TELKOMNIKA, Vol. 11, No. 2, February 2013, pp. 607~614
ISSN: 2302-4046

Practical Research of Electronic Transformer Based on Interpolation Algorithm

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Abstract

As a result of the adoption of new photovoltaic technology, electronic transformers have great advantages compared with traditional electromagnetic type, such as anti-saturated, high linearity, compact and lightweight etc. The working principle of sensing head of electronic current/voltage transformers is introduced in the paper. The causes of phase error in electronic transformer are analyzed. And a set of phase compensation methods based on the signal transfer principle of electronic transformer is presented. The phase-difference caused by Rogowski coil and time-delay in signal transferring from high voltage side to merging unit are analyzed, and the higher sampling rate and the method of linear interpolation is used to solve the problem. In the simulation test the phase error compensation effect is very good, and the simulation result shows that the integrated error after compensation is able to meet the requirements of the measurement and protection, and demonstrates the validity of the method.

Keywords*: electronic transformer, Rogowski coil, capacitive voltage divider, interpolation algorithm, phase compensation*

1. Introduction

With the continuous development of the intelligence of high-voltage equipment, the boundaries between the primary and secondary equipment will be gradually blurred. The traditional primary equipments are becoming smart devices through installation and integration of intelligent components [1] [2]. At the same time, with the development of the power system, power generation and transmission capacity is increasing continuously, the power grid voltage is raised, many new and more stringent requirements for current and voltage transformers are put forward [3]. Because of the insulation problems, inherent magnetic saturation phenomenon, the secondary-side open high voltage danger, the traditional electromagnetic power transformer has become increasingly unsuited to this development. So various new type transformers based on different measurement principle emerged. According to the International Electrotechnical Commission (IEC) standard, the new transformer is collectively referred to as electronic transformers.

Electronic type voltage/current transformers, due to its miniaturization and high measuring precision, are regarded as the key components of intelligent equipments and caused extensive attention. Based on photovoltaic technology, electronic transformer has anti-saturation and high linearity, compared with traditional transformer. It also has wide frequency response and doesn't matter of the second open/short circuit. Its small size and light weight, especially in the ultra-high and UHV field, promotes its development [4-8]. Electronic transformers effectively improve the correct action rate of the protection from the basic data collection. Therefore, the electronic transformer has caused a wide range of research in the application of smart equipment and digital substation [9] [10].

Compared to the traditional electromagnetic transformers, the sensing mechanism and signal transmission for electronic transformer are both different. And the second outputs of electronic transformers are digital signals [11] [12]. For these reasons, the causes of error between the electronic transformer output signal and the true original signal and correction method are not the same with electromagnetic transformer. Errors can be divided into two aspects of the phase and amplitude. The magnitude error within effective frequency band will be taken into account in the design of filters and the parameters determining process of the ratio

Received October 3, 2012; Revised December 21, 2012; Accepted January 10, 2013

coefficient. So the phase error of electronic transformer output is more serious compared with amplitude error, in order to make the signal of primary side within effective frequency band undistorted, phase compensation is necessary [13-18].

This paper describes the working principle of the sensor head part of the electronic current/voltage transformer. The equivalent circuit of Rogowski coil and the capacitor voltage divider are derived, and the causes of error are analyzed. The phase correction method is proposed through high sampling rate and linear interpolation for each channel, and the error compensation algorithm formula is derived and analyzed. Finally, based on the standard communication rate for electronic transformer defined by IEC, the phase compensation algorithm simulation is done. The simulation results fully meet the provisions of IEC 0.1 level accuracy requirements and verify the effectiveness of the proposed phase compensation method for electronic instrument transformers in the paper and its good practical value.

2. The overall structure of the electronic transformer

Digital substation measuring system consists of current / voltage sensor, converter and merge unit. IEC has developed "electronic voltage transformer standard IEC 60044-7" and "electronic current transformers standard IEC 60044-8", According to the standard, electronic type transformer is composed of a sensor, transmission system and converter component. The information transmitted is proportional to the signal being measured, which is supplied to the measuring instruments, the protection and control devices. The converter output of electronic transformer is supplied to the secondary devices typically through the merging unit (MU). The merging unit is first defined in the IEC 60044-8, and is used for the connection of electronic transformers whose output is digitized. Its main function is synchronized to capture multiple electronic transformer output signals. The measurement data is transmitted in accordance with the predetermined protocol (IEC60044-8 or IEC61850-9-1/2) to the secondary equipment, such as protection, measurement devices.

The electronic transformer structure diagram is shown in Figure 1. The Rogowski coil and the capacitor voltage divider principle are used in electronic transformer for the current and voltage measurements. The voltage and current analog signals acquired by sensor will be converted into digital signals by acquisition unit locally and then transmitted through fiber to the merging unit. The received data is organized according with the data format defined in IEC61850-9 by merging unit and then provided to protection, measuring equipments through the optical fiber Ethernet. Acquisition unit and merging unit can be used in accordance with the needs as one-to-one, one-to-many or many-to-one variety of combinations.

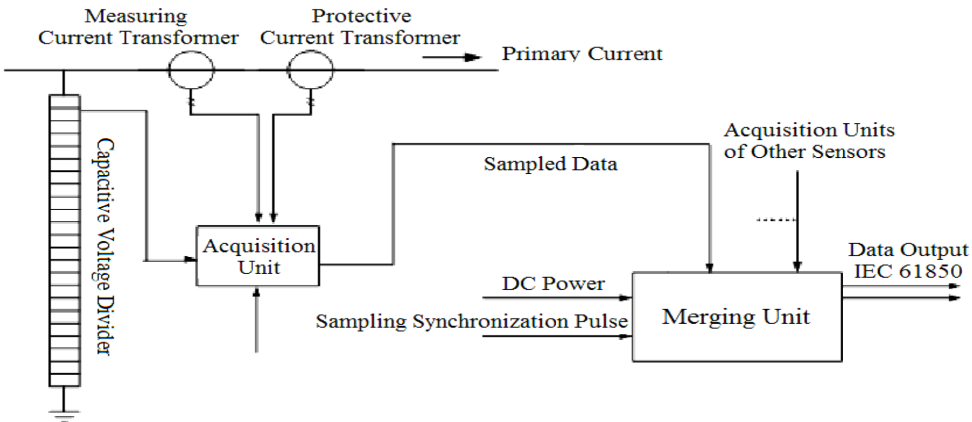

Figure 1. Electronic Transformer Structure Diagram

3. Working Principle of Sensing Heads

Rogowski coil, which is used to measure current, is able to solve the magnetic saturation problem caused by electromagnetic current transformer, and have a wide dynamic range. Because there is no ferromagnetic material, this kind of sensor has a good performance in linearity and anti-saturation and the hysteresis problem is also avoided. Therefore, there is good steady-state performance and transient response for the current sensor. Capacitance partial voltage method, which is used to measure voltage, is characterized by simple insulation structure, small size and fast transient response.

3.1 Principle Analysis of Rogowski Coil

The Rogowski coil is made of non-magnetic material as skeleton to constitute a hollow coil without magnetic saturation and hysteresis phenomenon. These features of Rogowski coil sensor determined its good linearity and transient characteristics. The equivalent circuit diagram of Rogowski coil is as shown in Figure 2. The conductor is through the Rogowski coil, and the current inducted in the second side is flowing through line, load, etc. which forms a closed loop.

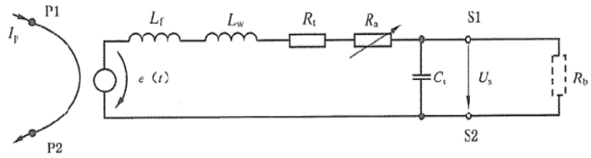

Figure 2. Equivalent Circuit of Rogowski coil

In the above diagram, i_p is the primary current, $e(t)$ is the Rogowski coil output voltage, L_f is the leakage inductance of secondary winding, L_w is the line inductance, R_t is the total resistance of the secondary winding and line, R_a is the corrected resistance, C_c is the equivalent capacitance of cable, U_S is the voltage required correction for output, R_b is the load resistance, P1 and P2 are the first terminals, S1 and S2 are the secondary terminals.

Under normal operating conditions, the output voltage of Rogowski coil is:

$$e(t) \approx \mu_0 \cdot N \cdot A \cdot \frac{\partial i_p(t)}{\partial t} \quad (1)$$

where: vacuum permeability $\mu_0 = 4\pi \cdot 10^{-7}\left[\frac{Vs}{Am}\right]$, N is the turns density (turns/ m), A is the single turn area (m2).

The phase shift and phase error between primary current i_p and the measured voltage output U_S are respectively as formula (2) and formula (3).

$$\varphi = -\arcsin\frac{\omega L}{R_t + R_a + R_b} \quad (2)$$

$$|\underline{\varepsilon}| = \frac{\sqrt{(R_t + R_a)^2 + (\omega L)^2}}{\sqrt{(R_t + R_a + R_b)^2 + (\omega L)^2}} \quad (3)$$

From the above-mentioned work process analysis and formulas, it is shown that due to the parameters error of coil itself, the induced electromotive force output for the sampled voltage will have a phase error. The error lead to phase difference between the coil output voltage and the current difference and it is no longer strictly differential relationship, and it affects the linearity of the coil. Thus the Rogowski coil itself introduces a certain difference.

The work environment for transformer is generally very complex, and Rogowski coil is easy to be affected by induced voltage caused by external magnetic field. Meanwhile temperature changes will make the skeleton and the winding thermal expansion and contraction effects, thus the area of coil and density of turns on the coil will be changed. So the inner or outer diameter of coil and mutual inductance are also changed. All these factors make the measured values will have error. In addition, due to installation and vibration in manufacturing process, it is difficult to ensure that a conductor is precisely located in the center of the coil. Therefore, the impact of the work environment, coupled with the Rogowski coil itself introduces a certain degree of difference between the Rogowski coil output voltage and measured current and it is difficult to maintain their consistency [19-20].

3.2. Principle Analysis of Capacitive Voltage Divider

Capacitive voltage divider is generally used for electronic voltage transformers. The main advantages of this method are that its insulated structure is simple, small size and the transient performance is very good. The working principle is as shown in Figure 3.

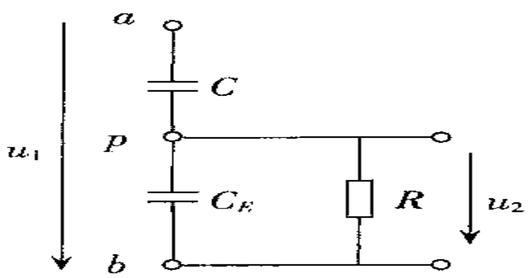

Figure 3. Voltage Sensor Schematic Diagram

Output voltage u_2 is proportional to the rate of change of the input voltage u_1, that is

$$u_2(t) = RC\frac{du_1(t)}{dt} \tag{4}$$

Seen from the formula (4), as long as the capacitor is appropriately selected, the desired sub-voltage values can be obtained. But what is shown in Figure 3 is an ideal case. There are stray capacitance between the actual divider capacitive element and earth or ground shield. There is external electromagnetic interference. And the ambient temperature also changes, etc. All of these factors will cause the divider measurement error. The distributed capacitance between the divider and ground is the main reason for the caused error, so that the secondary voltage measured value is smaller than the ideal situation. In order to reduce the error, a shielding case is needed from the high voltage side to compensate for the current to go away from the ground capacitance, as shown in Figure 4. This compensation method is effective particular in the field of high-voltage measurement.

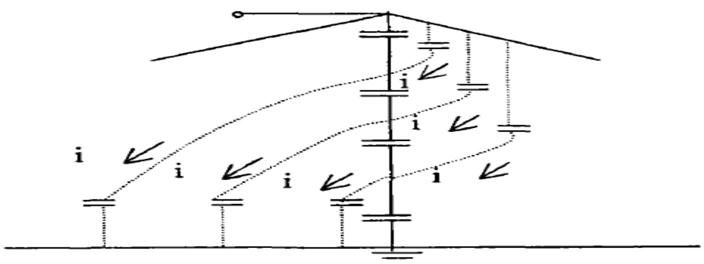

Figure 4. Shielding Type Capacitive Voltage Divider

4. Acquisition Units

The acquisition unit design is directly related to the transformer sampling accuracy and reliability of the data; it is one of the core components of the whole measuring system and provides the data package. Data package containing measuring current, protection current and voltage of each phase will be sent out through fiber after temperature, amplitude compensation by acquisition unit. From the acquisition unit, the data information is processed in digital type. The total delay of data caused in entire conversion process include filtering delay, A/D conversion time, CPU processing time and data transfer time. The output signal of Rogowski coil and capacitive divider is needed to be restored by an integral loop. In theory, it is best to fully restore the output data to the original signal that is before differential process, so that the error will be zero, but actually it is difficult to achieve [22]. There is an acceptable error tolerance of resistors, capacitors and other electronic components, and temperature changes will also affect the parameter values of the electronic components. Therefore, the parameters changes are needed to be considered in the phase compensation method.

5. Phase Correction Based on High Sampling Rate and Linear Interpolation

The electronic circuitry of acquisition unit for electronic transformer work in a complex electromagnetic environment, and its maintenance is difficult. So the electronic circuit should have high reliability modular, and its standardized board should be easy maintenance and replacement. In order to make the acquisition unit simple, reliable and modular, a high sampling rate and linear interpolation method is adopted for different sensor heads and the acquisition circuit to solve the problem of phase delay.

As shown in Figure 5, a channel signal sample sequence is selected as reference, the time difference of the other sampling sequences is Δt (Δt<TS).

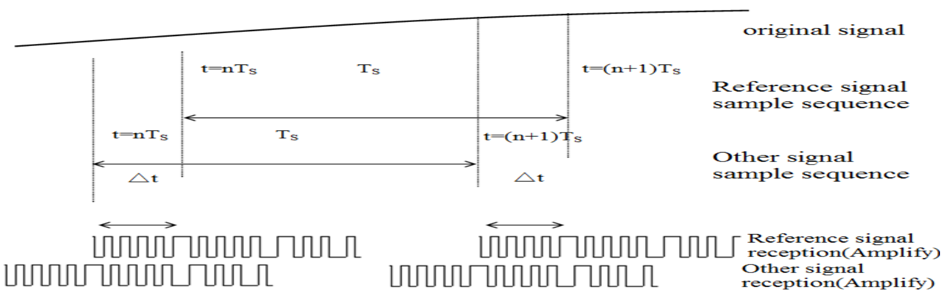

Figure 5. Sampled Digital Signal Sequence Transmitted in Optical Fibers

$$i_1(t) = \sin(w(t+\Delta t)+\phi_0) \tag{5}$$

$$\begin{aligned} i_2(t) &= \sin(wt+\phi_0)+(\sin(w(t+T_S)+\phi_0) \\ &\quad -\sin(wt+\phi_0))\Delta t / T_S \end{aligned} \tag{6}$$

where i_1 is the actual value corresponding to reference sampling sequence signals, i_2 is the calculated value after interpolation. The discretization formula (5) and (6) can be written as:

$$i_1(k,n,m,\phi_0) = \sin(2k\pi\,(nT_S+mT_C)/T_1+\phi_0) \tag{7}$$

$$\begin{aligned} i_2(k,n,m,\phi_0) &= \sin(2k\pi\; nT_S / T_1+\phi_0) \\ &\quad +(\sin(2k\pi\,(n+1)T_S / T_1+\phi_0) \\ &\quad -\sin(2k\pi\; nT_S / T_1+\phi_0))mT_C \end{aligned} \tag{8}$$

where T1 is the fundamental cycle, TS is the sampling interval, TC is the clock cycle used by crystal for receiver (combined unit), that is, interpolation of the smallest division, k is the harmonic frequency, n is the sample point sequence, m is the interpolation points, and m=$\triangle$T/TC. DFT transform of the above signals:

$$I(k,m,\phi_0)=\sum_{n=0}^{N-1} i(k,n,m,\phi_0)\exp(-j2(k-1)\pi\, n/N) \quad (9)$$

Fourier coefficients a and b, respectively:

$$\begin{aligned} a(k,m,\phi_0) &= 2real(I(k+1),m,\phi_0)/N \\ b(k,m,\phi_0) &= -2imag(I(k+1),m,\phi_0)/N \end{aligned} \quad (10)$$

The amplitude and phase are as follows:

$$I(k,m,\phi_0)=\sqrt{a^2(k,m,\phi_0)+b^2(k,m,\phi_0)} \quad (11)$$

$$\Phi(k,m,\phi_0)=\tan^{-1}(a(k,m,\phi_0)/b(k,m,\phi_0)) \quad (12)$$

The errors of sampled values, amplitude and phase brought by the interpolation algorithm are as follows:

$$\begin{aligned} \Delta i(k)\% = 100\times MAX\,((i_2(k,n,m,\phi_0) \\ -i_1(k,n,m,\phi_0))/i_1(k,n,m,\phi_0)) \end{aligned} \quad (13)$$

$$\Delta I(k)\% = 100\times MAX\,(I_2(k,m,\phi_0)-1) \quad (14)$$

$$\Delta\Phi(k) = MAX\,((\Phi_2(k,m,\phi_0)-\Phi_1(k,m,\phi_0)) \quad (15)$$

According to the communication speed of 2.5Mbps defined by IEC60044-8, if 10Bytes information containing 3-way alternating signals coupled with synchronous head and the CRC check information are sent, and the minimum idle between two frame is 35Bits, the maximum sampling rate can be obtained as follows: $2.5\times10^3/(8\times10+35)=23.8\text{kHz}$

6. Simulation Analysis

The above data are put into the equation (13), (14), (15), and then the errors after the compensation are calculated as shown in Table 1.

Table 1. Error Analysis of Simulation Results

Harmonic frequency	Phase error after compensation (degree)	Amplitude error after compensation（%）	0.1-class phase error defined by IEC（degree）	0.1-class amplitude error defined by IEC（%）
1	0.000004	0.004	-	-
2	0.00003	0.008	1	1
3	0.0001	0.03	1	1
4	0.003	0.05	1	1
5	0.005	0.08	2	2
6	0.008	0.12	2	2
7	0.012	0.16	4	4
8	0.02	0.2	4	4
9	0.03	0.25	4	4
10	0.04	0.31	8	8
11	0.05	0.38	8	8
12	0.07	0.45	8	8
13	0.08	0.53	8	8

The sampling rate is selected as 20 kHz. If the crystal oscillator frequency of the receiver (MU) is 20 kHz, then

$$T_S = 50us \quad T_C = 1/20us \quad N = 400$$

$$m = 0,1,2,...,999 \quad n = 0,1,2,...,399 \quad \phi_0 = 0 \sim 2\pi$$

It can be seen from Table 1, based on high sampling rate and interpolation algorithm, the phase error after compensation is very little, far less than the error allowed of 0.1 accuracy class specified in IEC60044-7 and IEC60044-8. Therefore, the integrated error after compensation through high sampling rate and interpolation algorithm is able to meet the requirements of the measurement and protection.

7. Conclusion

The phase error of electronic voltage/current transformer and its correction method is researched in the paper. The working principle of the electronic transformers is described, and the causes of the phase error are analyzed. Based on high sampling rate and linear interpolation a phase compensation method is proposed in order to solve the phase delay caused by different sensing heads and acquisition circuit. Then according to the standards developed by IEC the phase compensation algorithm simulation is carried out. And the phase error after compensation are obtained and analyzed. The simulation results show that the proposed phase compensation method has an excellent stability and the results fully meet the 0.1 accuracy requirements specified in IEC60044-7 and IEC60044-8. So the phase compensation method has a high practical value for electronic transformers.

References

[1] Wang Yong, Mei shengwei, He guangyu. The Characteristics and Realization of Digitization of Primary Equipment in Substations. *Automation of Electric Power Systems*, 2010; 34(13): 94-99.
[2] State Grid. Key equipment (system) development planning of smart grid. Beijing: state grid, 2010.
[3] Seljeseth H, Saethre EA, Ohnstad T, et al. *Voltage transformer frequency response. Measuring harmonics in Norwegian 300 kV and 132 kV power systems*. 8th International Conference On Harmonics and Quality of Power Proceedings, Athens, Greece, 1998.
[4] Tang Zhiguo, Xu Guobin, Zhang Fajin. Digital bus protection based on optical current transducer. *Electric Power Automation Equipment*. 2007; 27(5): 118-121.
[5] China Southern Power Grid. *Research Report of Digital Southern Power Grid*. Guangzhou: China Southern Power Grid, 2007.
[6] Guo Zhizhong. Review of electronic instrument transformers. *Power System Protection and Control*. 2008; 36(15) : 1-5.
[7] Fang qiong, Zhang Huijian, Fu Yanhua. Summary and Engineering Application Analysis of Electronic Instrument Transformer. *North China Electric Power*. 2008; 11: 22-27.
[8] Li Jiuhu, Zheng Yuping, Gu Shidong. Application of Electronic Instrument Transformer in Digital Substation. *Automation of Electric Power Systems*. 2007; 31(7): 94-98.
[9] Djekic Z, Portillo L, Kezunovic M. *Compatibility and interoperability evaluation of all-digital protection systems based on IEC 61850-9-2 communication standard*. IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008.
[10] Gentilini Ivano, Giubbini Paolo, Mancini Franco, et al. *Instrument transformers: Performances and characteristics for typical applications and new developments in enel distribuzione*. 20th International Conference and Exhibition on Electricity Distribution, 2009.
[11] Saitoh M, Kimura T, Minami Y, et al. *Electronic instrument transformers for integrated substation systems*. Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES, 2002.
[12] Miri SM, Lu F, Randall BE. *Design of low-leakage power supply transformers for high-precision electronic instruments*. IEEE Transactions on Instrumentation and Measurement. 2002; 42(4): 854-859.
[13] Ray WF, Davis RM. Wide Bandwidth Rogowski Current Transducers Part II: The Integrator. *European Power Electronics and Drives Journal*. 1993; 3(2): 116-122.
[14] Wang Peng, Zhang Guixin, Li Lianzi. Error analysis of electronic instrument transformers. *Journal of Tsinghua University (Science and Technology)*. 2007; 47(7): 1105-1108.
[15] Tan Hongen, Hu Haoliang, Lei Min. Experimental Analysis of On-site Calibration of Electronic Instrument Transformer. *High Voltage Engineering*. 2010; 36(12): 2990-2995.

[16] Ren Wengzhu, Yuan Yuan, Yang Zhongzhou. Steady-state Error Calibration Technology for Electronic Instrument Transformer. *High Voltage Apparatus*. 2011; 47(4): 64-68.
[17] Cao Tuanji, Yin Xianggen, Zhang Zhe. *Discussion on Data Synchronization of Electronic Instrument Transformers*. Proceedings of the Chinese Society of Universities for Electric Power System and Automation. 2007; 19(2): 108-113.
[18] Duan Xiongyin, Qu Jiyan, Zhang Kewei. Research on Combined Electronic Current and Voltage Transducers. Electrotechnical Journal. 2002; 21(5): 9-12.
[19] Bertrand P, Mendik M, Hazel T, et al. *CT saturation calculations are they applicable in the modern world part IV: CT sizing as per IEC standards and the benefits of non conventional instrument transformers*. Petroleum and Chemical Industry Conference. 2009.
[20] Alves, Simon, Costa, et al. Two-stage current transformers based on nanocrystalline materials for electronic energy meters. *Sensor Letters*. 2009; 7(3): 383-386.
[21] Slomovitz D. Electronic compensation of voltage transformers. *IEEE Transactions on Instrumentation and Measurement.* 1988; 37(4): 652-654.
[22] Qian Zheng, Sheng Du, Luo Chengmu. Application research of phase compensation in electronic photoelectric integrated current/voltage transformer. *Automation of Electric Power Systems*. 2002; 26(24): 40-44.