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SYSTEM FOR CALIBRATING ANALOGUE MERGING UNITS IN ABSENCE OF SYNCHRONIZATION SIGNALS

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Abstract

Synchronization signals are requisite for calibrating electrical measurement devices with digital output when using conventional calibration methods. However, since the signal sampling process of the analogue merging units (MUs) operating in an intelligent substation does not rely on external synchronization signals, accuracy calibration without the use of synchronization signals is of particular importance in order to guarantee the measurement accuracy in practical situations. So far, very little research on calibration systems independent of synchronization signals has been performed. This paper presents a design of the calibration system without dependence on synchronization signals. To verify the feasibility of the proposed design, the designed system and a conventional calibration system have been employed in testing the accuracy of the same analogue MU of a 0.2 accuracy class. The comparison of the test results shows that the differences of ratio errors are below 0.02%, and the maximum difference of phase errors is about 4′. This paper also provides a new efficient and significant calibration method which does not require any external synchronization signals.

Keywords: intelligent substation, analogue merging unit, peer-to-peer communication, calibration system, synchronization signal.

1. Introduction

Electronic transformers (ETs) have been widely applied to intelligent substations in the past few years [1–4]. However, the ETs are unable to meet the engineering application requirements due to their poor long-term stability and reliability [5, 6]. Considering the actual situations, analogue MUs are employed in the new generation of intelligent substations in China. The analogue MUs exhibit high stability and reliability, and meet the requirements of digitization. P. Castello and R. Rasolomampionona *et al.* have designed MUs and described their constructions and operations [7, 8].

In a substation, the primary large current and high voltage are transformed to relatively week signals, such as 5 A/1 A and 100 V/57.7 V, by conventional electromagnetic transformers firstly. Then, the analogue MUs sample the output signals from the electromagnetic transformers at a

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4 kHz sampling rate (80 points per cycle). The sample values (SVs) are eventually transferred to the relay protection and metering equipment. Since the analogue MUs serve as the data source of subsequent digital devices, so – if their measurement errors exceed specified limit values – either the related relay protection may operate incorrectly or the electrical energy is metered inaccurately. In order to guarantee the measurement accuracy of analogue MUs, accuracy calibrations are essential before putting them into operation.

The digital outputs of analogue MUs are discrete in nature, so – as a result – the absolute rather than differential measurement should be employed in accuracy calibration, and synchronization signals are requisite for obtaining phase and ratio errors accurately. Substantial research effort on accuracy calibration methods for analogue MUs has been carried out [9–11]. M. Gurbiel *et al.* proposed a test procedure which is applied towards the testing of analogue MUs [9]. C. A. Dutra *et al.* applied a digital fault recorder (DFR) towards implementation of the accuracy test [10]. A. Uzoamaka *et al.* performed a number of performance tests including the accuracy test [11]. It can be seen that all the existing calibration methods require synchronization signals such as pulse-per-second (PPS) and/or IRIG-B code applied towards synchronizing the analogue MU under test and the reference one.

However, in order to improve the reliability, the signal sampling process of analogue MUs should not rely on any external synchronization signal according to the technical guide for a smart substation, and a peer-to-peer communication is used in the process-to-bay level network to transmit the sampled values (SVs) in intelligent substations [12, 13]. Therefore, accuracy calibration without the use of synchronization signals should be recommended in order to guarantee the measurement accuracy in practical situations. For these reasons, research on the calibration systems' independence of synchronization signals is critically essential in validating the measurement errors of analogue MUs. H. Hu *et al*. have designed the first calibration system independent of synchronization signals, and used it to test an electronic instrument transformer [14], but the test results show that the accuracy of phase verification is about $20'$, which is unsatisfactory. This paper presents a design of calibration system for analogue MUs that does not require synchronization signals, and the accuracy of phase verification is about $4'$. Two key contributions are the structure design and the data synchronization method.

2. Design

The purpose of calibrating AC voltage/current measurement instruments is to obtain the amplitude and phase measurement errors. To construct a calibration system for analogue MUs, three key and necessary techniques, which can be summarized from many references [15–17], are: (1) building a high-accuracy standard measurement system which is also referred to as the reference; (2) synchronizing the data of the reference and the analogue MU under test; and (3) selecting an appropriate calibration algorithm to calculate the amplitude and phase error values. This paper focuses on how to obtain synchronization without using external synchronization signals.

2.1. Structure design

Since some working features shall be utilized in the structure design, it is necessary to address firstly how an analogue MU operates. As mentioned before, an analogue MU samples analogue output signals from conventional transformers at a 4 kHz sampling rate, then groups the SVs in standardized IEC61850-9-2(LE)-complied data frames which are then transmitted via the Ethernet. A sampling counter (smpCnt) located in the data frames counts from 0 to 3999 during the sampling process [18]. The time interval of the output sequences of an analogue MU is 250 μs, as shown in Fig. 1.

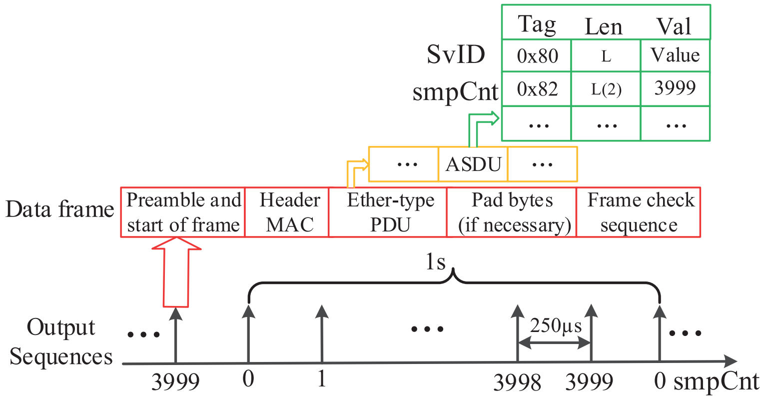

Fig. 1. Output sequences of an analogue MU.

The designed system consists of: (a) the measurement reference; (b) an IEC61850-9-2(LE)-complied hardware protocol analyser; (c) a high-precision time-interval measurement unit (TMU); (d) an industrial personal computer (IPC) with calibration software. A structure diagram of the designed system is presented in Fig. 2.

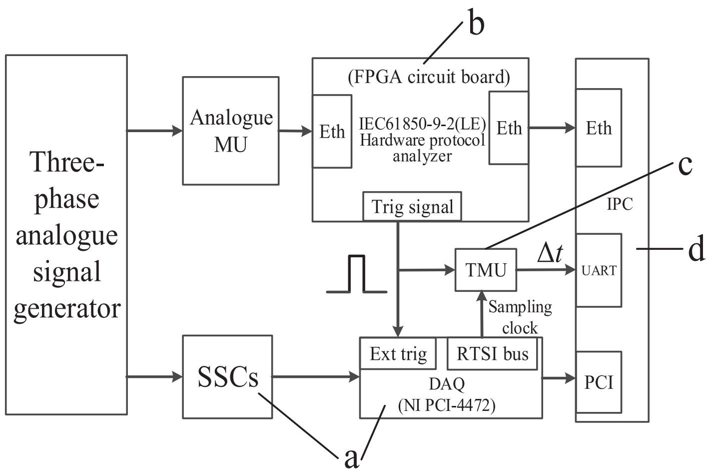

Fig. 2. A structure diagram of the designed system.

The measurement reference consists of standard second converters (SSCs) and a high-accuracy data acquisition (DAQ) card NI PCI-4472. The SSCs are instrument current/voltage transformers of a 0.02 accuracy class. The NI PCI-4472 is a 24-bit DAQ card with an on-board calibration reference with a ± 5 ppm/° temperature coefficient. Since an amplitude range of the input signal is ± 10 V, the SSCs are used for precise converting large signals to smaller than ± 10 V ones.

In order to meet the real-time requirement, the hardware protocol analyser is implemented with Verilog hardware description language on a field programmable gate array (FPGA) circuit board. The protocol analyser has two functions; one working as a data router, and the other generating a trigger signal. The DAQ card is triggered once the protocol analyser receives a data frame whose smpCnt value is 0.

The TMU is actually a time-to-digital converter [19]. According to practical requirements, if a frequency of counting pulse is 50 MHz, the TMU is able to measure the time interval with a precision of $\pm 0.02\ \mu$s.

Time-related sampling sequences of an analogue MU and the reference are shown in Fig. 3 during operation of the system shown in Fig. 2.

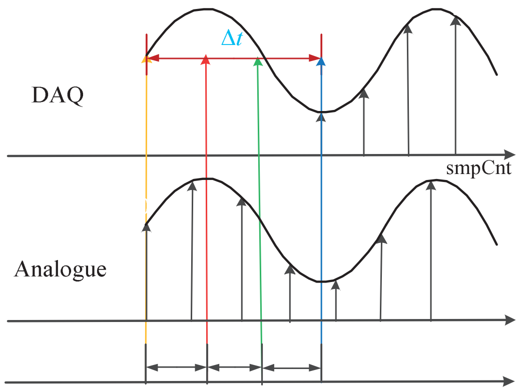

Fig. 3. Time-related sampling sequences of the analogue MU and the reference.

In Fig. 3, suppose the analogue MU samples signals at t_1, and then groups the SVs in a data frame whose smpCnt value is 0. After Δt_1, the data frame will appear at the data port of the analogue MU. The hardware protocol analyser receives the data frame at t_2, and then generates a trigger signal after Δt_2. The DAQ card receives the trigger signal at t_3, and starts to sample signals at t_4. Therefore, the time difference between the sampling moments of the two measurement systems is determined by the following formula (1):

$$\Delta t = \Delta t_1 + \Delta t_2 + \Delta t_3\,. \tag{1}$$

In the formula (1), Δt_1 which is a fixed value related to the hardware performance of the analogue MU is defined as a rated time delay and given by the analogue MU; Δt_2 is also a fixed value related to the hardware performance of the protocol analyser; Δt_3 can be measured by the TMU.

2.2. Data synchronization

The purpose of data synchronization is to eliminate the time difference of two sampling moments. Various methods are employed in the synchronization design. Interpolation methods need complex hardware [20, 21]. A phase-shift method is proposed by Z. Yao *et al.* [22], but its accuracy is influenced by the signal frequency, which can be seen from the derivation. In this paper, a phase-shift method based on the least-square fitting is presented, and the recursion formula is derived as well [23].

The phase-shift method is shown in Fig. 4. Suppose that the SV at T2 is A', and A'' at T1 can be calculated, then regard the A'' as the SV at T2. As a result, the solid line S can be achieved by shifting the dotted line S' with this method.

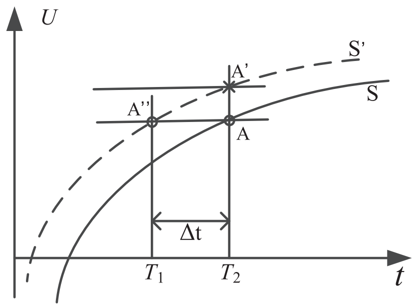

Fig. 4. A schematic of phase shift.

This paper employs the three-order polynomial fitting with eight-points, and the derivation process is presented as follows.

(1) The basic functions are $g_0(t) = 1$, $g_1(t) = t$, $g_2(t) = t^2$, $g_3(t) = t^3$. Therefore, the fitting function is

$$g(t) = k_0 + k_1 t + k_2 t^2 + k_3 t^3. \tag{2}$$

(2) Suppose that the values of eight points received from t_0 are $g(t_0)$, $g(t_1)$, $g(t_2)$, $g(t_3)$, $g(t_4)$, $g(t_5)$, $g(t_6)$, $g(t_7)$. We can obtain the following set of equations:

$$\begin{cases} k_0 + k_1 t_0 + k_2 t_0^2 + k_3 t_0^3 = g(t_0) \\ k_0 + k_1 t_1 + k_2 t_1^2 + k_3 t_1^3 = g(t_1) \\ \vdots \\ k_0 + k_1 t_7 + k_2 t_7^2 + k_3 t_7^3 = g(t_7) \end{cases}. \tag{3}$$

(3) The set of equations (3) can be rewritten as

$$Gk = y. \tag{4}$$

In the equation (4), $G = \begin{pmatrix} 1 & t_0 & \cdots & t_0^3 \\ 1 & t_1 & \cdots & t_1^3 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & t_7 & \cdots & t_7^3 \end{pmatrix}$, $k = (k_0, k_1, k_2, k_3)^{\mathrm{T}}$, $y = (g(t_0), g(t_1) \ldots g(t_7))^{\mathrm{T}}$, then the following result can be proved:

$$k = (G^{\mathrm{T}} G)^{-1} G^{\mathrm{T}} y. \tag{5}$$

(4) Suppose that $h(t_7)$ is the result of moving $g(t_7)$ Δt_4 forward, then the value of $h(t_7)$ is given by:

$$h(t_7) = k^{\mathrm{T}} \begin{pmatrix} 1 \\ t_7 - \Delta t \\ (t_7 - \Delta t)^2 \\ (t_7 - \Delta t)^3 \end{pmatrix}. \tag{6}$$

(5) By combining the equations (5) and (6), $h(t_7)$ can be derived by:

$$h(t_7) = \mathbf{y}^{\mathrm{T}}(K_1, K_2 \ldots K_8)^{\mathrm{T}}, \tag{7}$$

where K_1, K_2, …, K_8 are called phase-shifting constant coefficients which are given by

$$(K_1, K_2 \ldots K_8)^{\mathrm{T}} = \left((\mathbf{G}^{\mathrm{T}}\mathbf{G})^{-1}\mathbf{G}^{\mathrm{T}}\right)^{\mathrm{T}} \begin{pmatrix} 1 \\ t_7 - \Delta t \\ (t_7 - \Delta t)^2 \\ (t_7 - \Delta t)^3 \end{pmatrix}. \tag{8}$$

The discrete form of equation (7) is

$$e_{out}(n) = K_1 e(n) + K_2 e(n-1) + \cdots + K_8 e(n-7), \tag{9}$$

where $e_{out}(n)$ is a result of moving $e(n)$ Δt forward, and constant coefficients have a significance only when designing an analogue filter [24].

The feature of recursion makes it easy enough for the algorithm to be implemented with hardware. The implementation schematic is shown in Fig. 5, and z^{-1} means 1 unit delay.

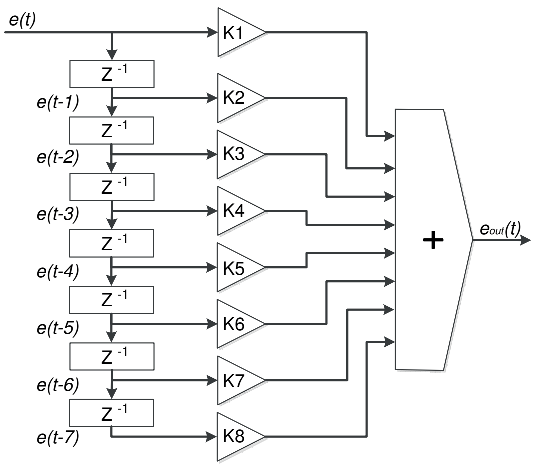

Fig. 5. A schematic of implementation with hardware.

2.3. Algorithm simulation

The simulations were performed to verify the algorithm feasibility. A sampling rate was set to 4 kHz, and Δt values were set to 62.5 μs and 250 μs. The values of phase-shifting constant coefficients, which are calculated according to the equation (8), are listed in Table 1, whereas the simulation results – in Table 2.

It can be seen from Table 2 that the three-order polynomial fitting with eight-points has a high precision and accuracy.

Table 1. Phase-shifting constant coefficients.

Δ*t*	**phase-shifting constant coefficients**							
	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8
62.5 μs	−0.1393	0.1821	0.1527	−0.0452	−0.2294	−0.2175	0.1728	1.1237
250 μs	−0.5000	0.5714	0.5714	0.0000	−0.6429	−0.8571	−0.1429	2.0000

Table 2. Simulation results.

Δ*t*	**Ratio error (%)**	**Phase error (′)**
62.5 μs	−0.0056	−0.05
250 μs	−0.0256	−0.27

3. Error analysis and application test

3.1. Error analysis

An error limit is used to evaluate the measurement accuracy of the designed system. The error sources in the designed system are: (1) the protocol analyser causing a time delay; (2) the TMU introducing a time measurement error; (3) the data synchronization algorithm; (4) the SSCs; and (5) the DAQ card NI PCI-4472. The specific errors of (1) and (2) can be measured accurately. The absolute errors caused by (3) are less than 0.0256% in magnitude and $0.27'$ in phase. The errors contributed by (4) and (5) are determined by verification. The error components based on a series of test data and calibration or verification certificates at a rated test point, are listed in Table 3.

Table 3. Absolute error components of the designed system.

Source	**Ratio error f (10^{-4})**	**Phase error δ (′)**
1	0.00	0.03
2	0.00	0.03
3	2.56	0.27
4	0.25	0.26
5	0.34	0.30

Since the error components above are independent of each other, the absolute complete ratio error and phase error limits are 0.0315% and $0.89'$, respectively. According to the uncertainty evaluation method of class B, the uncertainties of ratio and phase measurement are 0.018% and $0.51'$ $(k = 2)$, respectively.

3.2. Application test

The designed and conventional calibration systems have been employed to calibrate the same analogue MU of a 0.2 accuracy class. The accuracy class of the conventional calibration system is 0.05, and the uncertainties of ratio and phase measurement are 0.017% and $0.51'$ $(k = 2)$, respectively. The test results of three voltage measurement channels are presented in Table 4 and Table 5 (the test results of current measurement channels are not shown).

Table 4. Test results obtained with the conventional calibration system.

Voltage (Rated %)	Errors of Phase A		Errors of Phase B		Errors of Phase C	
	f (%)	δ (′)	f (%)	δ (′)	f (%)	δ (′)
80	−0.064	−3.08	0.005	−4.23	0.018	−1.98
100	−0.049	−3.34	0.007	−4.32	0.026	−2.38
120	−0.041	−2.26	0.007	−2.88	0.029	−1.21

Table 5. Test results obtained with the designed calibration system.

Voltage (Rated %)	Errors of Phase A		Errors of Phase B		Errors of Phase C	
	f (%)	δ (′)	f (%)	δ (′)	f (%)	δ (′)
80	−0.051	0.11	0.004	−0.62	0.015	1.80
100	−0.041	0.32	0.006	−0.33	0.022	1.85
120	−0.044	−2.38	−0.003	−2.71	0.017	−0.93

Comparing the test results, the differences of ratio errors are below 0.02%, and the maximum of phase error difference is about $4'$. The differences of ratio errors are small enough to be neglected. However, the case of phase error differences is different, since the actual values of Δt_1 are certainly random. Fluctuations of Δt_1, according to the electric power industry standard [25], are limited within ± 10 μs (1 μs corresponds to $1.08'$ at a normal frequency of 50 Hz). The experiments performed in Xuchang KETOP Electrical Apparatus Testing & Research Institute in 2012 demonstrated that the fluctuations of Δt_1 are less than 4 μs. That is to say, the calibration results coincide with the results of actual experiments. In the reference [14], the largest phase error difference is about $20'$; the system designed in this paper reduces this value to about $4'$.

4. Conclusions

Aimed at developing practical applications, this paper presents a calibration system without dependence on synchronization signals. Also, a new efficient and significant calibration method for analogue MUs is described. As explained earlier in this paper in Section 1, since the phase errors listed in Table 5 are the actual errors contributed by the subsequent pieces of equipment associated with the relay protection devices, the calibration method without the use of synchronization signals should be recommended when accomplishing accuracy calibrations.

The satisfactory performance of the designed system benefits from good data synchronization, which can reduce the phase calibration error. Because the problem of NI PCI 4472 is that the synchronous triggering is not strictly synchronous with the signal sampling, phase calibration errors will be introduced. The TMU has been used for measuring the time difference between triggering and sampling of the DAQ, so it is possible to correct the phase errors. In addition, the digital phase-shift method proposed in this paper exhibits a good performance in terms of accuracy and stability. The results of performed application tests show that the phase errors has been reduced from the original $21'$ to the present ones of about $4'$, which indicates that the designed system has a higher accuracy in phase calibration.

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