DOI:10.13334/j.0258-8013.pcsee.2003.10.001

文章编号：0258-8013（2003）10-0001-05　中图分类号：TM63　文献标识码：A　学科分类号：470·4027

电压互感器宽频特性的建模

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MODELING OF WIDE FREQUENCY CHARACTERISTIC OF POTENTIAL TRANSFORMER

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ABSTRACT: In substations, Switching operation will give rise to transient overvoltage. For prediction of the interference voltage in the secondary circuits of a potential transformer caused by the transient overvoltage in substation maincircuit, the wide frequency model for the transfer function of the potential transformer (PT) should be constructed. In the paper, a modified transfer function synthesis method is presented. After measuring the transfer characteristic of the PT, the wide frequency model of the PT can be set up with the synthesis method. The method is simple and effective; it can be used to constructed the wide frequency models for the transfer function of the coupling capacitor voltage transformer (CCVT) as well.

KEY WORDS: Substation; Potential transformer; Transient overvoltage; Circuit synthesis

摘要：在变电站内，开关的操作将产生瞬态过电压。为了预测这种瞬态过电压在变电站内二次回路中产生的干扰电压，应该建立变电站内的电压互感器（PT）传输函数的宽频模型。该文介绍了一种改进的传输函数综合方法。当PT的传输特性被测量后，就可以利用该综合方法建立该PT的宽频传输模型。该方法简单有效，同时，它还可以用来建立电容式电压互感器（CCVT）的宽频传输模型。

关键词：变电站；电压互感器；瞬态过电压；电路综合

1 INTRODUCTION

There are various electromagnetic relations between main circuits and transformer secondary circuits in the substations. The transient overvoltage caused by switching operation in the main circuit will be coupled into transformer secondary circuits, thus the normal performance of the secondary circuits may be interfered with. The transient overvoltage can be calculated with the finite-difference time-domain (FDTD) method based on the multi-conductor transmission line (MTL) [1,2]. For the prediction of the interference voltage that will stress on the devices that connected with PT secondary circuit, the wide frequency models for the transfer function of the PT and CCVT should be constructed.

Due to the complexity of the structure of the PT, it is very difficult to set up its wide frequency model from its physical structure. We build the model of the PT with the following steps: 1) the PT response is measured by using function generator and the numerical memory oscilloscope, thus the voltage transfer characteristic of the PT is gained; 2) the measured data is fitted with the rational approximation method [3,4], so the voltage transfer function in frequency domain is acquired; 3) for the convenience, the transfer function is synthesized to the circuit model with the circuit synthesis technology, thus the circuit model can be used in EMTP (Electro-Magnetic Transients Program). In the references [5,6], some transfer function synthesis methods have been proposed, but the order of the rational approximation for the PT is very high, these synthesis methods are inconvenient and the circuits acquired are very complex. In the paper, the high order rational function is written as the sum of the low order rational function,

基金项目：国家自然科学基金项目（50077006）；教育部高等学校优秀青年教师奖励基金计划和骨干教师计划项目。
Project Supported by National Natural Science Foundation of China (50077006).

then every low order rational function is synthesized to a simple circuit, at last all of the simple circuits are combined together, to form the wide frequency model. The method is simple and intelligible. The wide frequency model of the PT can be set up with the above synthesis method. And the method can also be used to build the wide frequency models for the transfer function of the CCVT.

2 MODIFIED CIRCUIT SYNTHESIS ME-THOD FOR HIGH ORDER TRANSFER FUNCTION

2.1 Introduction

When the transfer characteristic of the PT or CCVT has been measured, we can fit the measured data with the rational approximation method [3, 4]. No matter which method is adopted, the high order rational function acquired can be written as

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

The residues c_n and poles a_n are either real quantities or complex conjugate pairs, while d are real. N is the total number of poles.

We assume there are K complex conjugate pole pairs and N-$2K$ real poles in left half plane. The K complex conjugate pole pairs are

$$\left.\begin{aligned} a_{2n-1}&=-p_{rn}+\mathrm{j}.p_{in}\\ a_{2n}&=-p_{rn}-\mathrm{j}.p_{in}\end{aligned}\right\}\quad n=1,2,\cdots,K \tag{2}$$

where $p_{rn}>0$. The corresponding residues are

$$\left.\begin{aligned} c_{2n-1}&=c_{rn}+\mathrm{j}.c_{in}\\ c_{2n}&=c_{rn}-\mathrm{j}.c_{in}\end{aligned}\right\}\quad n=1,2,\cdots,K \tag{3}$$

N-$2K$ real poles are

$a_n<0$, $n=2K+1$, . .,.N.

The corresponding residues of these real poles are

c_n, $n=2K+1$, . .,.N.

The formula (1) is modified as

$$f(s)=\sum_{n=1}^{K}\left(\frac{2c_{rn}s+2c_{rn}p_{rn}-2p_{in}c_{in}}{s^2+2p_{rn}s+p_{rn}{}^2+p_{in}{}^2}\right)+\sum_{n=2K+1}^{N}\frac{c_n}{s-a}+d \tag{4}$$

$$f(s)=\sum_{n=1}^{K}f_{1n}(s)+\sum_{n=1}^{K}f_{2n}(s)+\sum_{n=2K+1}^{N}f_{3n}(s)+f_4(s) \tag{5}$$

and

$$f_{1n}(s)=\left(\frac{2c_{rn}p_{rn}-2p_{in}c_{in}}{s^2+2p_{rn}s+p_{rn}{}^2+p_{in}{}^2}\right) \tag{6}$$

$$f_{2n}(s)=\left(\frac{2c_{rn}s}{s^2+2p_{rn}s+p_{rn}{}^2+p_{in}{}^2}\right) \tag{7}$$

$$f_{3n}(s)=\frac{c_n}{s-a_n} \tag{8}$$

$$f_4(s)=d \tag{9}$$

Next we synthesize $f_{1n}(s)$, $f_{2n}(s)$, $f_{3n}(s)$and $f_4(s)$ respectively.

2.2 Synthesis Circuit Corresponding to the Co-mplex Conjugate Poles

（1） $f_{1n}(s)$ is written as

$$f_{1n}(s)=H_{1n}\cdot\frac{1}{X_{1n}.s^2+Y_{1n}.s+1} \tag{10}$$

and

$$H_{1n}=2\frac{c_{rn}p_{rn}-p_{in}c_{in}}{p_{rn}{}^2+c_{in}{}^2} \tag{11}$$

$$X_{1n}(s)=\frac{1}{p_{rn}{}^2+P_{in}{}^2}>0 \tag{12}$$

$$Y_{1n}=\frac{2p_{rn}}{p_{rn}{}^2+p_{in}{}^2}>0 \tag{13}$$

From formula (10), a circuit showed in figure 1 is obtained with the circuit synthesis technology.

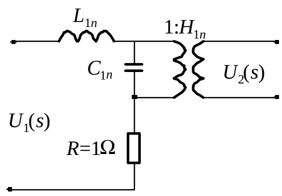


图 1 $f_{1n}(s)$对应的电路
Fig.1 Circuit for $f_{1n}(s)$

In figure 1, there are the relations:

$$C_{1n}=Y_{1n}=\frac{2p_{rn}}{p_{rn}{}^2+p_{in}{}^2}\,,\quad L_{1n}=\frac{X_{1n}}{C_{1n}}=\frac{1}{2p_{rn}} \tag{14}$$

（2） $f_{2n}(s)$ is written as

$$f_{2n}(s)=H_{2n}\cdot\frac{Y_{2n}s}{X_{2n}s^2+Y_{2n}s+1} \tag{15}$$

and

$$H_{2n}=\frac{c_{rn}}{p_{rn}} \tag{16}$$

$$X_{2n}=\frac{1}{p_{rn}{}^2+p_{in}{}^2}>0 \tag{17}$$

$$Y_{2n} = \frac{2p_{rn}}{{p_{rn}}^2 + {p_{in}}^2} > 0 \tag{18}$$

From formula (15), a circuit showed in figure 2 is obtained with the circuit synthesis technology. In the figure, there are the relations:

$$C_{2n} = Y_{2n} = \frac{2p_{rn}}{{p_{rn}}^2 + {p_{in}}^2}, \quad L_{2n} = \frac{X_{2n}}{C_{2n}} = \frac{1}{2p_{rn}} \tag{19}$$

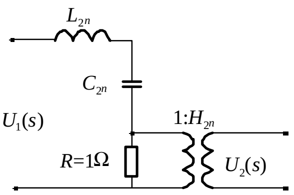


图 2　$f_{2n}(s)$对应的电路

Fig.2　Circuit for $f_{2n}(s)$

Since in figure 1 and figure 2 there are the following relations:

$$C_{1n} = C_{2n}, \quad L_{1n} = L_{2n} \tag{20}$$

We combine the circuit in figure 1 and the circuit in figure 2, thus the circuit showed in figure 3 is obtained.

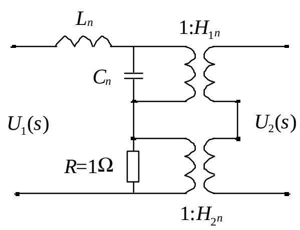


图 3　$f_{1n}(s)$+ $f_{2n}(s)$对应的电路

Fig.3　Circuit for $f_{1n}(s)$+ $f_{2n}(s)$

In figure 3, there are the relations:

$$C_n = C_{1n} = C_{2n} = \frac{2p_{rn}}{{p_{rn}}^2 + {p_{in}}^2} \tag{21}$$

$$L_n = L_{1n} = L_{2n} = \frac{1}{2p_{rn}} \tag{22}$$

2.3 Synthesis Circuit Corresponding to the Real Poles

$f_{3n}(s)$ is written as

$$f_{3n}(s) = \frac{c_n}{s - a_n} = H_{3n} \frac{1}{(s/p_n) + 1} \tag{23}$$

and

$$H_{3n} = \frac{c_n}{p_n} \tag{24}$$

$$p_n = -a_n > 0 \tag{25}$$

From equation (23), a circuit showed in figure 4 is acquired.

In figure 4, there is the relation:

$$L_{3n} = \frac{1}{p_n} \tag{26}$$

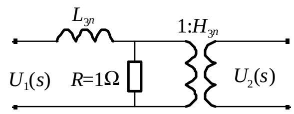


图 4　$f_{3n}(s)$对应的电路

Fig.4　Circuit corresponding to $f_{3n}(s)$

2.4 Synthesis Circuit Corresponding to the Constant d

From $f_4(s)=d$, we get an ideal transformer showed in figure 5. In the figure, the ratio of the ideal transformer equals to the constant d.

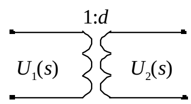


图 5　常数项 d 对应的理想变压器

Fig.5　Ideal transformer corresponding to the constant d

At last we gain the synthesis circuit for $f(s)$. The synthesis circuit is presented in figure 6.

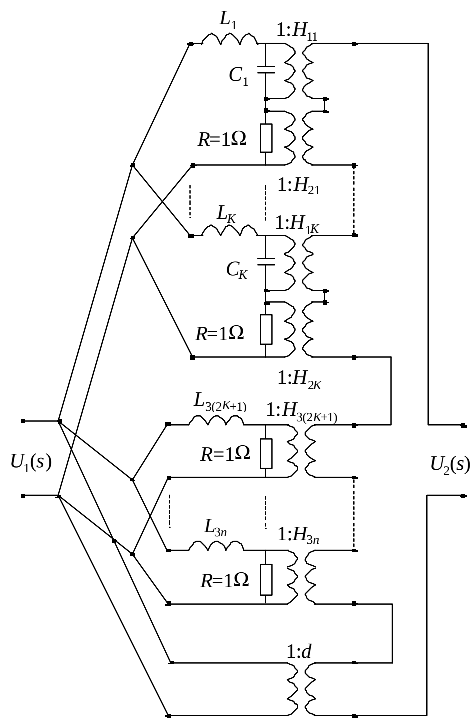


图 6　$f(s)$对应的电路

Fig.6　Circuit for $f(s)$

3　APPLICATION EXAMPLE

We have measured the voltage transfer charac-teristic of a 10kV/0.2kV PT with HP 33120A function generator and Tektronix TDS 340 oscilloscope. The frequency range of the transfer characteristic is from 1Hz to 15MHz.

The measured data was fitted with the rational approximation method. There are 40 poles in the acquired rational function. Based on the fitted result, the wide frequency model for the PT was obtained with the above synthesis method. Table 1 and 2 list the values of the elements of the model, and according to the constant *d*, the ratio of the ideal transformer is 1:d=1:5.8647E-002.

表 1 对应于复共扼极点的综合电路的元件

Tab.1 Elements of synthesis circuit corresponding to complex conjugate poles

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

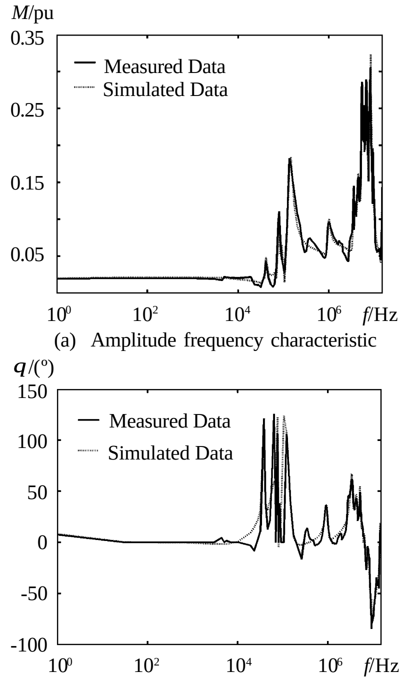
表 2 对应于实数极点的综合电路的元件

Tab.2 Elements of synthesis circuit corresponding to real poles

n	L_{3n} /mH	H_{3n}
1	2.71×10^{-2}	-6.44×10^{-3}
2	1.76×10^{-2}	4.04×10^{-3}

A good simulation result has been achieved. Figure 7 specially shows the low frequency transfer characteristic of the PT. The transfer ratio of the PT is about 0.02 under 20kHz. It indicates that the transfer characteristic of the PT is good under 20kHz.

The high frequency characteristic of the PT is very complex above 20kHz. Figure 8 specially shows the high frequency transfer characteristic of the PT. There are many resonance points in the high frequency characteristic of the PT. In figure 8, the high frequency simulation result is satisfying. If one wants a better result, the order of the rational approximation or the amount of the poles should be increased.

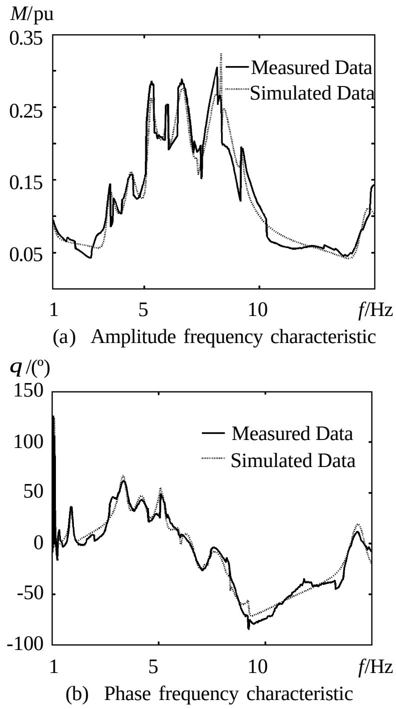


(a) Amplitude frequency characteristic

(b) Phase frequency characteristic

图 7 横坐标为对数坐标的电压互感器传输特性

Fig.7 Voltage transfer characteristic of a potential transformer with logarithm scale for abscissa



(a) Amplitude frequency characteristic

(b) Phase frequency characteristic

图 8 横坐标为线性坐标的电压互感器传输特性

Fig.8 Voltage transfer characteristic of a potential transformer with linear scale for abscissa

4 CONCLUSIONS

The paper presents a modified transfer function synthesis method. The method is simple and intelligible. The wide frequency model for the transfer function of the PT can be easily constructed with the synthesis method. And the structure of the model gained is simple. If combine the model of the PT and the FDTD method based on MTL [1,2], we can predict the interference voltages in the secondary circuits that are caused by switching operation in the substation main circuit. The modified transfer function synthesis method can be used to construct the wide frequency models for the transfer function of the CCVT as well.

REFERENCES

[1] Lu Tiebing，Cui Xiang，Li Lin．Transient analysis of aerial multi-conductor transmission lines with branch[J]．IEEE Transactions on Magnetics，2001，37(5)：3298-3302．

[2] 卢铁兵，崔翔（LU Tiebing，CUI Xiang）．变电站空载母线波过程的数值分析（Numerical analysis of wave processes for buses without load in substations using FDTD）[J]．中国电机工程学报（Proceedings of the CSEE），2000，20(6)：39-42．

[3] Soysal A O，Semlyen A．Practical transfer function estimation and its application to transformers[J]．IEEE Trans. on PWRD，1993，8(3)：1627-1637．

[4] Gustavsen B，Semlyen A．Rational approximation of frequency domain responses by vector fitting[J]．IEEE Transactions on Power Delivery，1999，14(3)：1052-1061．

[5] Miyata F．A new system of two-terminal synthesis[J]．IEEE Transactions on Circuit Theory，1955，2(12)：297-302．

[6] HO E C．RLC transfer function synthesis[J]．IEEE Transactions on Circuit Theory，1956，3(9)：188-190．

收稿日期：2003-02-24。

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