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Passive-compensation clamp-on two-stage current transformer for online calibration

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Abstract

Digital measurement equipment such as electronic transformers enable real-time functional control and monitoring systems to be built in power grids to accommodate the large-scale access of distributed renewable energy to the grid. However, the current offline calibration of electronic transformers is difficult to implement; therefore, an online calibration method for electronic transformers must be developed to ensure their accuracy. The design of a clamp-on two-stage current transformer (CTS-CT) with a passive compensation loop is presented herein. The compensation loop is utilised to reduce both the amplitude and phase errors, thereby achieving high accuracy. The formulas for calculating the resistance and capacitance of the passive compensation loop are presented. The expanded uncertainties (95% confidence level) of the proposed CTS-CT are estimated to be lower 0.03% for the amplitude error and 1′ for the phase error. Experimental results indicate that the proposed CTS-CT prototype is not affected by the external magnetic field nor the opening and closing times, thereby enabling good-quality online calibration for field applications. Moreover, the proposed CTS-CT adopts neither an active compensatory circuit nor software compensation; therefore, the manufacturing of the CTS-CT is steady and simple, and the calibration procedures are simplified.

1 INTRODUCTION

In response to global warming, countries worldwide have proposed low-carbon development requirements for energy systems. The large-scale integration of distributed renewable energy into the power grid causes significant and unprecedented changes in the power grid. Future power grid research plans have been developed in European institutes, and it has been indicated that the future power grid will require a control and monitoring system with real-time functions to ensure stability under increasingly complex and challenging conditions for distributed energy access [1]. Related measurement systems must be managed by accurate and reliable time synchronisations over a large range [2], and traditional analogue measurement equipment will not be able to optimally support the requirements of rapid control of the power grid [3]. Hence, the digital intelligence of the electronic current transformer (ECT) as a measuring equipment will be indispensable.

In recent years, with the development of smart grids, ECTs have been used in large-scale pilot applications [4]. ECTs, as key measurement equipment for power grids, must be calibrated regularly to ensure the accuracy of their measurement performance. According to the requirements of China's technical management regulations for electric energy metering devices, the calibration period of electromagnetic current and voltage transformers should not exceed 10 years [5], and the calibration period of capacitive voltage transformers shall not exceed 4 years. Because ECTs contain numerous electronic components, their stability is lower than that of traditional electromagnetic transformers. The calibration period of ECTs must be set to be shorter than that of the traditional electromagnetic transformer. If the calibration period of the electric energy meter for trade settlement in the substation is 2 years at the maximum based on different gate types, then the periodic calibration workload of the ECTs will be two to five times that of the traditional electromagnetic transformer, and the actual
implementation will become more difficult because of offline calibration. Therefore, the online calibration method of ECTs [6] must be further improved such that the calibration of ECTs without power failure can be realized and the calibration efficiency can be improved.

The principles of the online and offline calibration tests are similar [7]. The reference current transformer (CT) and the transformer to be calibrated are connected to the same circuit to determine the difference between them. The online calibration test circuit can be built automatically when the substation is in operation. The easy assembly of the reference CT is key to realising online calibration.

In a previous study [8], the open Rogowski coil CT was used as the reference CT; however, the air gap of the Rogowski coil affected its accuracy. Even if the printed circuit boards printed circuit board manufacturing process is adopted, the size of the open air gap must be less than 0.1 mm to achieve an accuracy of 0.05% [9]. In addition, the skeleton structure is easily affected by environmental factors, and the open Rogowski coil reference CT must be calibrated using a diverter before calibration is performed [10].

NXCT-F3 produced by Alstom can realise the online calibration of a transformer rated up to 550 kV; however, its accuracy does not fulfil the requirement of 0.1% [11]. Rahmatian introduced the application of optical voltage transformer (VT) and CT in online testing. The accuracy of the optical VT was 0.2%, whereas the accuracy of the optical CT was not provided comprehensively [12]. Josemir et al. [13] developed a clamp-on optical CT with an accuracy of 0.03%; however, no relevant test data were reported. Meanwhile, the optical CT is sensitive to temperature. Hence, the effect of the external magnetic field increases after the opening and errors are generated, thereby rendering it difficult to achieve a magnitude error accuracy of 0.05% [14].

Soft magnetic materials with high permeability and low eddy current loss are often used to improve the performance of core CTs. However, the effective permeability of the soft core is decreased significantly by the air gap. An uncompensated CT renders it difficult to realise high-precision measurement performance. The clamp-on CTs designed by Eddy and David Bennett adopt a multicore structure with a shielding device and use a high-magnification operational amplifier to form an active compensation circuit to achieve high precision [15]. Houtzager proposed an improved operational amplifier compensation circuit to improve the accuracy of clamp-on CTs, but the compensation structure remained extremely complex [16]. The multicore clamp structure CT developed by John uses operational amplifiers to form an active compensation circuit, which can achieve an accuracy of ratio error of less than 0.05% and a phase error less than 10° [17]. Doig et al. developed an open-type double-core CT for power system protection that uses an active compensation circuit composed of operational amplifiers, and high accuracy was achieved [18].

In this study, a clamp-on two-stage current transformer (CTS-CT) based on a two-stage CT [19] is proposed to develop a new clamp-on core reference CT. Compared with the clamp-on core transformer based on the current comparator principle, it simplifies the design of the compensation circuit, does not require software compensation, and is easier to manufacture. Furthermore, because the principle of a two-stage CT is applied, compared with the classical clamp-on single-stage core reference transformer, the error created by the air gap is reduced. When the air gap is within 0.3 mm, the accuracy is less than 0.05%, which renders the online calibration in substations more applicable.

The structure of this paper is as follows: In Section 2, the principle of the CTS-CT is introduced, and the error compensation formula is presented. Section 3 introduces the structural design and related parameters of the transformer. Section 4 introduces the error compensation test for an open two-stage core reference transformer. In Section 5, the detailed test of the prototype, which was performed based on three aspects, that is, the air gap opening, effect of external magnetic field, and opening and closing repeatability tests, is presented, followed by the results of measurement uncertainties. Section 6 presents the conclusions of this study.

2 | PRINCIPLE OF HIGH-ACCURACY CTS-CT

A schematic illustration of the proposed CTS-CT is shown in Figure 1. Iron cores I and II are the primary and auxiliary iron cores, respectively. \( n_1 \) is the primary winding, \( n_2 \) and \( n_3 \) are the secondary windings, and \( n_3 \) is the tertiary winding. \( n_f \) and \( n_g \) are the windings on the auxiliary iron core, which form the compensatory loops with resistance \( R \) and capacitance \( C \) to compensate for the amplitude and phase errors, respectively. \( Z_L \) is the load impedance, and is \( Z_3 \) the feedback impedor.

The magnetomotive force (MMF) equation [19] for iron core I is as follows:

\[
 n_1 i_1 + n_f i_2 + n_3 i_3 = n_1 i_{b1} .
\]  

In Equation (1), \( i_{b1} \) is the excitation current of iron core I. Before the compensatory loops are introduced, iron core II operates close to the zero-flux state (when the load is approximately zero, the core magnetic density can be as small as 8 Gs) [20], where the accuracy of the two-stage CT can be improved by optimising \( n_f, n_2, \) and \( Z_3 \) [21]. However, for the CTS-CT, the excitation current must be reduced.
After the compensatory loops are introduced, the MMF equation of iron core II becomes

\[ n_1i_1 + n_2i_2 + n_1i_f + n_5i_g = n_1i_{02}, \tag{2} \]

where \( i_{02} \) is the excitation current of iron core II. Equation (2) can be expressed as

\[ n_1i_1 + n_2i_2 = n_1i_{02} - (n_1i_f + n_5i_g). \tag{3} \]

The CT error is caused by the secondary load of the transformer, which must provide the induced potential. Hence, the core requires an excitation current, which contributes primarily to the error in the CT. After adding the compensation winding, the excitation current becomes \( n_1i_{02} - (n_1i_f + n_5i_g) \). Therefore, a combined error expression for the CTS-CT is obtained, as follows:

\[ \varepsilon = \frac{n_1i_{02} - n_1i_f - n_5i_g}{n_1i_1}. \tag{4} \]

As shown in Equation (4), a smaller \( n_1i_{02} - (n_1i_f + n_5i_g) \) results in a smaller combined error of \( \varepsilon \) the CTS-CT. When \( n_1i_{02} - (n_1i_f + n_5i_g) = 0 \) is satisfied, \( \varepsilon \) is approximately zero, suggesting complete compensation for the CTS-CT. The compensation quantities of the amplitude error \( \Delta f \) and phase error \( \Delta \delta \) are listed in Equations (5) and (6), respectively.

\[ \Delta f = \frac{i_1/n_f}{i_1/n_1} \approx \frac{n_2Z_fZ_L}{n_2n_5Z_3}, \tag{5} \]

\[ \Delta \delta = \frac{i_5n_5}{i_1/n_1} \approx \omega C \cdot n_5 \cdot \frac{n_2Z_fZ_L}{n_2n_5Z_3}, \tag{6} \]

where \( Z_f \) is the actual impedance value to insert a compensatory loop on the feedback impedor \( Z_3 \). Impedance \( Z_f \) is much lower than the impedances of \( R \) and \( C \), whereas the impedances of \( R \) and \( C \) are much higher than the excitation impedance of the loop. The current passing through \( Z_3 \) generally has the same phase as the secondary current \( i_2 \); therefore, the currents flowing through \( R \) and \( C \) primarily compensate for the amplitude and phase errors, respectively. The desired compensation quantities for the amplitude and phase errors can be obtained by adjusting the relevant parameters in Equations (5) and (6), respectively.

### 3 | DESIGN OF HIGH-ACCURACY CTS-CT

If the CTS-CT is used as a reference CT to calibrate a 0.2 class ECT, its expanded uncertainties (95% confidence level) should not exceed 0.05%.

Considering the conditions above, the parameters of the CTS-CT were designed as follows: transformation ratio, 800 A:1 A. To improve the anti-saturation feature of the CTS-CT, both iron cores I and II were prepared using silicon steel iron cores cut into symmetrical rings measuring 120 mm × 80 mm × 20 mm (silicon steel sheet was used as the iron core material; the initial permeability was 1200 H/m, and the maximum permeability was 40 000 H/m). The diameter of the copper wire of the secondary winding was 0.67 mm. As the other windings had a relatively small current (between 0.1% and 1% of the secondary winding current), copper wires with smaller wire diameters were selected. The number of turns of the secondary winding was \( n_2 = 800 \), and \( n_5 = 400 \). Meanwhile, based on the iron core size and electrical parameters, the number of turns of the feedback winding was \( n_5 = 400 \), and the number of turns of the compensatory winding was \( n_f = n_g = 400 \). The winding distributions were symmetrical. The feedback winding and compensatory winding were in the inner layers of iron cores I and II, respectively. Meanwhile, the secondary winding was distributed in the outer layer with isolation between every two layers.

The winding distribution is illustrated in Figure 2. The CTS-CT was fabricated based on the structure above. The actual image is shown in Figure 3. One side of each of the two half iron cores was fixed by a copper hinge such that the two half iron cores can be opened and closed unrestrictedly while ensuring the accuracy of their positions. The other side of each of the half iron cores was fitted with a fastening nut such that the nut can be tightened after the field installation was completed, allowing the tested primary conductor to pass through the centre of the iron core.

The secondary load of the CTS-CT, which was connected through a small CT, was measured to be 80 Ω (transformation ratio 1 A:0.05 A; the expanded uncertainty of the small CT error was less than 0.005%).

### 4 | PASSIVE COMPENSATION EFFECT TEST

#### 4.1 | Accuracy test of uncompensated CTS-CT

As shown in Equations (5) and (6), the compensation quantity for the error depends on the parameters of the compensatory loop. After the structure of the CTS-CT is determined, the \( R \) and \( C \) of the compensatory loop can be used to adjust the compensation for the error. Therefore, the amplitude and phase errors without the passive-loop compensatory loop were first tested. A diagram of the test is shown in Figure 4. The standard CT is a hollow-core electromagnetic transformer (manufacturer: Wuhan Pandian Technology Co., Ltd.; model: HLPD1000/1G18; 1% rated current; ratio error limit 0.02%; phase error limit 0.6°; 5–120% rated current; ratio error limit 0.01%; phase error limit 0.3°; rated transformation ratio 1000 A/1 A; rated load 0.25–5 VA; frequency 50 Hz). The amplitude error uncertainty of the calibrator (manufacturer: Shenzhen Xinlong Technology Co., Ltd.; model: XL 807) was 0.012%, and the phase error uncertainty of the calibrator was 0.35. The standard CT and calibrator were calibrated by the National Center for High Voltage Measurement in China.
The test current frequency was 50 Hz, and the test results are presented in Table 1.

As shown by the test results in Table 1, the CTS-CT without passive compensation did not satisfy the accuracy requirement of 0.05%. If a compensation of approximately 0.12% is performed for the amplitude error, then a compensation of $-2'$ is performed on the phase error, and the overall accuracy will reach 0.05%.

### Table 1: Error without passive compensation

| Percentage of rated current (%) | Amplitude error (%) | Phase error (') |
|--------------------------------|---------------------|-----------------|
| 5                              | 0.189               | 5.82            |
| 10                             | 0.139               | 3.16            |
| 20                             | 0.094               | 2.85            |
| 100                            | 0.076               | 2.21            |
| 120                            | 0.075               | 2.22            |

### Table 2: The error of CT with the amplitude error compensatory loop

| Percentage of rated current (%) | Amplitude error (%) | Standard deviations of amplitude error (%) | Phase error (') | Standard deviations of phase error (') |
|--------------------------------|---------------------|--------------------------------------------|-----------------|----------------------------------------|
| 5                              | 0.087               | 0.007                                       | 5.73            | 0.69                                   |
| 10                             | 0.036               | 0.003                                       | 3.08            | 0.34                                   |
| 20                             | 0.012               | 0.002                                       | 2.76            | 0.31                                   |
| 100                            | -0.024              | 0.002                                       | 2.14            | 0.25                                   |
| 120                            | -0.025              | 0.001                                       | 2.16            | 0.26                                   |

### 4.2 Function of amplitude error compensatory loop

When the feedback impedor $Z_2$ is $8 \Omega$ and $Z_f = 2 \Omega$, the compensatory resistance $R$ is 480 $\Omega$, as calculated using the amplitude error compensation equation show in Equation (5). The resistor was connected to the amplitude error compensatory loop, and the test current frequency was 50 Hz. The mean error of the CTS-CT with the amplitude compensatory loop is shown in Table 2 (the number of measurements for each test point was 10).

The results in Table 2 show that after connecting the compensatory resistor in the amplitude error compensatory loop, the amplitude error of the CTS-CT was approximately 0.1% less than that of the uncompensated CT, which is consistent with the expected result. In addition, the amplitude error compensatory loop did not compensate for the phase error.
4.3 | Function of phase error compensatory loop

The test results from Table 1 indicate that a $-2'$ compensation is required for the phase error. Using the phase error compensation equation presented in Equation (6), the $C$ of the capacitor connected in the phase error compensatory loop was calculated to be 4 $\mu F$. The mean error of the CTS-CT with the phase error compensatory loop was obtained, as shown in Table 3 (the number of measurements for each test point was 10), and the test current frequency was 50 Hz.

As shown by the results presented in Table 3, after the compensatory capacitor was connected to the phase error compensatory loop, the phase of the CTS-CT was approximately $2'$ lower than that of the no-compensation case, which is consistent with the expected result. In addition, the phase error compensatory loop did not compensate for the amplitude error.

4.4 | Accuracy test of CTS-CT with $R$ and $C$

Both the amplitude error and phase error compensatory loops were input to the CTS-CT. The test current frequency was set at 50 Hz. The mean error of the CTS-CT is shown in Table 4 (the number of measurements for each test point was 10).

As shown by the test results presented in Table 4, both the amplitude error and phase error compensatory loops improved the accuracy of the CTS-CT; at 20–120% rated current, the ratio error was lower than 0.05%, and the phase error was lower than 0.5'. At a rated current of 5%, the ratio error was 0.086%, which was greater than 0.05%, and the phase error was 0.6. However, based on IEC 61869-8, at a 5% rated current, the ratio error and phase error limits are 0.75% and 30' for ECTs, respectively. Therefore, the accuracy of the CTS-CT is sufficient to fulfill the calibration requirements.

It was observed that the compensation effect was consistent with the theory. The amplitude compensation and phase compensation did not affect each other because when $R$ and $C$ were high, the impedance after subjecting a partial voltage on $Z_3$ was significantly lower than the corresponding impedance of the $R$ compensation circuit and $C$ compensation circuit, that is, the effects of the compensation circuits on the transformer were negligible. Furthermore, in the $R$ compensation circuit, the resistance was significantly greater than the excitation impedance of its compensation winding; therefore, the partial voltage on $R$ was disregarded. For the $C$ compensation circuit, the capacitive reactance of the capacitor was significantly greater than the excitation impedance of its compensation winding; therefore, the partial voltage on $C$ was disregarded. Because the current in $Z_3$ was in phase with the secondary current, the compensation current in the $R$ compensation loop compensated primarily for the amplitude error, and the compensation current in the $C$ compensation loop compensated primarily for the phase error.

5 | PERFORMANCE TEST

5.1 | Sealing effect test for open–closed air gap

The field application of open CTs involves live work. Workers are sent to nearby wires by a lift truck. After the equipotential operation, the workers install open iron cores onto the wires, and the iron core is tightened with a screw (Figure 3) onto the CT to ensure a small opening air gap.

The air gap reduces the effective magnetic permeability of the iron core and affects the measurement accuracy of the CTS-CT. The size of the air gap was changed by inserting an A4 paper (laboratory A4 paper: 70 g/sheet size) into the gap to test the effect of the air gap on the accuracy of the CTS-CT. The paper inserted into the gap was ordinary printing paper, with a thickness of approximately 0.12 mm. During the test, one to five layers of the paper were sequentially inserted into the air gap. The primary current of the CTS-CT was 800 A, the transformation ratio was 800 A:1 A, and the frequency was 50 Hz. The test results are presented in Table 5.

Table 5 shows that after three paper layers were clamped in or when the air gap exceeded 0.36 mm, the amplitude and phase errors of the CTS-CT increased significantly; as such, the accuracy requirement of 0.05% was not satisfied. Therefore, in the mechanical structure design of the CTS-CT, the sealed air gap of the iron core must be less than 0.3 mm during field installation.
5.2 | Evaluating effect of return conductor

To study the effect of the electromagnetic environment on the accuracy of the CTS-CT, testing was performed by adopting a current-carrying return lead, as shown in Figure 5. After the primary conductor passed through the CTS-CT, it returned to the outer side opening, which was approximately 2 cm from the centre of the transformer. A current of 800 A with a frequency of 50 Hz was applied to the primary conductor. The test results are presented in Table 6.

Table 6 shows that the magnetic field generated by the return conductor did not significantly affect the CTS-CT.

5.4 | Uncertainty analysis

The uncertainty budgets for the amplitude and phase errors are listed in Tables 8 and 9, respectively.

The uncertainty of the experimental standard deviation was calculated based on Table 7.

The uncertainty components due to the standard CT and calibrator, which were the most important factors under these ideal circumstances, were obtained from the calibration certifi-
TABLE 9 Uncertainty budget for phase error

| Error contribution          | Standard uncertainty (%) |
|-----------------------------|--------------------------|
| Experimental standard deviation | 0.05                     |
| Standard CT phase error     | 0.17                     |
| Calibrator phase error      | 0.35                     |
| Influence of the air gap size | 0.18                     |
| Influence of the electromagnetic environment | 0.16                     |
| Total (level of confidence 95%) | 0.92                     |

cate provided by the National Center for High Voltage Measurement of China.

Regarding the uncertainty introduced by the stand CT used in the test, the maximum allowable indication error of the ratio difference was ±0.01%. It was uniformly distributed in the interval, and the inclusion factor \( k = \sqrt{3} \). The certainty component measured 0.01%/√3 = 0.006%. The maximum allowable indication error of the phase error was ±0.3, which obeys the uniform distribution in the interval, and the inclusion factor \( k = \sqrt{3} \). The uncertainty component measured 0.3/√3 = 0.17°.

Regarding the uncertainty introduced by the calibrator used in the test, the maximum allowable indication error of the ratio difference was ±0.02%, and it was uniformly distributed in the interval, including the factor \( k = \sqrt{3} \); furthermore, the uncertainty component measured 0.02%/√3 = 0.012%. The maximum allowable indication error of the phase error was ±0.6, which obeys the uniform distribution in the interval, and the inclusion factor \( k = \sqrt{3} \). The uncertainty component measured 0.6/√3 = 0.35°. For the uncertainty introduced by the air gap, based on the test data presented in Table 5, the maximum allowable air gap was two sheets of A4 paper (approximately 0.24 mm), and the maximum allowable error of the ratio difference was 0.012%. The maximum allowable indication phase error was 0.61, which obeys the uniform distribution in the interval; the uncertainty components of the amplitude and phase errors were 0.003% and 0.18, respectively.

For the uncertainty introduced by the external magnetic field interference, the effect of parallel conductors was considered primarily in this study. As shown by the test data in Table 6, the mean amplitude error of the two groups of data was 0.00065%, and the phase error was 0.32. The maximum variation error of the ratio difference from the initial value was 0.00395%. The maximum variation error of the phase error from the initial value was 0.57, which obeys the uniform distribution in the interval; the uncertainty components of the amplitude and phase errors were 0.001% and 0.16°, respectively.

6 | CONCLUSIONS

In this study, a new clamp-on reference CT was developed using the principle of a two-stage CT. A passive compensation circuit was proposed, and the parameter calculation formulas were presented. R–C compensation can accurately and effectively improve the accuracy of the amplitude and phase errors of the two-stage CT. As shown by the results of open air-gap, internal magnetic field effect, and opening and closing repeatability tests, the accuracy of the new CTS-CT satisfied the requirements of class 0.05 and guaranteed the accuracy when the air gap was within 0.3 mm. The new CTS-CT provides a feasible solution for the online calibration of CTs in high-voltage applications such as substations.

In this study, the mechanical design of live access was not fully investigated, and manual live work is still required. In future studies, we will investigate the operation of the proposed reference CT using mechanical lifting, opening, and closing to improve the safety of live access and provide a better implementation plan to promote the online calibration of high-voltage CTs.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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