A New Online Over-voltage Monitoring Method Based on the Numerical Inverse Laplace Transform

ZHANG Zhong-yuan, TANG Shuai, WANG Zhi-hui, WANG Xiao-liang

***Abstract*-- A new method for over-voltage on-line monitoring based on the transmission parameters (*T*-parameters) of the devices in the substation is presented in this study. This method models the potential transformer (PT), secondary cables and voltage divider as several two-port networks in cascade using their *T*-parameters which are obtained by measurements or calculation. Adoption of this model can inversely derive the over-voltage of the high-voltage port of the PT from the voltage signal of the secondary device by means of numerical calculation method such as NILT, Recursive Convolution (RC) and IFFT, etc. In order to conquer the limitations of the source in application of NILT, The arbitrary waveforms source was expressed in a series of unit step function in Laplace domain. Applying the principle, the over-voltage on-line monitoring system is put up in the laboratory. By means of NILT and RC, the over-voltage is calculated. Comparing the measurement results with the calculated by NILT and RC, it shows that NILT is better than the RC in reducing the numerical oscillation of the simulation effectively.**

***Keywords*: over-voltage on-line monitoring; potential transformer; transmission parameters; Numerical Inverse Laplace Transform; Recursive Convolution.**

I. Introduction

In the modern power systems, the phenomenon of over-voltage often occurs because of the lightning strike, failure, resonance, switching operation, etc. As soon as running across the over-voltage, the electrical equipments during operation are likely to generate breakdown, discharge, flashover, explosion accident and so on, therefore monitoring and analyzing for the over-voltage of power system is of utmost importance.

The key of the online over-voltage monitoring device is the obtainment of the overvoltage signal. At present, electric apparatus for over-voltage signal capture mainly includes capacitor voltage divider, potential transformer (PT), optical fiber voltage transducer, contactless voltage transducer based on electrostatic coupling, but they all have their limitations.

Capacitor voltage divider in [1] has simple structure, high measuring accuracy, fine transient response characteristic, good load property, but has oscillation in the process of measurement. When the capacitor divider is paralleled to the high voltage system, we must consider a series of questions such as operational reliability, heat dissipation, impedance matching, the A.C. impulse and the security attributes. The PT in [2] presents the characteristics of non-linear and frequency-dependent when subjected to the high frequency over-voltage. The secondary signal captured by Fault Recorder will have serious distortion, that can't be used directly. Although the optical fiber voltage transducer [3,4] has high security features and fine frequency response characteristic, its application is restrained in power system, because the active transducer in [4] needs high voltage divider installed in the system, and the measurement precision of passive optical fiber voltage transducer in [5] is affected by temperature greatly. The voltage transducer(capacitor voltage divider) which using the capacitance of the bushing tap as its high voltage arm and an additional grounding capacitor as its low voltage arm in [6] also has simple structure and fine transient response, but its isolation of high voltage side and low voltage side is knotty. In addition, it changes the grounding mode of the primary equipments, which may results in insulation or system accidents because of the discharge of the bushing tap. The contactless voltage transducer based on electrostatic coupling in [7] also has the advantages of fine frequency response characteristic and high precision measurement, but it is difficult to install. Otherwise, except the device getting the voltage waveforms with Fault Recorder, all the other monitoring devices need communication apparatus between the locale side and control rooms.

Therefore, a new method for over-voltage on-line monitoring based on the transmission parameters (***T*-parameters**) of potential transformer in the substation, as enunciated in [8], is provided in this study. Applying this method, Reference [9] calculates the over-voltage by means of Vector Fitting (VF) and Recursive Convolution (RC), whose result has some distinct oscillation. To reduce the oscillation, this article uses NILT instead of RC to calculate the over-voltage. In addition, a method in allusion to the arbitrary waveforms source for using NILT is proposed in this study,

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which could conquer the limitations of the source in application to NILT. Based on the principle, an over-voltage on-line monitoring system is put up in the laboratory and the two-port ***T***-parameters model of the system is built based on their frequency domain measurements by means of Agilent 4395A applying VF code to approximation. Surge generator EMS61000-5C and arbitrary waveform generator Agilent 33120A is selected to simulate the Lightning over-voltage in power system. Based on the *T*-parameters model and the secondary voltage signal, the Lightning over-voltage on the high voltage ports of the PT is inversely calculated by NILT and RC inversely. The comparison between the calculated results and measured data verify the feasibility of this method.

II. PRINCIPLE OF THE METHOD

The over-voltage on-line monitoring device designed in the paper is composed of PT, secondary cables, voltage divider, PCI and industrial computer connected in turn. The system of the monitoring device is shown in Fig. 1.

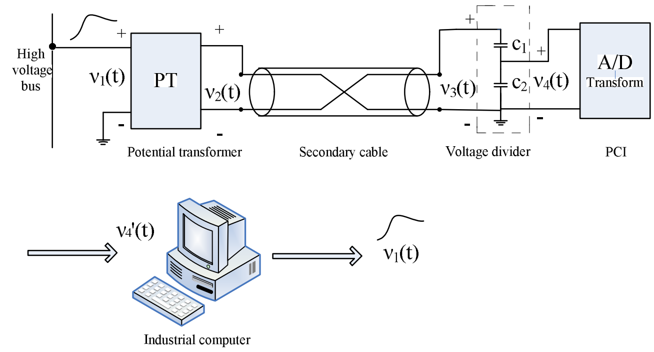


Fig.1. System of over-voltage on-line monitoring

The basic principle is described as follows: when the over-voltage $v_1(t)$ emerges on the high voltage bus, it is transformed into the voltage signal $v_4(t)$ after passing through PT, secondary cables and voltage divider in turn; Reading the voltage signal of the secondary side of the voltage divider by the PCI, the industrial computer put up the calculated model based on the wide frequency transfer property of the PT, secondary cables and voltage divider and then by means of the numerical calculation method computes the voltage signal of the primary side of PT inversely, which is also the over-voltage of the high voltage bus.

III. CALCULATION MODEL

Considering the timeliness of the monitoring system, we choose mathematical model for the system, which is simple, effective and convenient for the calculation of the voltage signal. The ***T***-parameters model is founded, which equals PT, secondary cables and voltage divider into three cascading two-port networks as shown in Fig. 2.

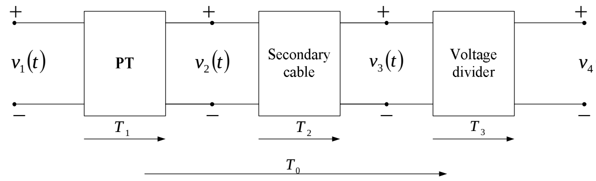


Fig.2. Calculation model of system

In figure 2, $v_1(t)$, $v_2(t)$, $v_3(t)$ and $v_4(t)$ are the time domain voltages of the high voltage bus (primary side of PT), secondary side of PT (in-port of secondary cables), out-port of secondary cables (primary side of the voltage divider) and secondary side of the voltage divider, whose frequency domain voltages are $V_1(s)$, $V_2(s)$, $V_3(s)$ and $V_4(s)$ respectively.

T_1, T_2 and T_3 are the ***T***-parameter matrixes of PT, secondary cables and voltage divider.

Equaling the three cascading two-port networks to one two-port network, we can gain the ***T***-parameters matrix T_0 of the whole model, then

$$\begin{pmatrix} V_1(s) \\ I_1(s) \end{pmatrix} = T_1 * T_2 * T_3 * \begin{pmatrix} V_4(s) \\ -I_4(s) \end{pmatrix} = T_0 * \begin{pmatrix} V_4(s) \\ -I_4(s) \end{pmatrix} \quad (1)$$

Where

$$T_i = \begin{pmatrix} A_i(s) & B_i(s) \\ C_i(s) & D_i(s) \end{pmatrix}, i = 0,1,2,3 \quad (2)$$

As shown in Fig.1, the secondary side of voltage divider is connected with the PCI, whose input impedance is high. Therefore, let the input current of the PCI $I_4(s) = 0$, we get,

$$V_1(s) = A_0(s) * V_4(s) \quad (3)$$

The element $A_0(s)$ of the whole transmission parameter matrix T_0 can be derived by (1) and (2) as shown in (4).

$$\begin{aligned} A_0(s) = &\left[A_1(s)*A_2(s)+B_1(s)*C_2(s)\right]*A_3(s)+ \\ &\left[A_1(s)*B_2(s)+B_1(s)*D_2(s)\right]*C_3(s) \end{aligned} \quad (4)$$

IV. CALCULATION METHOD

A. *Numerical Approximation by VF*

Numerical approximation for $A_0(s)$ can gain the partial fraction form as follows by means of VF [10].

$$A_0(s) = \sum_{i=1}^{N} \frac{c_i}{s-\alpha_i} + d + sh \quad (5)$$

In the equation (5), α_i are the poles and c_i are the corresponding residues, d and h are constants, N is the number of the poles.

B. *NILT algorithm based on Pade approximation*

The equation of Laplace inverse transform is given as follows [11]:

$$v(t) = \frac{1}{2\pi j} \int_{c-j\infty}^{c+j\infty} V(s) e^{st} ds \quad (6)$$

Where, s is the complex frequency domain variables, c is any positive constant and the poles s_i of $V(s)$ satisfy the conditions of $\mathrm{Re}(s_i) < c$.

By substituted z to st, equation (6) becomes:

$$v(t) = \frac{1}{2\pi jt} \int_{c'-j\infty}^{c'+j\infty} V\left(\frac{z}{t}\right) e^z dz \tag{7}$$

Using the Pade approximation to approximate the exponential function e^z, and the basic inverse transform formula of NILT can be deduced by the Residue Theorem as follows:

$$\hat{v}(t) = -\frac{1}{t} \sum_{i=1}^{m} K_i V\left(\frac{z_i}{t}\right) \tag{8}$$

Where, $\hat{v}(\cdot)$ is the time domain response, $V(\cdot)$ is the complex frequency domain response, which is the frequency domain voltage $V_4(s)$ in this study, m is the order of Pade expansion, z_i and K_i are the poles and residues for the exponential function e^z.

C. Frequency domain expression of the excitation

Excitation source of electromagnetic transient process is generally got by calculation or measurement, which is a set of discrete data. Assuming an arbitrary excitation contains M data points, which can be considered as $M-1$ discontinuous function, is shown in Fig. 3.

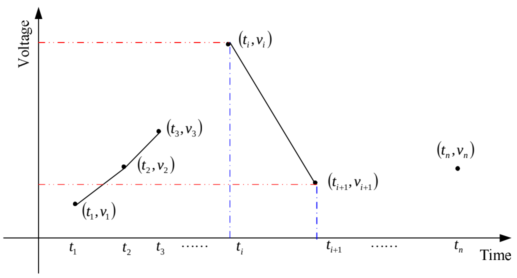


Figure 3. An any source containing of M data points

When the coordinates of M data points are known, the i and $i+1$ data points is used as an example for analysis, then the straight line expression for the two points is shown as equation (9) by using point-slope method.

$$\frac{v_{i+1} - v_i}{t_{i+1} - t_i}(t - t_i) = v - v_i \qquad t_i \le t \le t_{i+1} \tag{9}$$

Let the slope $k_i = \dfrac{v_{i+1} - v_i}{t_{i+1} - t_i}$, the line can be expressed as:

$$v = k_i t + b \tag{10}$$

Where, $b_i = -k_i t_i + v_i$.

Expressing this line segment with a unit step function:

$$v_i = (k_i t + b_i)\left[u(t - t_i) - u(t - t_{i+1})\right] \tag{11}$$

Using the linear nature, the delay nature and the fundamental function of Laplace transform, this line segment can be obtained [12]:

$$\begin{aligned} L[v_i] = &k_i \cdot (1/s^2) \cdot e^{-st_i} + (k_i t_i + b_i) \cdot (1/s) \cdot e^{-st_i} \\ &- k_i \cdot (1/s^2) \cdot e^{-st_{i+1}} - (k_i t_i + b_i) \cdot (1/s) \cdot e^{-st_{i+1}} \end{aligned} \tag{12}$$

Similarly, other data points can be followed to carry out such operations, and then the frequency domain expression of excitation signal can be obtained by uniting all of them:

$$V(s) = \sum_{i=1}^{M-1} L[v_i] \tag{13}$$

The frequency domain expression $V_4(s)$ is obtained by the above method. Then the voltage signal of the primary side of PT $v_1(t)$ can be obtained by substituting equation (3) to equation (8).

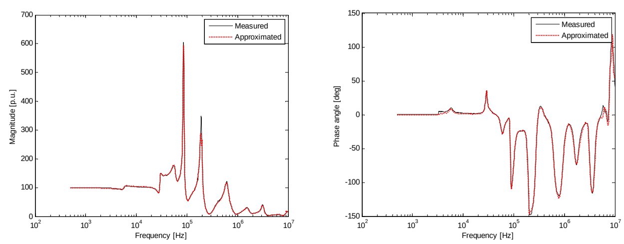
V. Measurement of Network Parameters

The Agilent 4395A Network/Spectrum/Impedance Analyzer is selected to measure the ***S***-parameters of PT, secondary cables and voltage divider, whose frequency range is 500Hz ~ 10MHz.

The conversion between the ***T***-parameters matrix ***T*** and the ***S***-parameter matrix $\boldsymbol{S} = \begin{pmatrix} \boldsymbol{S}_{11} & \boldsymbol{S}_{12} \\ \boldsymbol{S}_{21} & \boldsymbol{S}_{22} \end{pmatrix}$ is shown in equation (14).

$$\begin{aligned} A(s) &= \frac{1}{2\boldsymbol{S}_{21}}\left[(1+\boldsymbol{S}_{11})(1-\boldsymbol{S}_{22}) + \boldsymbol{S}_{12}\boldsymbol{S}_{21}\right] \\ B(s) &= \frac{Z_{02}}{2\boldsymbol{S}_{21}}\left[(1+\boldsymbol{S}_{11})(1+\boldsymbol{S}_{22}) - \boldsymbol{S}_{12}\boldsymbol{S}_{21}\right] \\ C(s) &= \frac{1}{2\boldsymbol{S}_{21}Z_{01}}\left[(1-\boldsymbol{S}_{11})(1-\boldsymbol{S}_{22}) - \boldsymbol{S}_{12}\boldsymbol{S}_{21}\right] \\ D(s) &= \frac{Z_{01}}{2\boldsymbol{S}_{21}Z_{02}}\left[(1-\boldsymbol{S}_{11})(1+\boldsymbol{S}_{22}) + \boldsymbol{S}_{12}\boldsymbol{S}_{21}\right] \end{aligned} \tag{14}$$

Where, Z_{01}, Z_{02} are the reference impedance of the Agilent 4395A, which are both 50Ω.



(a) Magnitude characteristic (b) Phase angle characteristic

Fig.4. Frequency characteristic of potential transformer

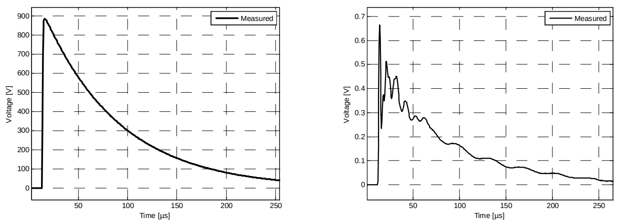
The $A_1(s)$ of PT can be derived by the ***S***-parameters. Fig.4 shows the magnitude and phase angle frequency characteristic of the PT, where the black solid line is the measured data and the red dotted line is the fitting results approximated by VF. The comparison displays the fitting value and measured value matched to each other very well.

The frequency component of lightning over-voltage is generally under 2MHz. The $A_2(s)$ and $A_3(s)$ of secondary cables and voltage divider are both constant within 2MHz, with resonant frequency points above 5MHz. Therefore, the secondary cables can be considered as a lossless transmission line, whose $A_2(s)$ is 1 and the $A_3(s)$ of the voltage divider is equal to its ratio which is 20:1.

VI. LABORATORY PROOFING

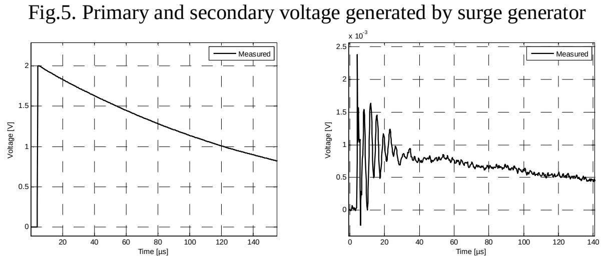
The over-voltage on-line monitoring system is put up in the laboratory. In the system the type of PT is JDZX19 – 10G, 10kV, 50HZ, with the transformation ratio of 100:1; the type of secondary cables is KVVP22 4*1.5mm^2, with the length of 1.65m; the transformation ratio of voltage divider is 20:1. The signal source is surge generator EMS61000-5C and arbitrary waveform generator Agilent 33120A. The time domain voltage is measured by the digital oscillograph Agilent Technologies MSO 6104A 1GHz. The impulse voltages generated by surge generator and arbitrary waveform generator are applied on the primary side of PT to simulate the lightning over-voltage. The voltage signal of secondary side of the voltage divider is acquired by the oscillograph instead of PCI.

The time domain voltage of the system is shown in Fig. 5 and Fig. 6. Fig. 5 shows the voltage generated by surge generator and Fig. 6 shows the voltage generated by arbitrary waveform generator, where the Fig. (a) is the voltage of the primary side of PT and the Fig. (b) is the voltage of secondary side of the voltage divider.



(a) The voltage of the primary side of PT (b) The voltage of secondary side of the voltage divider

Fig.5. Primary and secondary voltage generated by surge generator



(a) The voltage of the primary side of PT (b) The voltage of secondary side of the voltage divider

Fig.6. Primary and secondary voltage generated by arbitrary waveform generator

The voltage of the primary side of PT can be calculated by means of NILT and RC. The comparison of the calculated value and the measured ones is shown in Fig. 7 and Fig. 8, where the black solid line is the measured data, the red dotted line is the results calculated by NILT and the green dash dotted line is the results calculated by RC. The results reveal that the on-line monitoring method proposed in this paper can get the overvoltage waveform from the voltage signal of the secondary side of the voltage divider by inverse calculation with NILT and RC except some small oscillation. At the same time, the comparison between the measurement results with the calculated by NILT and RC shows that NILT is better than the RC in reducing the numerical oscillation of the inverse simulation effectively.

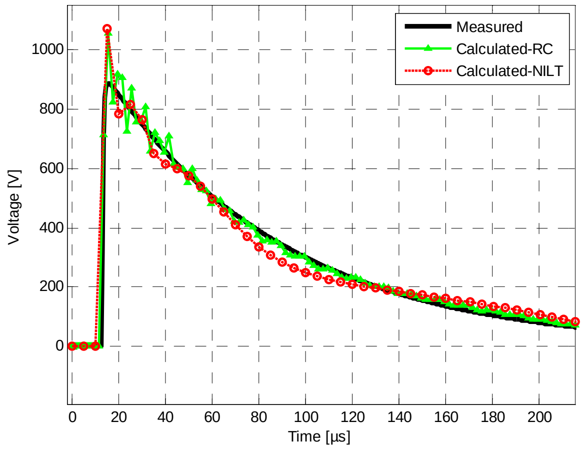


Fig.7. Comparation of measured value and calculated value of surge generator

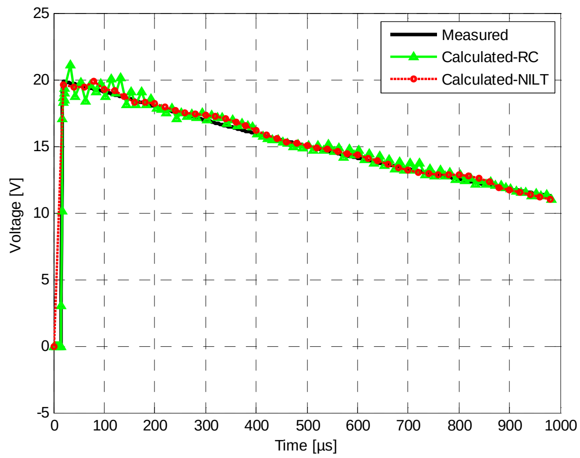


Fig.8. Comparation of measured value and calculated value of arbitrary waveform generator

VII. CONCLUSION

Contraposing the problems of the existing on-line over-voltage monitoring systems, this paper presents a new method for on-line over-voltage monitoring based on the ***T***-parameters of the devices in the substation, which models the PT, secondary cables and voltage divider as several two-port networks in cascade. Adoption of this model, the over-voltage of the high-voltage port of the PT was derived inversely from the voltage signal of the secondary device by means of NILT and RC. In application of NILT, the arbitrary waveforms source was expressed in a series of unit step function in order to conquer the limitations to the source. Applying the principle, the over-voltage on-line monitoring system is put up in the laboratory and the over-voltage is calculated. Comparing the measurement results with the calculated by NILT and RC, It shows that NILT is better than the RC in reducing the numerical oscillation of the simulation effectively. The experiments and calculation presents in this paper indicate that the proposed method is feasible and promising.

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