Research on lightning stroke model and characteristics of electronic transformer

Mu LI[1], Lian Lian LI[1], Shu Bo FANG[1] and Jing Jing WANG[1]

[1]*Wuhan NARI Limited Liability Company, State Grid Electric Power Research Institute, Wuhan 430074, China*

Abstract. In order to improve the reliability of power supply, a large number of electronic voltage and current transformers are used in digital substations. In this paper, the mathematical model of the electronic transformer is analyzed firstly, and its circuit model is given. According to the difference of working characteristics between voltage transformer and current transformer, the circuit model of voltage type electronic transformer and current type electronic transformer is given respectively. By analyzing their broadband transmission characteristics, the accuracy of the model is verified, and their lightning analysis models are obtained.

1 Introduction

In order to improve the reliability of power supply, a large number of electronic transformers are used instead of traditional transformers in the digital substation, so as to avoid the differential saturation, ferroresonance and other risks. At the same time, it also solves the problem of heavy equipment, inconvenient installation and transportation under the high voltage level.

To ensure the safe and reliable operation of the electronic transformer, it is necessary to comprehensively and accurately grasp the characteristics of the over voltage surge in lightning wave shows, according to the characteristics of lightning and risk to develop the corresponding protective measures and strategies. Now we focus on analyzing the lightning stroke model of electronic voltage and current transformer and its lightning characteristics[1-3].

2 Model of electronic transformer

The mathematical model of electronic transformer is using the network analyzer and other measuring instruments to measure the wide band voltage transmission characteristics of the electronic transformer equipment, broadband current transmission characteristics and scattering parameters, and then convert the measured data and rational approximation, and get their rational approximation expression. On the basis of the expression of rational approximation, the circuit model is established, and the broadband transmission model of the electronic transformer device or the T equivalent circuit model are obtained. The method of establishing wide band model of electronic transformer is explained here. Firstly, taking voltage transformer as an example, it explains the method of establishing wide band mathematical model of transformer[4-5].

2.1 Mathematical model of electronic transformer

The broadband transmission characteristics of the measured electronic transformer, whether it is voltage transformer or current transformer, can be mathematically approximated by rational fitting method. Its typical description form is:

$$f(s) = \sum_{n=1}^{N} \frac{c_n}{s - a_n} + d \qquad (1)$$

Here, the pole an and the corresponding cn residue can be real, can also be a complex conjugate; d is a real number, N is the total number of poles.It is assumed that there are k pairs of conjugate complex poles and N-2k real poles in the left half plane, and K pairs of conjugate complex poles are:

$$\left.\begin{aligned} a_{2n-1} &= -p_{rn} + jp_{in} \\ a_{2n} &= -p_{rn} + jp_{in} \end{aligned}\right\} n = 1,2,\cdots,K \qquad (2)$$

Here, p_{rn}>0. Then the residue corresponding to complex conjugate poles:

$$\left.\begin{aligned} c_{2n-1} &= -c_{rn} + jc_{in} \\ c_{2n} &= -c_{rn} + jc_{in} \end{aligned}\right\} n = 1,2,\cdots,K \qquad (3)$$

The other N-2k real poles are:

$$a_n < 0, n = 2K + 1,\cdots,N \qquad (4)$$

The corresponding residue:

$$c_n < 0, n = 2K + 1,\cdots,N \qquad (5)$$

Thus it can be obtained:

$$f(s)=\sum_{n=1}^{K}\left(\frac{2c_{rn}s+2c_{rn}p_{rn}-2p_{in}c_{in}}{s^2+2p_{rn}s+p_{rn}{}^2+p_{in}{}^2}\right)+\sum_{n=2K+1}^{N}\frac{c_n}{s-a_n}+d \quad (6)$$

$$f(s)=\sum_{n=1}^{K}f_{1n}(s)+\sum_{n=1}^{K}f_{2n}(s)+\sum_{n=2K+1}^{N}f_{3n}(s)+f_4(s) \quad (7)$$

Among them:

$$f_{1n}(s)=\left(\frac{2c_{rn}p_{rn}-2p_{in}c_{in}}{s^2+2p_{rn}s+p_{rn}{}^2+p_{in}{}^2}\right) \quad (8)$$

$$f_{2n}(s)=\left(\frac{2c_{rn}s}{s^2+2p_{rn}s+p_{rn}{}^2+p_{in}{}^2}\right) \quad (9)$$

$$f_{3n}(s)=\frac{c_n}{s-a_n} \quad (10)$$

$$f_4(s)=d \quad (11)$$

Using the mathematical approximation expressions, the circuit model corresponding to f1n (s), f2n (s), f3n (s) and f4n(s) can be obtained.

From equation 8, f1n(s)can be rewritten as:

$$f_{1n}(s)=H_{1n}\frac{1}{X_{1n}s^2+Y_{1n}s+1} \quad (12)$$

Among them:

$$H_{1n}=2\frac{c_{rn}p_{rn}-p_{in}c_{in}}{p_{rn}{}^2+c_{in}{}^2} \quad (13)$$

$$X_{1n}=\frac{1}{p_{rn}{}^2+P_{in}{}^2}>0 \quad (14)$$

$$Y_{1n}=\frac{2p_{rn}}{p_{rn}{}^2+p_{in}{}^2}>0 \quad (15)$$

The circuit diagram corresponding to equation 12 is shown in Figure 1.

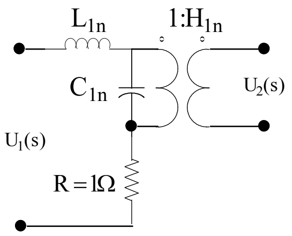


Figure 1. Circuit model corresponding to f1n (s).

In Figure 1, the calculation of the parameters of each component can be given by the following formula:

$$C_{1n}=Y_{1n}=\frac{2p_{rn}}{p_{rn}{}^2+p_{in}{}^2}, \quad L_{1n}=\frac{X_{1n}}{C_{1n}}=\frac{1}{2p_{rn}} \quad (16)$$

Similarly, from equation 9, f2n(s)can be rewritten as:

$$f_{2n}(s)=H_{2n}\cdot\frac{Y_{2n}s}{X_{2n}s^2+Y_{2n}s+1} \quad (17)$$

The circuit diagram corresponding to equation 17 is shown in Figure 2.

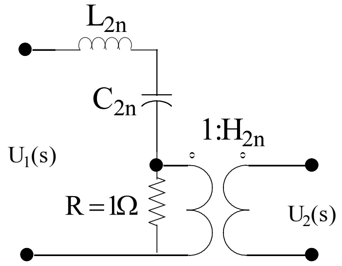


Figure 2. Circuit model corresponding to f2n (s).

From equation 10, f3n(s) and f4n(s) can be rewritten as:

$$f_{3n}(s)=\frac{c_n}{s-a_n}=H_{3n}\frac{1}{s/p_n+1} \quad (18)$$

The equivalent circuit model of f3n (s) and f4n(s) is as follows:

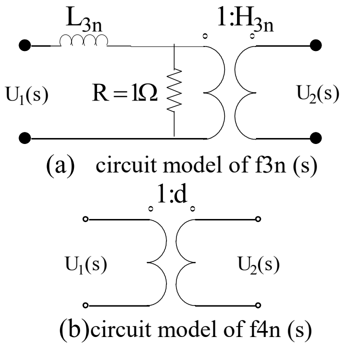


Figure 3. Equivalent circuit model of f3n (s) and f4n(s).

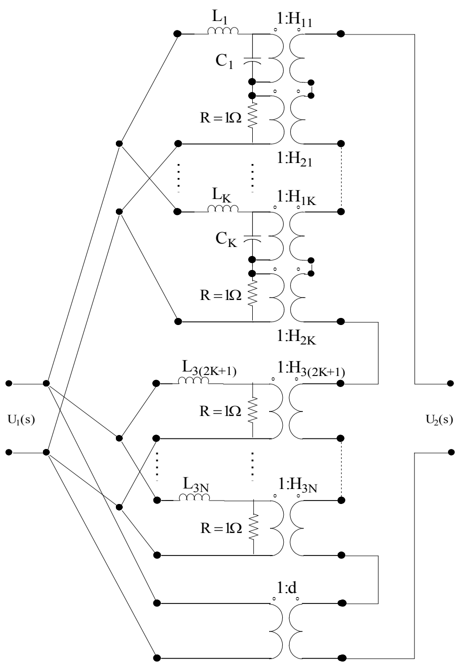


Figure 4. Circuit model corresponding to f (s).

By combining the Figure 1, Figure 2 and Figure 3 according to equation 7, the equivalent circuit model corresponding to the voltage transfer function f (s) can be obtained as shown in Figure 4, in which all the transformers are ideal transformers.

2.2 Circuit model of electronic voltage and current transformer

The instrument transformer is the key transmission channel for transmitting lightning overvoltage along overhead lines or primary equipment to the two equipment. There are three main types of electronic transformer products.

The first is an electronic current and voltage transformer for GIS. Each phase needs to install two transformers, which are installed on both sides of the switch fracture. Each transformer consists of two independent groups of sensors and their corresponding sensing modules. Each sensor consists of a capacitive divider, a low power iron core coil and an air core coil.

The second is an open type independent installation of electronic current and voltage transformers, which consists of two independent groups of sensors and their corresponding sensing modules. Each sensor consists of a capacitive divider, a low power iron core coil and an air core coil.

The third is the low power transformer (LPCT). The economy and advantage of the electronic voltage and current transformer are proportional to the voltage level. Because of the higher voltage level transformer, its saturation characteristics, insulation complexity, large volume, high cost and other shortcomings are more obvious.Therefore, it is not necessary to popularize and apply electronic transformers blindly in each substation voltage level. We believe that the application of electronic transformers is unnecessary and uneconomical for systems below 110kV voltage, especially for 10-35kV systems, and the use of LPCT is a realistic and economical solution.

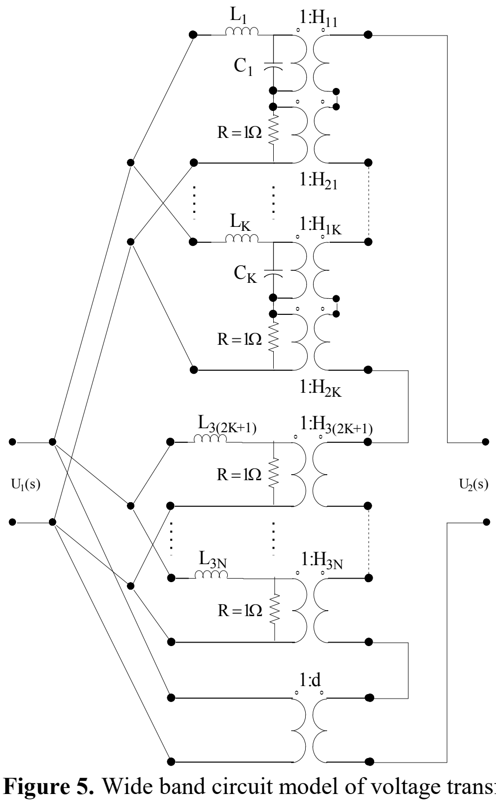


Figure 5. Wide band circuit model of voltage transformer.

According to the structural characteristics of electronic voltage and current transformer and the mathematical model of transformer, the broadband circuit model of electronic voltage transformer and electronic current transformer is obtained, as shown in Figure 5 and Figure 6.

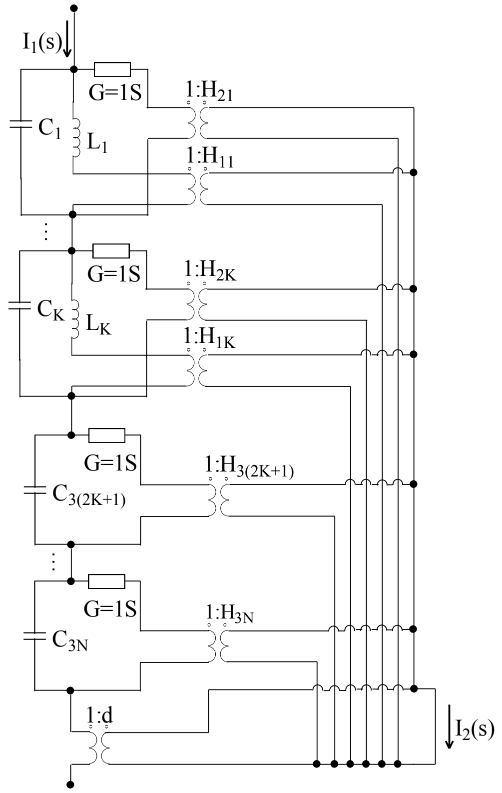


Figure 6. Wide band circuit model of current transformer.

3 Analysis of model characteristics

Here, we give the model of voltage transformer and current transformer based on test results, and study their characteristics.

3.1. Voltage transformer

The scattering parameters of a 500kV capacitor voltage transformer are measured. The model of the voltage transformer is $TYD500/\sqrt{3}-0.005H$, and the rated voltage ratio is $5000/\sqrt{3}kV\big/0.1/\sqrt{3}\,kV$.

On the basis of the measurement of scattering parameters, the mathematical data are approximated by rational fitting method. The approximation result has 40 poles of the left half plane. Using the proposed modeling method, we can obtain the wide band transmission model of the voltage transformer.

Component parameters in the model are shown in Table 1 and Table 2, and the constant term corresponding to the ideal transformer for 1:d=1:5.8647 * 10-2. The voltage transmission characteristic of the wide band transmission model of the transformer is shown in the virtual curve in Figure 7. As shown in Figure 7, the measured voltage transmission characteristics are in good agreement with the voltage transmission characteristics of the circuit model. Figure 7 shows the voltage transfer characteristics of the voltage transformer in the lower frequency range. It can be seen that when the ratio between the voltage of the low voltage side of the transformer and the voltage of the high voltage side is below 20kHz, the value of the amplitude frequency characteristic of the voltage transmission is basically kept at 0.02, which shows that the voltage ratio of the voltage transformer in the 20kHz is kept better. This shows that the voltage ratio of the voltage transformer is kept better in 20kHz. When the frequency is higher than 20kHz, the voltage transfer characteristics of the transformer are complex, and some resonance points appear.

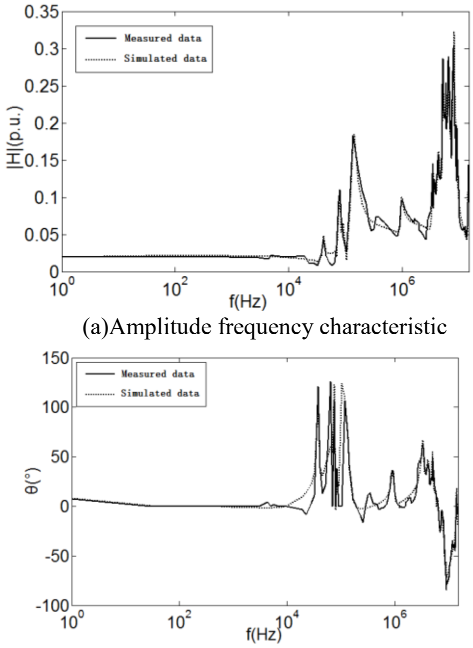
Table 1. Component parameters of circuit models corresponding to conjugate complex poles.

Pole number	L_n(mH)	C_n(μF)	H_{1n}	H_{2n}
1	7.66E-02	2.09E-01	-2.47E-03	-2.61E-03
2	3.93E-02	1.29E-01	1.21E-03	6.69E-03
3	2.70E-01	1.53E-02	-3.59E-03	3.07E-01
4	1.48E-02	1.99E-01	2.17E-03	5.81E-02
5	5.33E-03	2.52E-01	-3.76E-02	2.87E-02
6	1.22E-03	2.20E-02	-5.47E-03	2.17E-02
7	4.85E-04	4.36E-03	-6.84E-03	6.88E-03
8	3.42E-04	3.89E-03	-6.18E-03	3.37E-02
9	2.02E-03	4.83E-04	-2.89E-04	-5.63E-03
10	4.99E-04	1.84E-03	-7.15E-03	5.54E-02
11	1.47E-03	4.77E-04	6.76E-04	5.49E-02
12	2.39E-04	2.35E-03	8.99E-03	1.24E-01
13	2.10E-03	2.26E-04	1.96E-04	-1.42E-02
14	5.96E-04	6.32E-04	2.09E-04	-2.60E-02
15	1.35E-04	2.73E-03	1.65E-02	1.81E-01
16	9.82E-02	3.71E-06	2.21E-04	-3.59E-02
17	2.08E-03	1.45E-04	-3.34E-04	1.49E-02
18	1.05E-03	2.85E-04	8.10E-04	2.50E-02
19	2.21E-04	5.41E-04	-2.37E-03	4.79E-02

Table 2. Component parameter of circuit model corresponding to real number pole.

Pole number	L3n (mH)	H3n
1	2.71E+02	-6.44E-03
2	1.76E-02	4.04E-03

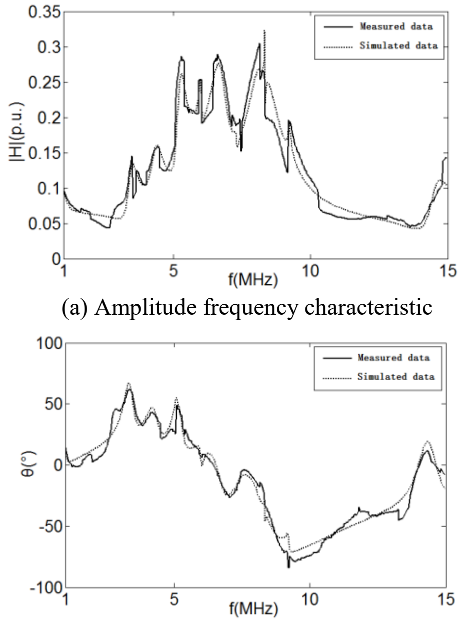
Figure 8 shows the voltage transfer characteristics at high frequencies, and the measured voltage transmission characteristics at high frequencies coincide with the voltage transmission characteristics of the circuit model. If we want to obtain better approximation results, we can increase the number of poles in the data fitting, but this will lead to the increase of the order of rational approximation expression and the number of circuit elements.



(a)Amplitude frequency characteristic

(b) Phase frequency characteristic

Figure 7. Wide frequency voltage transmission characteristics of voltage transformer.



(a) Amplitude frequency characteristic

(b) Phase frequency characteristic

Figure 8. Voltage transmission characteristics of voltage transformer with frequency higher than 1MHz.

3.2 Current transformer

The scattering parameters of a 500kV current transformer are measured. The model of the current transformer is LB1-500, and the rated current ratio is 1250A/1A.

The mathematical data are approximated by the rational fitting method, and the fitting results of 24 poles are obtained. Using the proposed modeling method, we can obtain the wide band transmission model of the current transformer. Component parameters in the model are shown in Table 3 and Table 4, and the current ratio of ideal transformer corresponding to F4 (s) =d is 1:d = 1:0.014069.

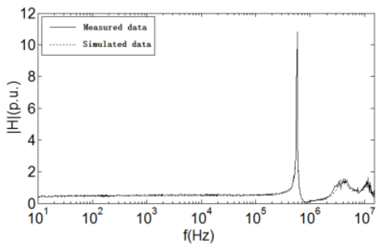
Table 3. Component parameters of circuit models corresponding to conjugate complex poles.

Pole number	Ln(mH)	Cn(μF)	H1n	H2n
1	6.38E-4	1.59E+4	-3.39E-4	-2.58E-3
2	1.14E-6	7.43E+1	9.20E-3	-7.65E-1
3	1.58E-6	4.98E+1	1.39E-1	-8.26E+0
4	1.80E-6	4.26E+1	1.36E-1	1.01E+1
5	2.05E-6	9.97E+0	8.53E-4	-3.64E-2
6	1.45E-5	1.17E-1	5.39E-1	2.46E-1
7	1.20E-6	4.00E-1	-1.27E-2	-1.63E-1
8	4.09E-8	4.83E+0	1.45E-3	-1.38E-1
9	3.43E-6	5.67E-2	-3.21E-1	-5.3E-1
10	7.53E-8	2.33E+0	3.54E-3	-1.94E-1
11	4.08E-9	3.25E+1	-4.16E-4	1.65E-2

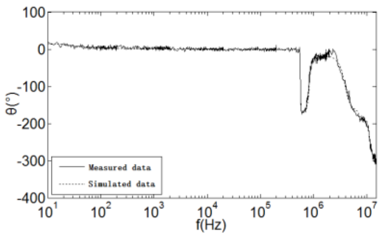
Table 4. Component parameter of circuit model corresponding to real number pole.

Pole number	L3n (mH)	H3n
1	1.15E+05	-3.58E-01
2	7.92E+03	-1.44E-01

The current transmission characteristics of the circuit model are shown in the dashed line curves of Figure 9 and Figure 10, and they are consistent with the measured data. Figure 9 shows the current transmission characteristics of the current transformer under low frequency. Figure 10 shows the current transmission characteristics of the current transformer at higher frequency. Under the 20kHz frequency, the current transfer characteristic of the current transformer is relatively stable, and the current ratio is 10A/5A=2. When the frequency is more than 20kHz, the change of current transmission characteristics of current transformer is large, and there is a resonance point occurred near 580kHz.

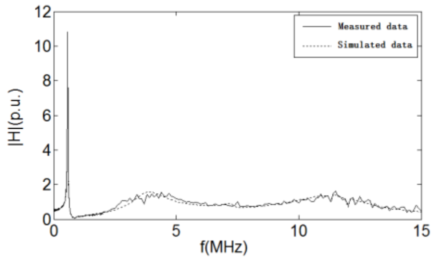


(a)Amplitude frequency characteristic

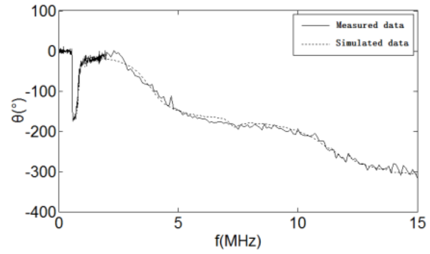


(b) Phase frequency characteristic

Figur 9. Wide band current transmission characteristics of current transformer.



(a)Amplitude frequency characteristic



(b) Phase frequency characteristic

Figure 10. Current transmission characteristics of current transformer under higher frequency.

4 Conclusion

Based on the above analysis results, it can be seen that the electronic transformer model has good accuracy in high frequency range, but the model is complex, and it is not easy to use. Therefore, if we only need to consider the transformer model suitable for analyzing the lightning overvoltage, it is only necessary to ensure the accuracy of the model in the 1MHz band. Therefore, for the voltage transformer mentioned above, only the first 6-order parameters need to be considered, and the current transformer only needs to consider the 1-order model.

References

1. W.Xiong, Z.Wenliang, Technical problems of electromagnetic compatibility in power system, High voltage technology, 23,53-58 (1997)
2. V. S. Rashkes, L. D. Ziles, Very high frequency overvoltages at air EHV substations during disconnect switch operations, IEEE on PD, 3,1618-1623(1996)
3. S.Zhusen, Z.Yufang, Z.Guangzhou, et al. Research on electromagnetic disturbance and protection measures in 500kV substation (1), high voltage technology,26,16-18(2000)
4. C.Dingxin, Q.Xuedi, Calculation method of magnetic field produced by line current in "wire earth" loop, Proceedings of the Symposium on electromagnetic environment and electromagnetic compatibility of power system, Guangzhou, 27-29(2002)
5. W.Xiong, Electromagnetic disturbance and level of 500kV substation, Symposium on electromagnetic environment and electromagnetic compatibility of power system, Guangzhou,5-8(2002)