
A Novel Calibrator for Electronic Transformers Based on IEC 61850

Baoxiang Pan

Jiangsu Institute of Metrology
Guanghua Street 3rd Nanjing Jiangsu China 02584636980/02584636980
e-mail: bx_pan@yahoo.com.cn

Abstract

It is necessary for electronic transformer to make calibration before putting it into practice. To solve the problems in actual calibration process, a novel electronic transformer calibrator is designed. In principle, this system adopts both the direct method and the difference method, which are two popular methods for electronic transformer calibration, by this way the application of the system is extended with its reliability improved. In the system design, based on virtual instrument technology, LabVIEW and WinPCap toolkit are used to develop the application software, and it is able to calibrate those electronic transformers following the standard of IEC 61850. In the calculation of ratio and phase error based on fast Fourier transform, a new window function is introduced, and thus the accuracy of calibration, influenced by the frequency vibration, is improved. This research provides theoretic support and practical reference to the development of intelligent calibrator for electronic transformers.

Keywords: transformer calibration; electronic transformer; direct method; difference method.

Copyright © 2013 Universitas Ahmad Dahlan. All rights reserved.

1. Introduction

For a long time, electromagnetic current and voltage transformers have been dominated in relay protection and current/voltage measurement [1]. However, with further increase of transmission voltage grade and power capacity of the system, it is difficult for traditional transformers to overcome their inherent disadvantages according to electromagnetic induction principle. On the contrary, electronic transformers using photonics technology and optical fiber sensing technology manage to overcome the aforementioned shortcomings. Thus it becomes an inevitable trend to use electronic transformers as the signal source for measurement and relay protection in power systems [2].

Electronic transformers differ greatly with traditional transformers in sensing principle and secondary output, whose secondary outputs are digital signals or analog signals. The existing calibration systems cannot be applied to electronic transformers yet. Thus, calibration methods and device for calibrating electronic transformers have always been the research focus both in China and abroad [3]. There are two types of calibration approaches now: the direct method and the difference method. Apart from accurate results, the former can also obtain harmonic component, output amplitude and phase information, however, with a high demand for acquisition devices. On the contrary, the latter doesn't ask a lot for the acquisition devices, but requires that the electronic transformer output is strictly equal to the standard electromagnetic transformer output [4].

Combining the above two calibration methods with the mature difference measuring module from traditional calibrators, a novel multi-approach electronic transformer calibrator is proposed in this paper. Application of the device is extended. Appropriate calibration methods can be chosen in accordance with practical scene. Meanwhile, the equipment redundancy is ensured to improve the reliability of the system.

2. Calibration Method Analysis

This section mainly introduces two kinds of existing calibration methods for electronic transformers, the direct method and the difference method.

2.1. Direct Method

The direct method is conducted by delivering digital signals of the standard electromagnetic transformer and the examine electronic transformer to computer and letting the software compute phase and ratio errors between them. Those signals are obtained from the secondary outputs of the standard transformer and the transformer under test after signal conditioning and analog-to-digital converting, or Ethernet packet decoding [5]. The traditional electromagnetic transformer is generally adopted as the standard. For standard current transformer, the voltage signal proportional to the secondary current can be gained as the standard by means of a proper accurate resistance. For standard voltage transformers, an accurate voltage divider is used to reduce the amplitude of secondary voltage to a suitable level for analog-to-digital converting.

The direct method has high demands for the sampling circuit, which must adopt the synchronous sampling method. Let $x[n]$ and $y[n]$ denote standard sampled data and sampled data under test respectively. Then FFT (Fast Fourier Transformation) is employed to calculate the fundamental frequency components of both signals. The RMS values are defined as A_x and A_y respectively and the initial phases are φ_x and φ_y . After that, the ratio error ε can be obtained from

$$\varepsilon = \frac{A_y - A_x}{A_x} \quad (1)$$

The phase error φ_e can be calculated by

$$\varphi_e = \varphi_x - \varphi_y \quad (2)$$

A typical block diagram of electronic transformer calibrator based on direct method is shown in Figure 1.

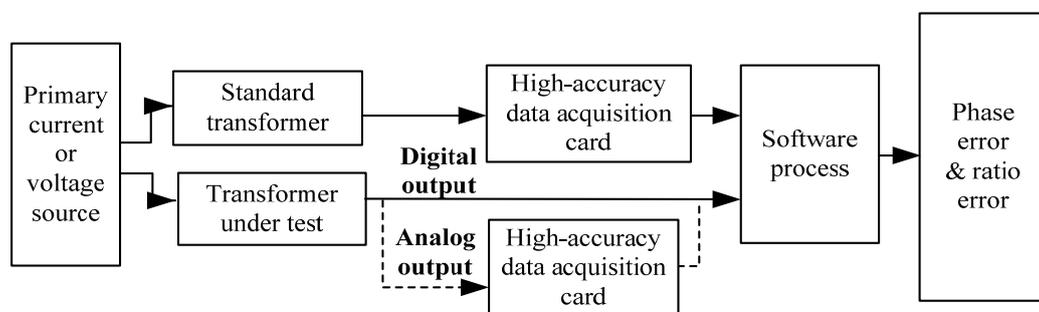


Figure 1. Block diagram of electronic transformer calibrator based on direct method

Standard transformer does not have to adopt the same rated transformer ratio with the electronic ones when using direct method, so as to facilitate the selection of standard transformer. Not only phase and ratio error, but also fundamental and harmonic amplitudes can be obtained from the measurement. However, great errors may be introduced for the phase error measurement if signals are not sampled simultaneously. What's more, to assure high accuracy, the acquisition card with high quality must be adopted. In a way the cost is increased. And calculation errors in the software processing must also be small enough to meet the requirements. Those shortcomings all set a limit for the application of direct method.

2.2. Difference Method

In the case of employing difference method, first, the difference between outputs of the standard transformer and the transformer under test should be gotten after signal conditioning or digital-to-analog converting. After that, the difference signal and standard signal will be sent

to IPC (Industrial Personal Computer) through data acquisition card. By applying some software algorithm, the phase and ratio errors can be obtained finally [6]. Taking the calibration of electronic voltage transformer for example, the basic principle of difference method is shown in Figure 2.

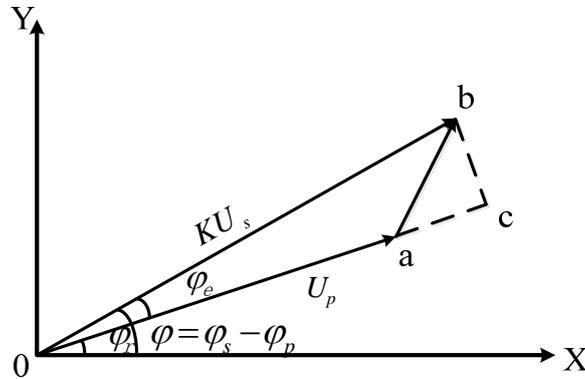


Figure 2. Basic phasor diagram based on difference method

In Figure 2, U_s and K denote the fundamental RMS value of the secondary voltage output and the rated ratio of the electronic voltage transformer under test (EVTUT) respectively. And U_p is the fundamental RMS value of the primary voltage under test. φ is the phase difference resulting from converting the primary voltage to the secondary voltage of EVTUT. φ_s represents the fundamental initial phase angle of primary voltage under test, while φ_p represents the fundamental initial phase angle of secondary voltage output from EVTUT. φ_r stands for the innate phase error of the standard transformer. φ_e is defined as the phase error of EVTUT.

First of all, it is assumed that the innate phase error of the secondary voltage output has been compensated for EVTUT. Then, after being multiplied by the rated ratio, the secondary voltage output of EVTUT shall be compared with the fundamental RMS value of the primary voltage. As the phase error φ_e is small enough, ε and φ_e can be rewritten as

$$\varepsilon = \frac{KU_s - U_p}{U_p} \approx \frac{ac}{U_p} \quad (3)$$

$$\varphi_e \approx \frac{cb}{U_p} \quad (4)$$

The complex error can be defined as $\dot{\varepsilon} = \varepsilon + j\varphi_e = \frac{ac + jcb}{U_p} = \frac{\Delta \dot{U}}{\dot{U}_p}$, where its real

part represents the ratio error and the imaginary part represents the phase error. Thus, the ratio and phase errors can be easily figured out as long as the difference signal and the standard signal have been obtained in advance.

Now, relative errors imported from the measurement device has a little effect on the measurement results of phase and ratio errors since the difference method does not require much for the device. A difference measuring device with high sensitivity and stability can guarantee high measurement accuracy as long as the two signals under test get close to one another enough. The only defect of difference method lies in its strict demand that the rated secondary output of the electronic transformer should be nearly equal to the output of the standard transformer. A typical block diagram of electronic transformer calibrators based on difference method is shown in Figure 3.

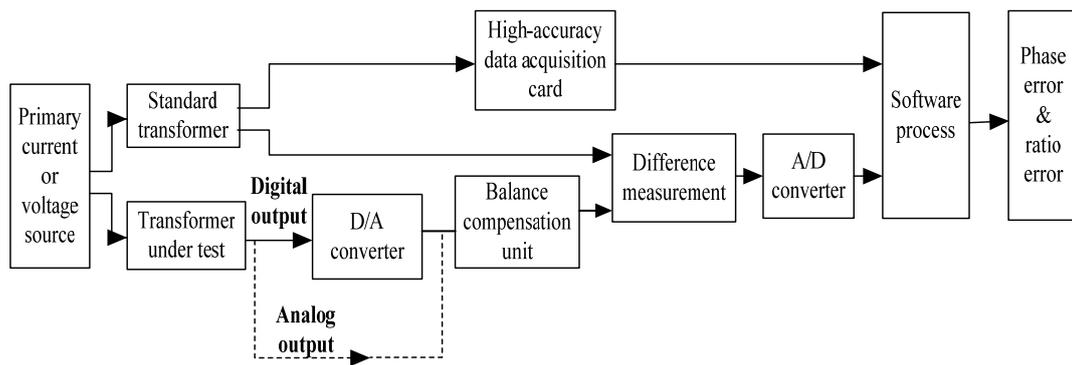


Figure 3. Block diagram of electronic transformer calibrator based on difference method

3. Design Scheme

This paper designs a novel electronic transformer calibrator compatible with both the direct method and the difference method, which can calibrate both the electronic transformer with analog output and that with digital output. The application range of the calibration system is extended based on the design scheme proposed in this paper, meanwhile, the system reliability is improved by using system redundancy design. As shown in Figure 4, the whole system is composed of signal adjustment module, difference measurement module, balancing compensation module, data acquisition module, industrial personal computer, application software, and so on.

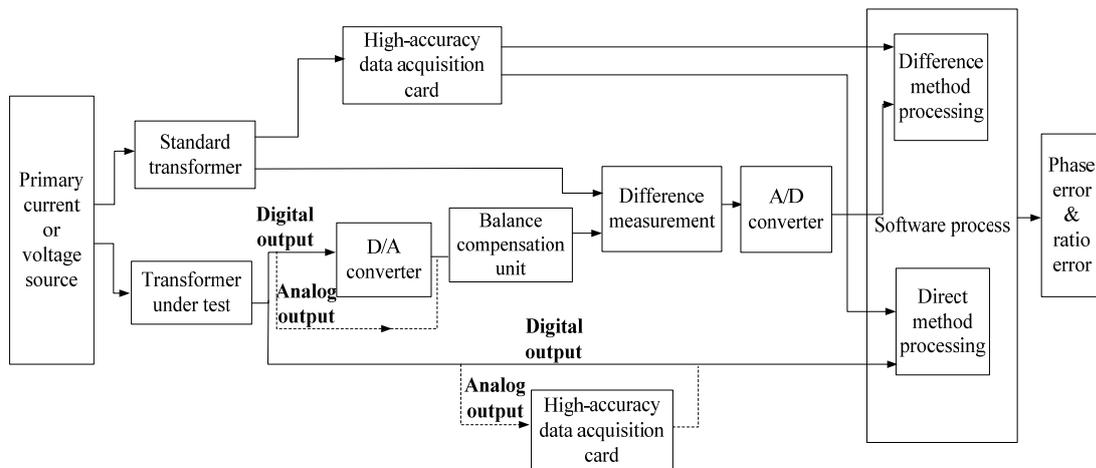


Figure 4. Block diagram of electronic transformer calibrator based on multiple approaches

In the calibration plan of direct method, high-accuracy traditional electromagnetic voltage/current transformer is used as calibration standard. Besides, data acquisition card with high sampling rate and high precision is used to sample the output of calibration standard and transformer under test. Through comprehensive consideration, this paper adopts NI PCI-4070 and NI PCI-4461 from National Instrument Co. to fulfill analog-to-digital conversion. NI PCI-4070 is used for calibrating those electronic transformers with digital output, and NI PCI-4461 is used for calibrating those ones with analog output and supporting digital-to-analog conversion with high precision. The main performance of NI PCI-4070 is as follows: 1.8 MS/s maximum sampling rate with 10-bit resolution; 23 bit maximum resolution with 5S/s sampling rate; input range of AC voltage from ± 100 mV to 300 V; input range of AC current from 20 mA to 1 A. The

main performance of NI PCI-4461 is as following: 2 simultaneously sampled analog inputs interfaces; 2 simultaneously updated analog outputs interfaces; 118 dB dynamic range, 24-bit resolution; 204.8 KS/s maximum sampling rate; 92 kHz alias-free bandwidth; input range from ± 316 mV to 42.4 V.

In the plan of difference method, for calibrating the electronic transformer with digital output, first the data packets from merging unit of electronic transformer are decoded in the IPC by application software, and then the current/voltage values obtained from data packets are converted into analog signal by NI PCI-4461 after being processed by interpolation algorithm. It should be noted that the interpolation algorithm is used to eliminate phase error caused by digital-to-analog conversion. After the above-mentioned processing, the analog output of digital-to-analog converter in NI PCI-4461 is processed by balancing compensation module, and then it is compared with the analog output of standard transformer in the difference measurement module. At last, the outputs of difference measurement module and standard transformer are simultaneously sampled by analog-to-digital converters in NI PCI-4461, so ratio error and phase error can be computed according to Eq.(3) and Eq.(4) by the application software. For calibrating the electronic transformer with analog output based on difference method, we use the principle similar to that of calibrating the electronic transformer with digital output, in which the operation of digital-to-analog conversion can be omitted.

In our design scheme, the precision signal adjustment module is used to convert the secondary output of standard transformer to small voltage signal, so the signal can be sampled by data acquisition card. In order to improve the measuring precision of difference method, the balancing compensation module is used to compensate for the phase and amplitude of signal under test roughly. To make the scheme easier to understand, we will introduce some key technologies in details, such as implementation of signal adjustment module, design of network data capture and analysis module, selection of error analysis algorithm and so on.

3.1. Implementation of Signal Adjustment Module

The secondary outputs of standard voltage and current transformers are 57.7 V and 0.1 A, 1 A or 5 A respectively, which cannot directly be sampled by analog-to-digital conversion. To satisfy the requirements of data acquisition card for sampled signals and to make it more suitable for practical calibration, a precision signal adjustment module has to be designed. It should meet the needs of signal transformation both for standard current and voltage transformer outputs. In our scheme, the adjustment module consists of linear regulated power supply circuit, voltage transformation circuit, current transformation circuit and relay driving circuit, whose block diagram is shown in Figure 5.

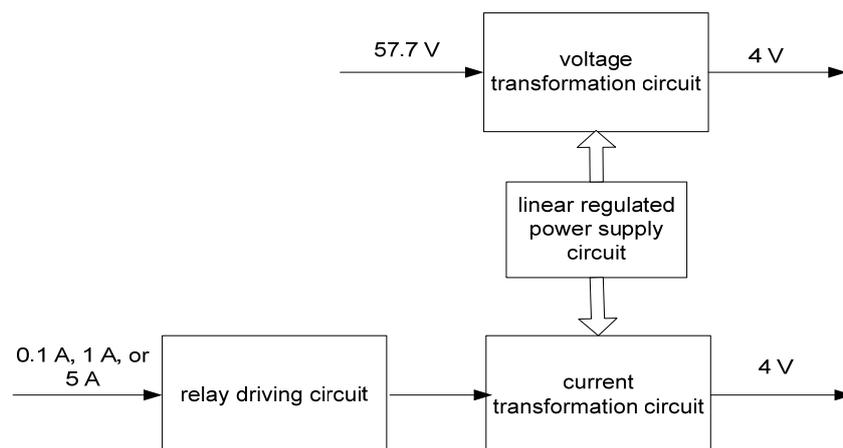


Figure 5. Block diagram of signal adjustment module

Among them, the linear regulated power supply circuit provides power for current and voltage transformation circuits. After inputting AC 220 V, it can generate three kinds of outputs,

DC +12 V, -12 V and +5 V. In the voltage transformation circuit, a precision resistor is used to divide the voltage output of AC 57.7 V from the standard transformer, and then followed by an operational amplifier to output a voltage signal of AC 4 V suitable for analog-to-digital conversion. The current transformation circuit is also adopted to transform the secondary currents of 0.1 A, 1 A or 5 A from the standard current transformer to a voltage signal of AC 4 V. To switch from 0.1 A, 1 A and 5 A, a relay driving circuit is employed. Considering the accuracy demand for calibration, some experiments are conducted to test the error of signal adjustment module. And the results are shown below.

Table 1. Error Test Results of Signal Adjustment Module

1. Current transformation		
Percentage	Amplitude transformation error (%)	Phase transformation error (°)
100%	0.019	0.45
50%	0.018	0.33
20%	0.003	0.23
10%	-0.007	0.17
2. Voltage transformation		
Percentage	Amplitude transformation error (%)	Phase transformation error (°)
120%	-0.012	-0.37
100%	-0.011	-0.26
80%	-0.012	-0.52

From Table 1 we can see the accuracy of voltage and current transformation parts in signal adjustment module can exactly meet the design requirements.

3.2. Design of the Network Data Capture and Analysis Module

Electronic transformers have two kinds of output: digital signals and analog signals. The electronic transformer with digital output follows IEC 61850-9-1/2 standard, and packets the sampled values of primary current and voltage signals into a message, which is to be exported through the network port. The IEC 61850-9-1 standard illustrates a unidirectional multidrop point-to-point fixed link mapping, which only supports the "SendMSVMessage" service. To meet real-time requirements, application layer data is mapped directly to the data link layer in communication, thus the presentation layer, session layer, transport layer and network layer is all empty. The IEC 61850-9-2 standard illustrates a mapping based on ISO/IEC 8802-3 link and mixed protocol stack. On the one hand, it supports both the "SendMSVMessage" service, which is mapped directly to the link layer, and the "GetMSVCBValues/SetMSVCBValues" service, which is mapped to MMS (Manufacturing Message Specification). On the other hand, it can not only support point to point communication, but also transform data on the network. In general, to calibrate the electronic transformer with digital output, we have to receive and analyze its network data package firstly. This design uses application software that runs on the industrial personal computer to finish the above function, which is developed based on WinPCap toolkit.

WinPcap network developing toolkit is based on Windows system and provides direct access to network for win32 applications, by using which, underlying network packets can be captured, sent and filtered conveniently. Based on WinPCap toolkit, we can develop applications on the computer easily to receive and analyze the network packets from electronic transformers with digital outputs, so the design and development process of the system is simplified greatly.

WinPCap includes a module running on operating system kernel level, which can provide a direct interface to the network device driver. By this way, WinPcap can bypass the communication protocol stack and provide packets from the link layer for upper applications

directly. In addition, a dynamic link library at the bottom named Packet.dll and one library independent of the operating system named Wpcap.dll are also provided by WinPCap. WinPCap fully considers the optimization of the performance and efficiency, so after setting the Ethernet card correctly, capturing or sending messages on the network can reach microsecond level by using the functions provided by it. Consequently, the delay requirement of IEC 61850 for sampled value messages can be satisfied. In general, the steps of packet capture and analysis using WinPCap are shown as follows:

Step 1: Find and open the network equipment.

Step 2: Set filter conditions and only capture the messages of sampled values. The IEC 61850-9-2 messages include GOOSE (Generic Object Oriented Substation Event) messages and sampled value messages, where Ethernet type code is used to distinguish these two kinds of messages. The Ethernet type code of GOOSE messages is 0x88b8, and that of sampled value messages is 0x88ba. In our system, we focus only on the sampled value messages, which are used for applying voltage and current signals to devices. So there is a filter condition should be set that the Ethernet type code must be 0x88ba, by this way only those messages of sampled values will be captured.

Step 3: Capture data packets. WinPCap provides two kinds of methods to capture network packets namely the callback mode and the direct mode. We use direct mode in the system because of the high real-time requirement of the sampled value messages, so that whenever a packet arrives at the network device, WinPCap just captures and returns it to the user. In the direct mode, packet capture process is similar to the way of interrupt, which has higher execution efficiency.

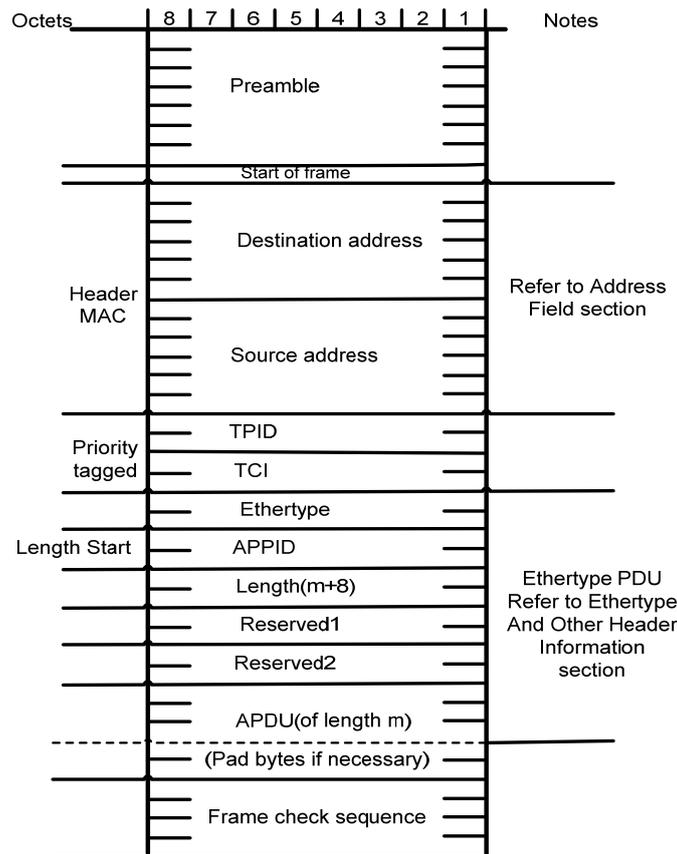


Figure 6. Format of Ethernet frame with priority

Step 4: Analysis data packets. For calibration, firstly, we should parse the sampled value messages from electronic transformers captured by WinPCap. IEC 61850-9-1/2

messages use the Ethernet frame format with priority based on ISO/IEC 8802-3. The frame format is defined as shown in Figure.6, where we can see that PDU is application data unit, including sampled values and other related information, and the outside part of PDU includes network information such as preamble, MAC address and so on, by using which we can determine the correctness of the message. In this step, the corresponding sampled data of voltage or current signal is extracted from PDU according to the type of the electronic transformer under test.

In our design, the system application software is developed based mainly on LabVIEW. So we package the network data capture and analysis functions based on WinPCap for a dynamic library, which provides parameters configuration, data output and other function interfaces. LabVIEW uses the CLF (Call Library Function) node to call library functions.

3.3. Selection of Error Analysis Algorithm

In order to compute the ratio error and phase error, the RMS value and phase of fundamental component of the input signal should be obtained firstly by Fourier transformation. FFT is usually used in power harmonic analysis and detection, where synchronous sampling is required. But in fact, the sampling frequency of analog-to-digital converter is not an exact multiple of the signal frequency, which is fluctuant. Consequently, in the practical application, FFT can cause unavoidable signal spectral leakage and picket fence effect. In order to reduce the effect of signal spectral leakage and picket fence effect, the sampled signals should be multiplied by a weighting window before FFT. This paper uses the weighting window $\omega(n)$ as follows:

$$\omega(n) = \begin{cases} \frac{1}{6}n^3 - \frac{1}{6}n & 0 \leq n \leq \frac{N}{4} - 1 \\ -\frac{1}{2}n^3 + \frac{N}{2}n^2 + (\frac{1}{2} - \frac{N^2}{8})n + (\frac{N^3}{96} - \frac{N}{6}) & \frac{N}{4} \leq n \leq \frac{N}{2} - 1 \\ \frac{1}{2}n^3 - Nn^2 + (\frac{5}{8}N^2 - \frac{1}{2})n + (\frac{N}{3} - \frac{11}{96}N^3) & \frac{N}{2} \leq n \leq \frac{3N}{4} - 1 \\ -\frac{1}{6}n^3 + \frac{N}{2}n^2 + (\frac{1}{6} - \frac{N^2}{2})n + \frac{1}{6}(N^3 - N) & \frac{3N}{4} \leq n \leq N - 1 \end{cases} \quad (5)$$

$$W(e^{j\omega}) = \frac{\sin^4(N\omega/8)}{\sin^4(\omega/2)} e^{-j\frac{N}{2}\omega} = W_0(\omega)e^{-jC\omega} \quad (6)$$

where $W_0(\omega) = \frac{\sin^4(N\omega/8)}{\sin^4(\omega/2)}$, $C=N/2$. Eq.(5) and Eq.(6) are respectively time-domain and

frequency-domain expressions of the weighting window proposed in this paper, which can reduce spectral leakage and decrease the interference of harmonics effectively [7].

Electric signal can be expressed by $x(t) = \sum_{i=0}^p A_i \cos(2\pi f_i t + \varphi_i)$, where f_i , A_i and φ_i

are respectively the frequency, amplitude, and phase of the i^{th} harmonic; p is the order of the highest harmonic. Meanwhile, we assume that $x(n)$ is the discrete expression of $x(t)$. The window function $\omega(n)$ given by Eq.(5) is used to weight $x(n)$, and the weighted signal $x_\omega(n)$ is given by follows:

$$x_\omega(n) = x(n) \cdot \omega(n) \quad n = 0, 1, 2, \dots, N - 1. \quad (7)$$

Considering of asynchronous sampling, we assume that

$$\frac{T_\omega}{T_1} = m + \lambda. \quad (8)$$

where T_1 is the period of electric signal, T_ω is the sampling time, m is a integer that is nearest to T_ω/T_1 , and λ is the remainder. By combining Eq.(5), (6), (7), (8), we can obtain the formulas of computing the fundamental amplitude A and phase φ of $x(n)$, which are shown as follows:]

$$A = 2|X_\omega(m)|/[W_0(-\lambda\Delta\omega)]. \quad (9)$$

$$\varphi = \arg[X_\omega(m)] - C\lambda\Delta\omega. \quad (10)$$

where $\Delta\omega=2\pi/N$, $X_\omega(k)$ is the FFT spectrum value of $x_\omega(n)$. In order to compute λ , we assume that N is an even number, let $x_1(n)=x_\omega(n)$ and $x_2(n)=x_\omega(N/2+n)$, where $0\leq n\leq N/2-1$. Meanwhile, we assume that $X_1(k)$ and $X_2(k)$ are the FFT spectrum values of $x_1(n)$ and $x_2(n)$, and the corresponding phase values are $\Phi_1(k)$ and $\Phi_2(k)$, where $k=0,1,2,\dots,N/2-1$. Then there is $\lambda=(\Phi_1(m)-\Phi_2(m))/2\pi$.

4. Conclusion

After studying two calibration approaches of electronic transformers, namely the direct method and the difference method, a multi-way electronic transformer calibrator is proposed in this paper. Based on virtual instrument technology, the calibration device mainly relies on the software algorithm and uses the data acquisition system as an adjunct. It can effectively calibrate the electronic transformers both with digital output and analog output. In addition, the calibration device adopts two kinds of calibration methods at the same time, making its application expanded, the equipment redundancy ensured and the reliability of the system improved.

Acknowledgement

This work was financially supported by General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China.

References

- [1] Sabahi M, Goharrizi AY, Hosseini SH, Sharifian MBB and Gharehpetian GB. Flexible Power Electronic Transformer. *IEEE Transactions on Power Electronics*. 2010; 25(8): 2159-2169.
- [2] Zhi Zhang, Li Hongbin. An Accurate System for Onsite Calibration of Electronic Transformers with Digital Output. *Review of Scientific Instruments*. 2012; 83(6): 065111- 065111-7.
- [3] Ning Weihong, Yang Yihan, Li Jing, Zhang Guoqing and Yu Wenbin. Review on Development of Transformer Calibration. *Power System Protection and Control*. 2009; 37(10): 131-135.
- [4] Chen Wensheng, Gu Lixin. Research on the Application of Electronic Voltage Transformer. *East China Electronic Power*. 2009; 37(8): 1327-1330.
- [5] Yang Huixia, Guo Wei and Deng Yingjun. Study and Comparison on Several Different Electronic Transformer Calibration Methods. *Power System Protection and Control*. 2009; 37(22): 99-101.
- [6] Hu Haoliang, Li Qian, Lu Shufeng, Yang Shihai, Li He and Li Dengyun. Comparison of Two Electronic Transformer Error Measuring Methods. *High Voltage Engineering*. 2011; 37(12): 3022-3027.
- [7] Chen Fusheng, Ou Chaolong, Wan Quan and Li Kai. Design and Development of Calibrator for the Electronic Transformer. *Electronic Measurement & Instrumentation*. 2011; 48(541): 55-58.