Design of a Transmission-line Transformer in the Construction of Strong Electromagnetic Field

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Abstract. Principle and design process of a transmission-line transformer are introduced in this paper. This design is mainly used to solve the problem of antenna impedance matching in the process of constructing strong electromagnetic environment, in order to improve the space radiation efficiency of low frequency band and realize the effective construction of strong electromagnetic environment.

1. Introduction
In recent years, with the breakthrough of very large scale integration technology, high-power communication equipment, radar and jamming facilities have been widely used in military and civilian fields, and the electromagnetic environment faced by various electronic equipment and systems has become more complex. In such a complex and varied electromagnetic environment, the ability to survive and work effectively is an important indicator for measuring and evaluating the electromagnetic compatibility of electrical equipment and systems. GJB151B-2103, GJB1389A-2005 and GJB8848-2016 standards have been published and implemented for the above-mentioned equipment-level and system-level evaluation of complex electromagnetic environment capability in China. Through the construction of High intensity radiation field (HIRF), the testing and evaluation of equipment and large-scale system in complex electromagnetic environment can be achieved, and the foundation of testing and evaluation is the construction of field.

Strong electromagnetic field is usually constructed by amplifying the signal through high power amplifier and radiating by the antenna into space to form the required field strength of the space electromagnetic field. In the high frequency range of ≥1GHz, the antenna impedance is well matched, and 80% of the energy can be used for the construction of the space electromagnetic field. When the frequency is less than 1 GHz, especially when the frequency is less than 100 MHz, the antenna impedance varies greatly, which makes the space radiation echo larger and the radiation efficiency greatly lower, which makes it difficult to construct the strong electromagnetic field in the low frequency band, even the equipment may be damaged. In view of the above requirements, this paper proposes a transmission-line transformer method to improve the impedance matching of low-frequency radiation antenna, effectively enhance the space radiation efficiency of low-frequency band, in order to achieve the construction of strong electromagnetic field.

2. Principle analysis
In the construction of low-frequency strong electromagnetic field, the impedance of the radiation antenna varies greatly from 10 kHz to 100 MHz, which results in strong reflection power and seriously
restricts the simulation of strong electromagnetic environment signal, when high-power signal is input. In view of this problem, two main reasons are proposed.

2.1. Analysis of antenna impedance varying with frequency
The impedance of the antenna has a great relationship with the frequency. The impedance of radiation antenna contains reactance component, which is a function of frequency. Therefore, the matching of antenna is to eliminate the reactance component in the input impedance of antenna and make its resistance as close as possible to the characteristic impedance of feeder.

2.2. Analysis of antenna characteristics changing with temperature
Radiation antenna, the thin film resistor load composed of parallel transmission lines and tantalum nitride releases a lot of heat, and expands due to heating, resulting in deformation, which makes the electromagnetic performance of the radiation antenna change in varying degrees, when the radiation antenna works. When the power reaches 1000W, the temperature of tantalum nitride rises sharply, impedance increases, and standing wave ratio of radiation antenna voltage increases correspondingly, which leads to the decrease of radiation efficiency.

The simulation results show that the frequency and power have great influence on the impedance, standing wave and radiation efficiency of the radiation antenna. Therefore, this paper is focus on the analysis between antenna and frequency, and apply the theory of transmission-line transformer to design and improve the impedance matching of antenna, in order to realize the construction of strong electromagnetic field in low frequency band.

3. Design of transmission-line transformer
In the construction of low frequency strong electromagnetic field, the echo power of antenna is greatly increased with the matching problem between high power amplifier and antenna. For this problem, the best solution is to use impedance matching network, while the matching network to cover the entire frequency range from 10kHz to 100MHz. In this case, the transmission-line transformer theory is introduced.

Transmission-line transformer, is a new component formed by the combination of transmission line and transformer theory. Signal energy is transmitted by transmission line or transformer according to the different frequency of excitation signal. Therefore, the transmission-line transformer has good broadband transmission characteristics. Compared with ordinary transformers, transmission-line transformers are characterized by extremely wide operating frequency band, the upper limit frequency is as high as 1GHz and the frequency coverage factor (ratio of upper limit frequency to lower) reaches 10000. While the upper limit frequency of the ordinary high-frequency transformer can only reach tens of MHz, and the frequency coverage factor is only hundreds. Since the transmission-line transformer has good high and low frequency characteristics, and have characteristics of small size, easy to produce, to withstand high power, low loss, is a powerful means to build strong low frequency electromagnetic fields.

In this paper, the principle, structure, material design and test simulation of transmission-line transformer are introduced.

3.1. Working principle
Since high frequency characteristics of ordinary transformers are poor, in order to improve the low frequency response, it is necessary to increase the number of primary coil turns, that is, to increase inductance, which leads to the increase of distributed capacitance and deterioration of its high frequency response. The characteristics of high and low frequency can be greatly improved by using high permeability core. But the core has its best working frequency band, the loss of the core increases and the transmission efficiency decreases, when the frequency band is higher. Meanwhile, due to the influence of distributed capacitance and leakage inductance, even ordinary transformers with high
permeability cores may not effectively transmit broadband signals in higher frequency bands, while this problem can be solved effectively by the transmission-line transformer.

The transmission-line transformer is composed of a ring core and a transmission line. Because the two wires are close together, the capacitance between wires at any point is larger and distributed uniformly throughout the line. The conductor is wound around the high permeability magnetic core, which makes the inductance of each small section of the conductor larger and evenly distributed. Thus, the transmission line can be seen as a coupling chain composed of many inductances and capacitors. The transmission-line transformer uses the coupling between these inductances and capacitors to complete the energy transmission. Therefore, in the transmission-line transformer, the distributed capacitance between the two lines will not affect the high frequency energy transmission, but also is a necessary condition for electromagnetic energy conversion. The influence of core loss on signal transmission will be greatly reduced, due to electromagnetic wave mainly propagates in the medium between wires. So the working frequency of transmission-line transformer can be greatly improved.

The current passing through the two coils is equal in magnitude and opposite in direction when the load matches, as shown in Figure 1. The magnetic field generated in the core just cancels each other, so no power loss in the core, which is great advantageous to the working mode of transmission line. Port 2 and 3 are grounded, the signal voltage $V_1$ is added to the beginning and end of the transmission line, and is also applied to the ports of the coils 1, 2, and the load is also connected to the port 3 and 4 of the coil, as shown in Figure 2, the transmission line The transformer works as a transformer at the same time. Due to electromagnetic induction, the load is also obtained with the same size and the opposite phase of the $V_1$ voltage $V_2$. Meanwhile, the voltages at port 1, 3, 2 and 4 are still $V_1$ and $V_2$ respectively, which also ensures the voltage relationship of the transmission line working mode.

![Figure 1. Working principle of transmission line.](image1)

![Figure 2. Working principle diagram of transformer.](image2)

There are two ways of energy transmission between signal source and load. In high frequency operation, the excitation inductance is larger, the excitation current can be neglected, and the transmission line mode plays a major role. The upper limit frequency is no longer limited by leakage inductance and distributed capacitance, nor by the upper limit of core frequency, when the leakage inductance and distributed capacitance of transformer are all part of the characteristic impedance of transmission line. In the middle frequency band, the leakage inductance is not obvious, the excitation inductance is still large, the excitation current can be ignored, and the transmission transformer is
close to the ideal transmission line. Meanwhile, the electric length of the transmission line is very short, usually less than one eighth wavelength, can be regarded as a short connection, the input signal will be directly added to the load, and the energy transmission will not be affected by the transformer, so the transmission-line transformer has good high frequency characteristics. The output will decrease due to the decrease of excitation inductance and the increase of exciting current, when it works at low frequencies. while because of the high permeability core and the close coupling between the two coils, the signal can still be well output from the secondary, and the transformer transmission mode plays a major role. Therefore, the transmission-line transformer in low frequency section still has better characteristics.

3.2. Structure and material design of transmission-line transformer

3.2.1. Structure principle
The transmission-line transformer consists of a ring core and a transmission line. The core is made of ferrite material with high permeability and low loss. Its diameter depends on the power. The transmission-line transformer is formed by winding transmission lines such as twisted strands, parallel lines and coaxial lines on the magnetic core. Its structure is shown in Fig. 3. The typical transmission-line transformer has four ports, which can be connected to the signal source and the load separately.

![Figure 3. Transmission-line transformer structure diagram](image)

The core of transmission-line transformer is usually made of ferrite, which can be divided into permanent magnet ferrite, soft magnet ferrite and rotating magnet ferrite. Permanent magnet ferrite is also called ferrite magnet steel. After magnetization, the strength of residual magnetic field is very high, and the residual magnetic field can be maintained for a long time. After the magnetic field of the soft ferrite is disappearing, the residual magnetic field is very small. Rotary ferrite is a ferrite material with magnetic properties. Soft magnetic ferrite is used in the production of transmission-line transformer.

3.2.2. Design scheme
The space impedance of antenna wave is about 377Ω. Under the low frequency condition, the antenna impedance changes greatly. It is necessary to design a transmission-line transformer to meet the impedance matching and realize the effective construction of the space strong electromagnetic field in the low frequency band. According to the principle of transmission-line transformer, the space wave impedance 377 is realized in two parts. The impedance of 1:4 is converted from 50Ω to 200Ω, and the impedance of 1:1.885 is converted from 200Ω to 377Ω.

3.2.2.1. Design of 1:4 transmission-line transformer
The principle of 1:4 transmission-line transformer is shown in Figure 4. The transmission-line transformer acts as an impedance converter between the signal source and the load. The equivalent resistance of the load resistance RL at the input end after passing through the transmission line should be equal to the internal resistance RS of the signal source (if the signal source is a power amplifier, it should be equal to its optimal load resistance). The transmission system will be matched. According to the principle of transmission line, the characteristic impedance of transmission line satisfying the
optimal power transmission condition can be obtained, such as the type of magnetic core, the length of wire, the number of coil turns, and so on. The principle diagram and physical diagram of the coaxial transmission-line transformer are shown in Figures 5.

![Figure 4. Schematic diagram of 1:4 impedance transformation](image1)

Figure 4. Schematic diagram of 1:4 impedance transformation

![Figure 5. (a) Impedance transformation principle of 1:4 coaxial line; (b) physical diagram of 1:4 coaxial line impedance transformation](image2)

(a)  (b)

Figure 5. (a) Impedance transformation principle of 1:4 coaxial line; (b) physical diagram of 1:4 coaxial line impedance transformation

3.2.2.2. Design of 1:2.25 transmission-line transformer

The design principle of the 1:2.25 transmission-line transformer is shown in Figure 6, which $R_{12}$, $R_{34}$, and $R_{56}$ are equal. When the input is connected to port 1 and port 4, and the output is connected to port 1 and port 6, the input resistance is $R_{12}$ and $R_{34}$, and output resistance is $R_{12}$, $R_{34}$, and $R_{56}$. The output voltage is 3/2 of the input voltage, $I$ is the current between 12 and 34. Thus, the input is $I/3$ and output is $2I/3$, so the ratio is 1:2.25. The schematic and physical map of the 1:2.25 coaxial transmission-line transformer are shown in Figure 7.

![Figure 6. schematic diagram of 1:2.25 impedance transformation](image3)

Figure 6. schematic diagram of 1:2.25 impedance transformation

![Figure 7. (a) Schematic diagram of impedance transformation for 1:2.25 coaxial line; (b) 1:2.25 coaxial line impedance transformation physical map](image4)

(a)  (b)

Figure 7. (a) Schematic diagram of impedance transformation for 1:2.25 coaxial line; (b) 1:2.25 coaxial line impedance transformation physical map

3.2.2.3. Design of 1:1.885 transmission-line transformer
The impedance of the 1:1.885 transmission-line transformer can be changed from 200 to 377Ω. It is included in the working range of 1:2.25, thus the design of 1:1.885 can be realized just by calculating the specific position between the inner conductors on the two coaxial lines in Figure 7 (a). Its location is located in 0.74590604 places (from left to right) and its simulation results are shown in Figure 8.

Figure 8. simulation result diagram of 1:1.885 transmission-line transformer

3.3. Experiment simulation
Taking radiation antennas commonly used in EMC as the object of application at present in China, after completing the design of 1:4 and 1:1.885 transmission-line transformers and physical manufacture, simulation test of the design scheme has been verified whether the desired impedance matching, so as to realize the effective construction of low frequency strong electromagnetic environment.

The ATP10K100M3 radiation antenna is chosen as the application object in the simulation test, and the antenna operates from 10kHz to 100MHz. The standing wave ratio of antenna without transmission-line transformer and with transmission-line transformer is compared and verified. The experimental results are shown in figs. 9 and 10. It can be seen from the figure that the antenna has a significant improvement in the standing wave ratio in the low frequency band.

Figure 9. ATP10K100M3 radiating antenna standing wave ratio, when no transmission-line transformer is added
Figure 10. ATP10K100M3 radiating antenna standing wave ratio, when loading the transmission-line transformer

4. Conclusion
The radiation efficiency of low-frequency strong electromagnetic environment field has always been a difficult problem for EMC engineers. To improve the radiation efficiency of high-power field, it is necessary to solve the impedance matching of low-frequency antenna. This paper innovatively combines the theory of transformer and transmission line to form the design concept of transmission-line transformer, which is used to solve the impedance matching of radiation antenna in low frequency band. Three kinds of transmission-line transformers, 1:4, 1:2.25 and 1:1.885, are designed and
manufactured. The effectiveness of the radiation antenna in low frequency band is verified by simulation experiments.

Subsequently, the author will continue to carry out more proportionality transformer design and verification tests, and try to achieve automatic adjustment of proportionality relationship through application program, so as to realize the adaptive matching of low-frequency radiation antenna impedance and effectively improve the radiation efficiency of low-frequency strong electromagnetic field, which is of great high application value in the professional field.

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