Z parameter conversion. Mou et al. established a cascaded model based on multi-port equivalent circuits for electromagnetic emission systems. In terms of specific applications, Ma Mingming deeply investigated the multi-port parameter characteristics of key RF front-end circuits, while Huang Xin combined the Method of Moments (MoM) with multi-port network theory to effectively solve crosstalk calculation problems in wayside signal cables. Additionally, Li Mengxia et al. proposed an N-terminal equivalent modeling method based on discrete state-space models for power electronic equipment, and Padma Priya et al. explored methods for calculating the parameter matrices of composite multi-port networks. Despite significant progress, existing methods mostly focus on using "black-box" S-parameters or equivalent circuits to characterize subsystems, often overlooking the voltage and current constraint relationships between sub-modules within the cascaded network.

In summary, existing methods suffer from low computational efficiency and unclear definitions of port coupling relationships when dealing with complex systems characterized by cascading. In view of this, this paper proposes a system EMC analysis method based on cascaded multi-port networks. This method utilizes Z-matrices to describe cascaded multi-port networks, segmenting the complex system into multiple cascaded multi-port network modules for solution. By establishing precise port connection models and constructing the current-voltage constraint relationships between sub-modules, the method enables the efficient calculation of the EMI transfer characteristics of the entire cascaded multi-port network.

II. NETWORK MODEL

A. Multi-Port Networks and Their Characteristic Parameters

The EMC analysis of complex electronic systems fundamentally entails the study of the coupling, transmission, and dissipation processes of electromagnetic energy among different subsystems. In system-level EMC analysis, the external electromagnetic interaction interfaces of components—whether cable bundles, PCBs, or functional modules—can all be treated as equivalent to ports. Consequently, complex electromagnetic coupling problems can be abstracted into a cable multi-port network model.

For a network possessing N ports, its port characteristics can be described by the Z-matrix (Impedance Matrix), as illustrated in Figure 1. The Z-matrix is an intrinsic property of the multi-port network; it depends solely on the network's internal topological structure, dielectric parameters, and physical dimensions, and is independent of external load impedances, source impedances, or the magnitude of excitation sources. This implies that regardless of variations in external connecting cables or terminal devices, the Z-matrix remains constant provided the system itself remains unaltered. This characteristic renders the Z-matrix an ideal parameter for characterizing the electromagnetic properties of complex systems, thereby providing a theoretical foundation for modular modeling and cascade analysis.

Consider an N-port network where the voltage at the i-th port is denoted as U_i and the injected current as I_i .According to Ohm's law, the relationship between the voltage and current at each port of the network can be expressed as:

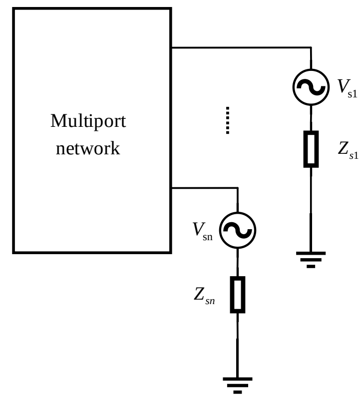


Figure 1. Schematic diagram of a multi-port network

$$\boldsymbol{U} = \boldsymbol{ZI} \tag{1}$$

The expanded matrix form can be expressed as:

$$\begin{bmatrix} U_1 \\ U_2 \\ \vdots \\ U_N \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1N} \\ Z_{21} & Z_{22} & \cdots & Z_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{N1} & Z_{N2} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} \tag{2}$$

The impedance matrix (Z-matrix) serves as the core parameter for describing the characteristics of multi-port networks. Each element within the matrix holds a distinct electromagnetic physical meaning. A deep understanding of these physical meanings aids in revealing the electromagnetic coupling mechanisms of the system.

The elements on the main diagonal of the matrix characterize the self-impedance of the ports. These parameters reflect the intrinsic circuit characteristics of the ports themselves. Their magnitudes primarily depend on the internal structural characteristics and the parameters of energy storage elements within the port.

The off-diagonal elements of the matrix characterize the mutual impedance between ports. These parameters directly describe the coupling capability of electromagnetic energy between different ports.

A larger value of mutual impedance indicates a stronger coupling effect between ports, meaning that interference signals can easily transmit from one port to another through this path. Conversely, a smaller mutual impedance value implies good electromagnetic isolation between the ports. For a linear passive network, the Z-matrix exhibits symmetry, indicating that the transmission of electromagnetic interference between ports is reciprocal. Utilizing this characteristic can reduce the computational load of parameters by half, thereby significantly improving the analysis efficiency of complex networks.

The interference source ports are first identified. Both the interference source ports and the sensitive ports are modeled as Thevenin equivalent circuits. Assuming there are k interference source ports in the network, the equivalent interference voltage source vector is defined $\mathbf{V}_S = [V_{S,1}, V_{S,2}, ..., V_{S,k}]^T$.

The impedance of each port in the network is represented by a matrix, which is a diagonal matrix, describing the equivalent impedance of each individual port.

Consequently, for the entire system, the external connection conditions based on the ports are given by:

$$\boldsymbol{U} = \boldsymbol{V}_s - \boldsymbol{Z}_s \cdot \boldsymbol{I} \tag{3}$$

Here, U and I represent the vectors of the system port voltages and currents, respectively. V_s denotes the equivalent voltage vector of the interference sources, and Z_s denotes the equivalent output impedance of the ports.

Based on the above two equations describing the system:

$$\begin{aligned} \boldsymbol{U} &= \boldsymbol{Z} \cdot \boldsymbol{I} \\ \boldsymbol{U} &= \boldsymbol{V}_s - \boldsymbol{Z}_s \cdot \boldsymbol{I} \end{aligned} \tag{4}$$

By simplifying the above equations, the port voltage U and port current I are derived as:

$$\begin{aligned} \boldsymbol{U} &= (\boldsymbol{Z} + \boldsymbol{Z}_s)^{-1} \cdot \boldsymbol{Z} \cdot \boldsymbol{V}_s \\ \boldsymbol{I} &= (\boldsymbol{Z} + \boldsymbol{Z}_s)^{-1} \cdot \boldsymbol{V}_s \end{aligned} \tag{5}$$

The above derivation demonstrates that the computational method based on the Z-matrix effectively separates the internal coupling mechanisms of the system from its external boundary conditions. In practical applications, this implies that when external loads vary, there is no need to repeat full-wave simulations or measurements for the complex system.

B. *Cascaded Multi-Port Network Model*

In practical complex systems, the overall system is often composed of multiple functional modules connected according to a specific topological sequence. While the impedance matrix model for a single module was established in the previous section, a core issue in system-level analysis remains: how to derive the overall equivalent Z-matrix of the entire cascaded link based on the Z-matrices of individual sub-modules.

Consider the most fundamental case of two cascaded multi-port networks, as illustrated in Figure 2.

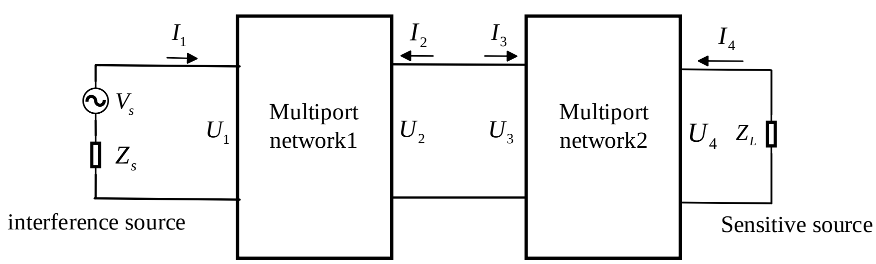


Figure 2. Schematic diagram of two cascaded networks

Assume that the output ports of Network 1 are connected to the input ports of Network 2. According to circuit topology theory, the connecting ports must satisfy the constraint conditions imposed by Kirchhoff's laws, namely, voltage continuity and current continuity:

$$\begin{aligned} U_2 &= U_3 \\ I_2 &= -I_3 \end{aligned} \tag{6}$$

Assume there are two networks, Network 1 and Network 2, with their impedance matrices given by:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11}^{(1)} & Z_{12}^{(1)} \\ Z_{21}^{(1)} & Z_{22}^{(1)} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} Z_{11}^{(2)} & Z_{12}^{(2)} \\ Z_{21}^{(2)} & Z_{22}^{(2)} \end{bmatrix} \begin{bmatrix} I_3 \\ I_4 \end{bmatrix} \tag{8}$$

Based on the constraint conditions at the connecting ports, the overall equivalent impedance matrix of the cascaded network is derived through variable elimination $\mathbf{Z}_{eq}$ as:

$$\boldsymbol{Z}_{eq} = \begin{bmatrix} Z_{11}^{(1)} - Z_{12}^{(1)} A^{-1} Z_{21}^{(1)} & Z_{12}^{(1)} A^{-1} Z_{12}^{(2)} \\ Z_{21}^{(2)} A^{-1} Z_{21}^{(1)} & Z_{22}^{(2)} - Z_{21}^{(2)} A^{-1} Z_{12}^{(2)} \end{bmatrix} \tag{9}$$

Where the intermediate impedance matrix $A = Z_{22}^{(1)} + Z_{11}^{(2)}$.

The above conclusion can be generalized to complex systems composed of N cascaded sub-modules. A recursive algorithm is employed to efficiently calculate the overall characteristic parameters of the system, as shown in Figure 3.

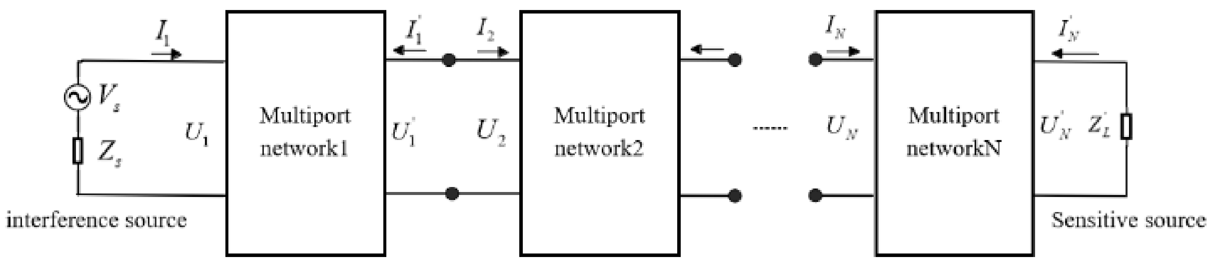


Figure 3. Schematic diagram of the cascaded network

Here, the Z-matrix representation for each network is identical. Let the Z-matrix of the k-th network be denoted as:

$$\boldsymbol{Z_k} = \begin{bmatrix} \boldsymbol{A_k} & \boldsymbol{B_k} \\ \boldsymbol{C_k} & \boldsymbol{D_k} \end{bmatrix} \tag{10}$$

Assume $\mathbf{Z}^{(k)}$ denote the equivalent impedance matrix resulting from the cascading of the first k networks, with its block form expressed as:

$$\boldsymbol{Z}^{(\boldsymbol{k})} = \begin{bmatrix} \boldsymbol{A}^{(\boldsymbol{k})} & \boldsymbol{B}^{(\boldsymbol{k})} \\ \boldsymbol{C}^{(\boldsymbol{k})} & \boldsymbol{D}^{(\boldsymbol{k})} \end{bmatrix} \tag{11}$$

When the (k+1)-th network is introduced, the preceding k networks are treated as a single entity, forming a two-stage cascaded model with the (k+1)-th network. The intermediate impedance matrix at the junction of the first k stages and the (k+1)-th stage is defined as $\mathbf{S}^{(k)} = \mathbf{D}^{(k)} + \mathbf{A}_{k+1}$. By applying the two-stage cascade formula, the equivalent impedance matrix parameters for the (k+1)-stage system can be recursively derived as follows:

$$\begin{aligned} \mathbf{A}^{(k+1)} &= \mathbf{A}^{(k)} - \mathbf{B}^{(k)} \mathbf{S}^{(k)} \mathbf{C}^{(k)} \\ \mathbf{B}^{(k+1)} &= \mathbf{B}^{(k)} \mathbf{S}^{(k)} \mathbf{B}_{k+1} \\ \mathbf{C}^{(k+1)} &= \mathbf{C}_{k+1} \mathbf{S}^{(k)} \mathbf{C}^{(k)} \\ \mathbf{D}^{(k+1)} &= \mathbf{D}_{k+1} - \mathbf{C}_{k+1} \mathbf{S}^{(k)} \mathbf{B}_{k+1} \end{aligned} \tag{12}$$

By applying the recursive relationship described above, the calculation proceeds stage-by-stage from the first module up to the N-th module. Ultimately, the total impedance matrix $\boldsymbol{Z}^{(N)}$, which describes the entire complex cascaded system, is obtained:

$$\boldsymbol{Z}^{(N)} = \begin{bmatrix} \mathbf{A}^{(N-1)} - \mathbf{B}^{(N-1)}\mathbf{S}^{(N-1)}\mathbf{C}^{(N-1)} & \mathbf{B}^{(N-1)}\mathbf{S}^{(N-1)}\mathbf{B}_N \\ \mathbf{C}_N\mathbf{S}^{(N-1)}\mathbf{C}^{(N-1)} & \mathbf{D}_N - \mathbf{C}_N\mathbf{S}^{(N-1)}\mathbf{B}_N \end{bmatrix} \quad (13)$$

Where $\mathbf{S}^{(N-1)} = \mathbf{D}^{(N-1)} + \mathbf{A}_N$ represents the system intermediate impedance matrix, serving to facilitate the expression of the total impedance matrix of the cascaded system.

After calculating the Z-matrix for the N cascaded multi-port networks, regardless of the complexity of the internal cascade structure, the entire system can be equivalently represented as a generalized multi-port network with input and output ports.

$$\begin{bmatrix} \boldsymbol{V}_{in} \\ \boldsymbol{V}_{out} \end{bmatrix} == \begin{bmatrix} \boldsymbol{Z}_{11}^{(N)} & \boldsymbol{Z}_{12}^{(N)} \\ \boldsymbol{Z}_{21}^{(N)} & \boldsymbol{Z}_{22}^{(N)} \end{bmatrix} \begin{bmatrix} \boldsymbol{I}_{in} \\ \boldsymbol{I}_{out} \end{bmatrix} \quad (14)$$

The generalized boundary conditions are determined by the impedances of the interference sources and the sensitive loads of the cascaded multi-port network. Assuming that the interference sources are modeled as Thevenin equivalent circuits, the matrix form of the generalized boundary conditions for the system's external connections is constructed as follows:

$$\begin{bmatrix} \boldsymbol{V}_{in} \\ \boldsymbol{V}_{out} \end{bmatrix} = \begin{bmatrix} \boldsymbol{V}_S \\ 0 \end{bmatrix} - \begin{bmatrix} \boldsymbol{Z}_S & 0 \\ 0 & \boldsymbol{Z}_L \end{bmatrix} \begin{bmatrix} \boldsymbol{I}_{in} \\ \boldsymbol{I}_{out} \end{bmatrix} \quad (15)$$

Here, the open-circuit voltage vector is denoted as V_s the internal impedance matrix as Z_s and the sensitive load as Z_L is defined by its impedance matrix.

Through simplification, the responses for port current and port voltage are derived as:

$$\begin{aligned} \boldsymbol{I} &= \left(\boldsymbol{Z}^{(N)} + \boldsymbol{Z}_{ext}\right)^{-1} \cdot \boldsymbol{V}_{exc} \\ \boldsymbol{U} &= \boldsymbol{Z}^{(N)} \cdot \left(\boldsymbol{Z}^{(N)} + \boldsymbol{Z}_{ext}\right)^{-1} \cdot \boldsymbol{V}_{exc} \end{aligned} \quad (16)$$

Where $\mathbf{V}_{exc} = [\mathbf{V}_S, \mathbf{0}]^T$ denotes the external excitation source vector, and $\mathbf{Z}_{ext} = \mathrm{diag}(\mathbf{Z}_S, \mathbf{Z}_L)$ represents the external impedance matrix.

For components with known and simple physical structures (such as connectors and transmission lines), electromagnetic simulation methods can be adopted. Full-wave simulation software is utilized to establish physical models and perform calculations. The simulation results can be directly extracted as Z-matrix data.

For "black box" devices with unknown internal structures or complex modules, physical measurement methods can be employed. The Vector Network Analyzer (VNA) serves as the standard equipment for acquiring such data.

Since high-frequency measurement equipment typically outputs scattering parameters (S-parameters), matrix parameter conversion is required. Based on microwave network theory, the standard formula for converting S-parameters to Z-parameters is as follows:

$$\boldsymbol{Z} = \boldsymbol{Z}_0(\mathrm{E}+\mathrm{S})\,(\mathrm{E}-\mathrm{S})^{-1} \quad (17)$$

Through this conversion, both measured data and simulation data are unified into the Z-matrix format.

In summary, this method not only achieves the decoupling of the system's internal structure from the external environment but also provides efficient theoretical support for the rapid prediction and mechanism analysis of EMC in complex cascaded systems under variable load conditions.

III. CALCULATION OF ELECTROMAGNETIC INTERFERENCE COUPLING

To validate the effectiveness and accuracy of the aforementioned EMC analysis method based on cascaded multi-port network theory, a simulation example of a typical electronic system composed of multiple cascaded modules is constructed in this paper. As shown in Figure 4, the physical structure of the system consists of three parts connected in series: Metal Enclosure 1, a connecting cable, and Metal Enclosure 2.

In this topology, the system is decomposed into three independent multi-port sub-networks:

Housing 1: Contains two input ports and internal ports connected to the connecting cable.

Connecting Cable: Acts as a transmission channel connecting the two enclosures.

Housing 2: Contains ports connected to the connecting cable and two output ports of the system.

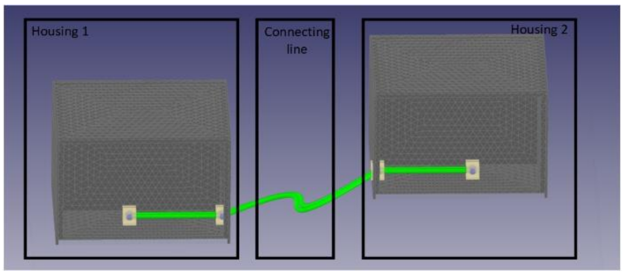


Figure 4. Cascaded network model

In the simulation settings, the frequency range is set to 10–100 MHz. The impedance matrices for each module are obtained, and the three sub-networks are cascaded using the recursive cascade formula proposed in Eq. (13) to calculate the total equivalent impedance matrix describing the input-output characteristics of the entire system.

After obtaining the total impedance matrix of the entire system, the EMI responses of the ports are calculated by incorporating the boundary conditions of the external circuit. The port configuration is shown in Figure 5. A voltage source with an amplitude of 5 V and an internal resistance of 1 Omega is applied to the excitation source port, while all other ports are terminated with 50 Omega matched loads with no active excitation.

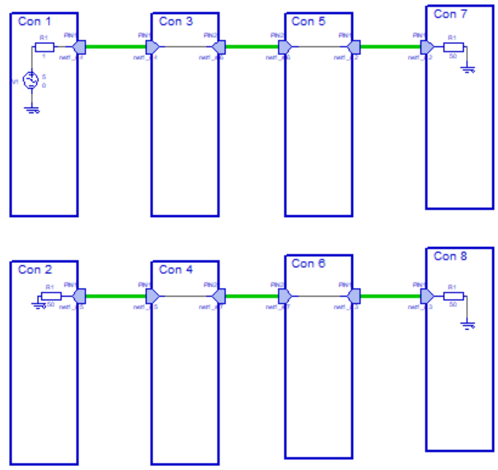
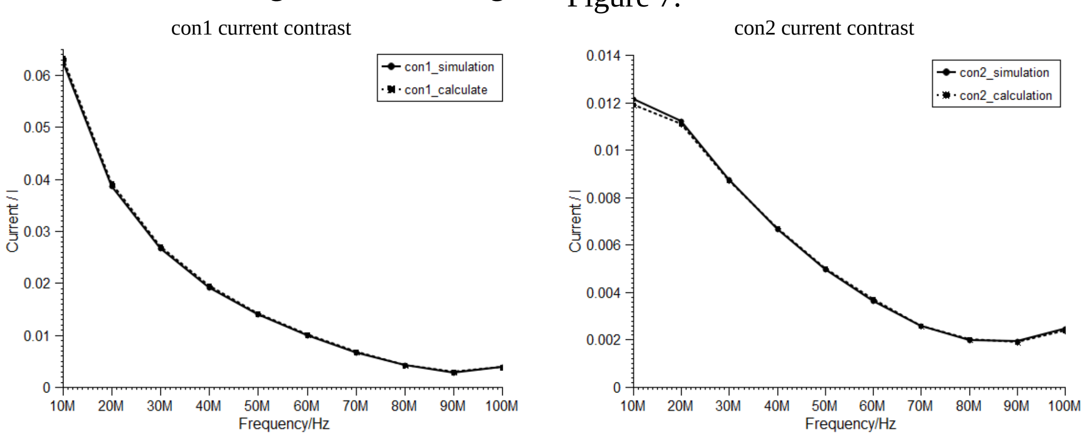


Figure 5. Cascaded port configuration

Based on the analytical expression derived from Eq. (16), utilizing the external excitation source vector $\mathbf{V}_{exc} = [5, 0, 0, 0]^T$ and the external impedance matrix $\mathbf{Z}_{ext} = \text{diag}(1, 50, 50, 50)$ the numerical values of the voltage and current responses at each system port can be rapidly obtained through matrix operations.

To validate the accuracy of the cascaded matrix calculation method proposed in this paper, the calculated results are compared with the direct results obtained from the full-wave simulation of the overall structure, as shown in Figure 6 and Figure 7.



(a) (b)

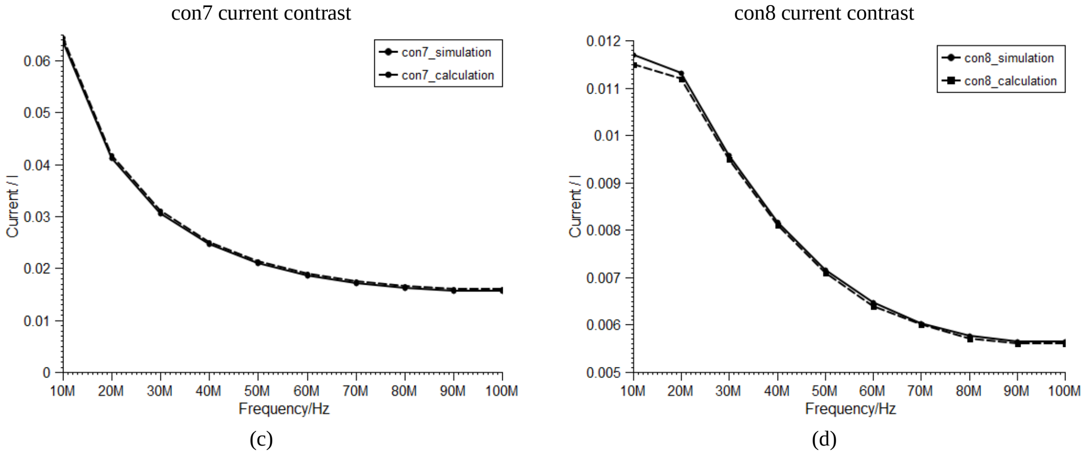


Figure 6. Comparison of port current simulation data and cascaded calculation data

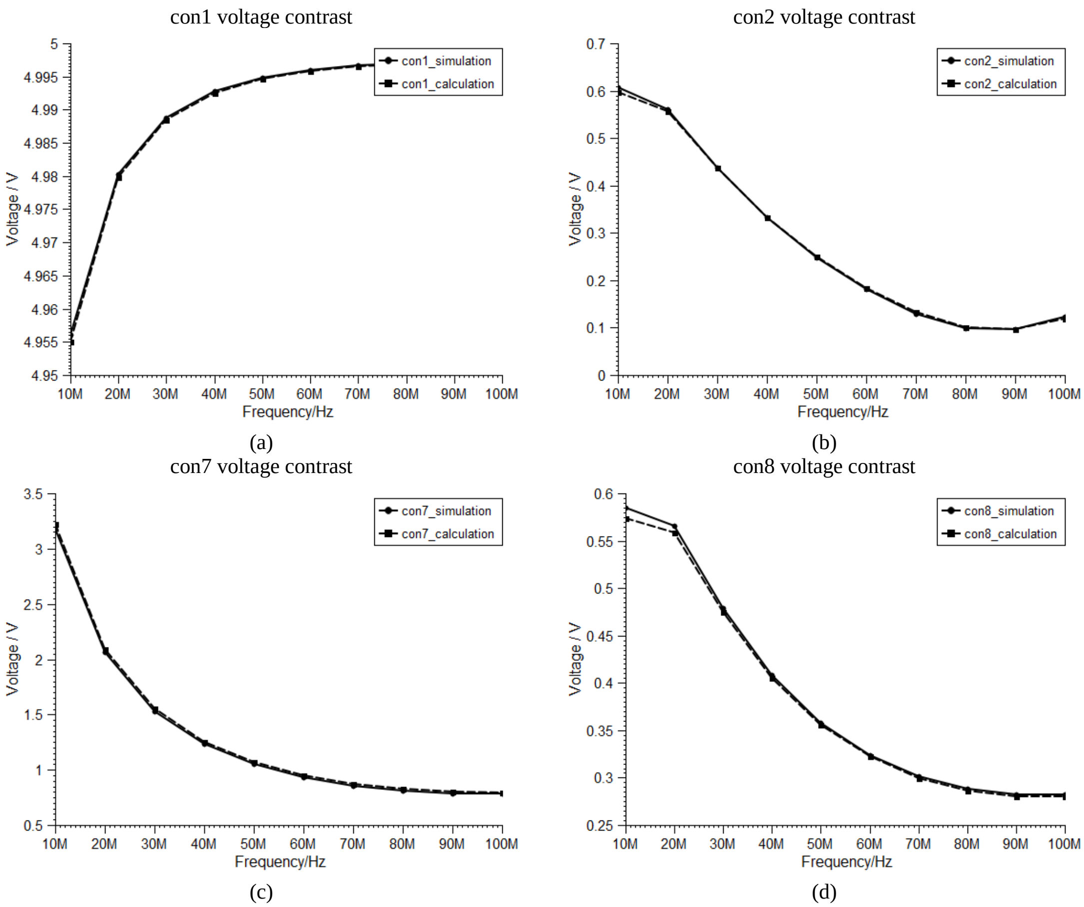


Figure 7. Comparison of port voltage simulation data and cascaded calculation data

Figure 6 (a)-(d) and Figure 7 (a)-(d) illustrate the comparisons of current and voltage responses, respectively, at ports con1, con2, con7, and con8. A comparison between the simulation and the cascaded matrix calculation was conducted on the critical ports of a three-stage cascaded system (Enclosure 1 - Cable - Enclosure 2) within the 10 MHz to 100 MHz frequency band. The curves in Figures 6 and 7 visually demonstrate a high degree of consistency between the results obtained by the two methods. The curves representing "full-wave simulation data" and "cascaded calculation data" overlap almost perfectly, both in the stable response regions at lower frequencies and near potential resonance points at higher frequencies. This indicates that the recursive cascade algorithm based on the Z-parameter matrix can accurately reproduce the electromagnetic energy transmission characteristics of complex structures involving cables and enclosures, thereby verifying the correctness of the port voltage-current constraint relationships in multi-stage network analysis.

Based on the above data, the error values between the simulation method and the cascaded calculation are calculated, as shown in Figure 8. and Figure 9.

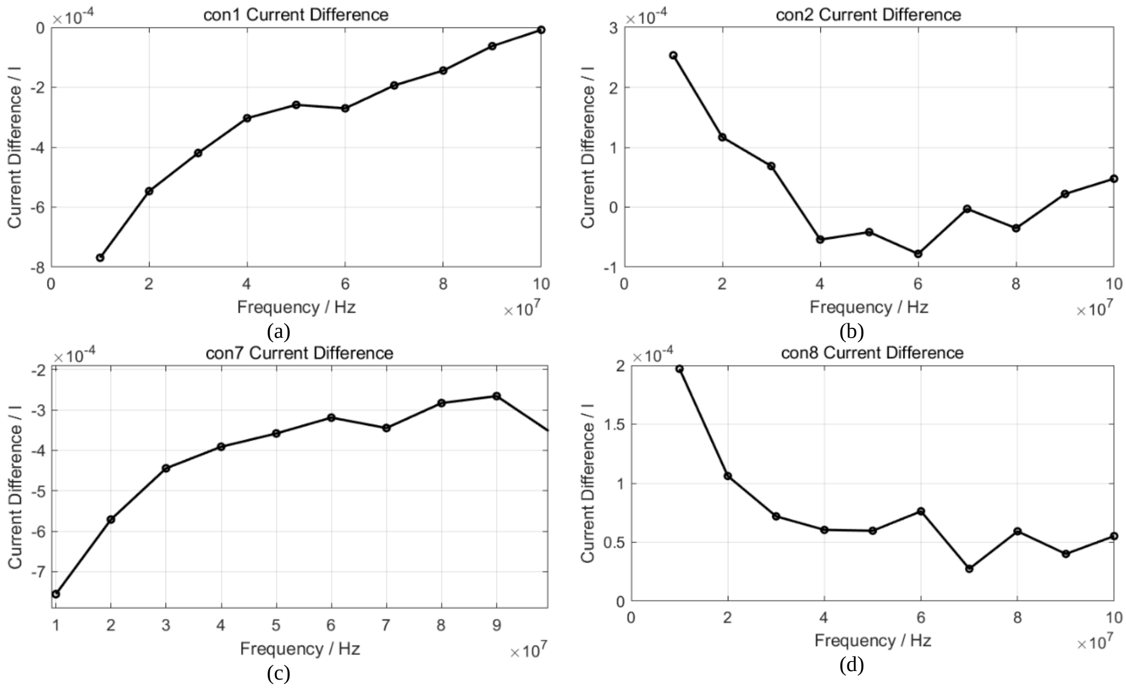


Figure 8. Data plot of port current difference

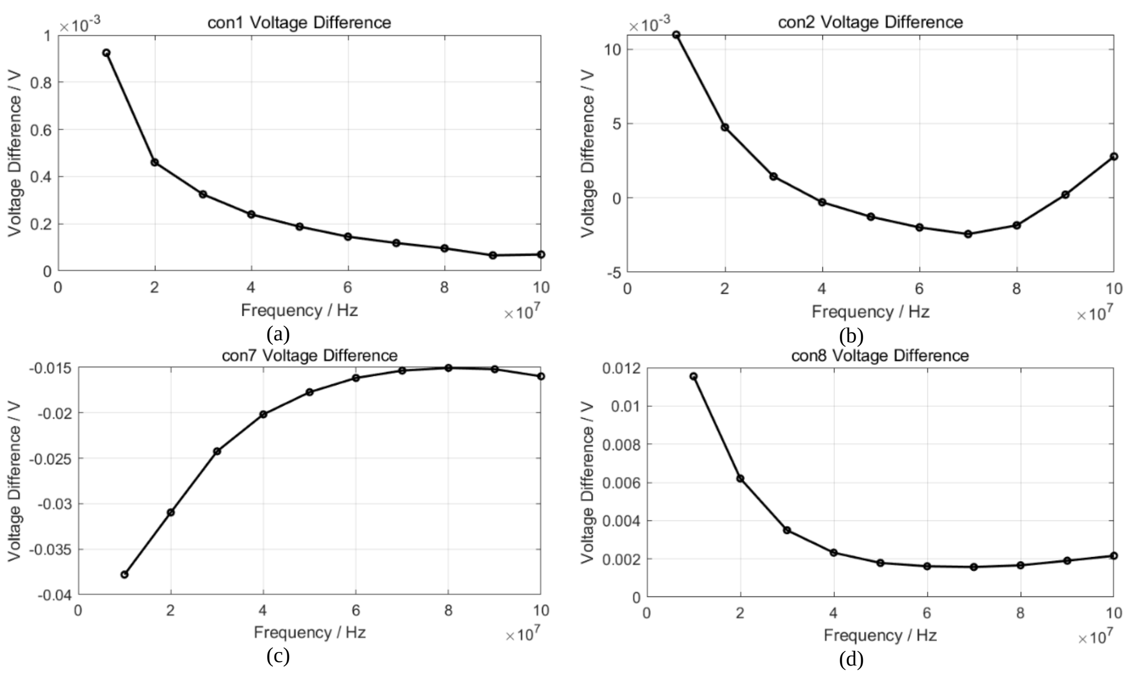


Figure 9. Data plot of port voltage difference

Figures 8(a)–(d) and 9(a)–(d) quantitatively illustrate the deviation between the calculated results and the full-wave simulation results for port current and voltage, respectively. These figures verify the algorithmic precision across the entire 10–100 MHz frequency band. Detailed numerical analysis reveals that the error is strictly controlled within a negligible range for all observed ports (con1, con2, con7, and con8). Specifically, the maximum absolute error for the current response is limited to 0.7 mA (occurring at 10 MHz), while the peak absolute error for voltage is merely 0.037 V. For the vast majority of frequency points, the deviation is far below these peaks, with the average current error maintained at a magnitude of approximately 0.1 mA. Overall, the maximum relative error is consistently kept within 0.2%. This high level of fidelity demonstrates that the proposed method significantly reduces mesh complexity and computational resource consumption without compromising calculation accuracy. Consequently, provided that the port characteristics of individual sub-modules are accurately extracted, the matrix cascade algorithm can precisely predict the electromagnetic response of complex systems, meeting the rigorous requirements of system-level EMC forward design.

IV. Conclusions

This paper presents an EMC analysis method based on cascaded multi-port network theory, which achieves the decoupling calculation of the complex system's internal topology from its external loads by utilizing Z-matrices and a recursive algorithm. Comparative case studies demonstrate that the calculation error for key port responses is less than 0.2%. This method significantly enhances simulation efficiency while maintaining high accuracy, offering substantial practical engineering value.

This study is primarily limited to the analysis of conducted interference in linear passive networks. Impedance modeling for nonlinear devices, time-varying topologies, and high-frequency heterogeneous systems remains to be investigated in depth, and the coverage of spatial radiation coupling mechanisms is currently insufficient. Future work will focus on the equivalent representation of nonlinear multi-port networks and the incorporation of time-domain algorithms to accommodate the analysis requirements of wider frequency bands and complex electromagnetic environments.

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