Uncertainty Analysis in Potential Transformer Calibration Using a High Voltage Capacitance Bridge

Jae Kap Jung†, Sang Hwa Lee*, Jeon Hong Kang*, Sung Won Kwon* and Myungsoo Kim*

Abstract – Precise absolute measurement of the errors in a potential transformer (PT) can be achieved using high voltage capacitance bridge (HVCB) and capacitive divider. The uncertainty in a PT measurement using the HVCB system was evaluated by considering the overall factors affecting during the calibration of a PT. The expanded uncertainties are found to be not more than 30 × 10^{-6} for ratio and 30 μrad for phase up to the primary voltage of V_p = 22 kV. For same PTs, the measured errors in KRISS (Korea Research Institute of Standards and Science) using our bridge are well coincide with those in NMIA (National Measurement Institute of Australia) and PTB (Physikalisch-Technische Bundesanstalt) within the corresponding uncertainties.

Keywords: High Voltage Capacitance Bridge, Potential Transformer, Ratio Error, Phase Displacement, Uncertainty, PT Comparator, Capacitor

1. Introduction

Potential transformers (PTs) are normally used in the power industry for high voltage and power loss measurements [1–3]. The most widely used method for calibrating PTs in the calibration laboratory is one in which the PT under test is compared to a standard PT having the same nominal ratio [4-5]. The errors of the PT under test are measured using a PT comparator by comparing its values with those of a standard transformer of higher accuracy. The "absolute errors" of PT under test is obtained by adding the "absolute errors" of a standard PT to the errors measured by a PT comparator. One of effective methods for measuring "absolute error" of a standard PT utilizes the high voltage capacitance bridge (HVCB). This method can be possible to establish the traceability chain to the national standards. Thus, national metrology institutes (NMIs) have performed the PT calibration using HVCB up to now [6-10].

A calibration system of a standard PT in KRISS has been set up recently. The system consists mainly of HVCB, high voltage (HV) capacitor and low voltage (LV) capacitor. The uncertainty in a standard PT measurement using HVCB is analyzed by considering the whole possible effects during the calibration of PT. Especially, the uncertainty contributions due to the linearity of HVCB dial and the error of the PT burden are estimated by the analysis of a PT equivalent circuit. For the validity check of the PT calibration system using the HVCB system, experimental results of the PTs measured in KRISS using our system are compared with those measured in NMIs.

2. Analysis of Pt Equivalent Circuits

An equivalent circuit for a PT with a zero burden is shown in Fig. 1 [6, 11]. Z_0 in Fig. 1 is the leakage output impedance of the secondary of the PT, written as $Z_0 = R_0 + jX_0$. The complex ratio of the primary voltage vector (V_p) to the secondary voltage vector (V_s) of the PT is given by [6, 11]

$$\frac{V_p}{V_s} = N(1-\alpha_0)e^{-j\beta_0} \tag{1}$$

where N is the rated transformation ratio. α_0 and β_0 are ratio error and phase displacement, respectively, at a zero burden.

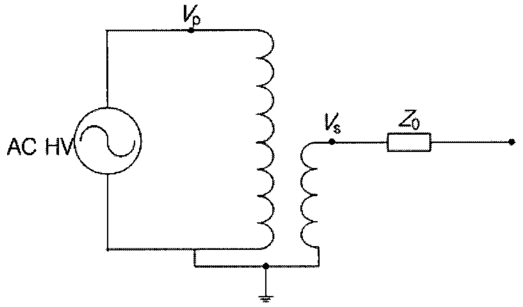

Fig. 1. An equivalent circuit for a PT with a zero burden.

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Received 17 November, 2006 ; Accepted 2 February, 2007

We now consider the effect of the external burden on the ratio error and phase displacement of the PT. An equivalent circuit for the PT with an external burden, Z_b, is shown in Fig. 2 [6, 11]. The PT burden consists of a serial connection of the resistance and the inductor, expressed as $Z_b = R_b + jX_b$. The complex ratio of the primary voltage vector (V_p) to the secondary voltage vector (V_b) of a PT with an external burden is given by

$$\frac{V_p}{V_b} = N(1-\alpha_b)e^{-j\beta_b} \tag{2}$$

where α_b β_b is ratio error and phase displacement, respectively, with the external burden. Equating the currents passing through Z_0 and Z_b, as shown in Fig. 2, we obtain as follows.

$$\frac{1}{V_b} = \frac{Z_0 + Z_b}{V_s Z_b} \tag{3}$$

This can be rewritten in the following form:

$$\frac{V_p}{V_b} = \frac{V_p}{V_s}\left(1 + \frac{Z_0}{Z_b}\right) \tag{4}$$

Eq. (4) can be changed into eq. (5) using eqs. (1) and (2), as:

$$(1-\alpha_b)e^{-j\beta_b} = (1-\alpha_0)e^{-j\beta_0}\left(1+\frac{Z_0}{Z_b}\right) \tag{5}$$

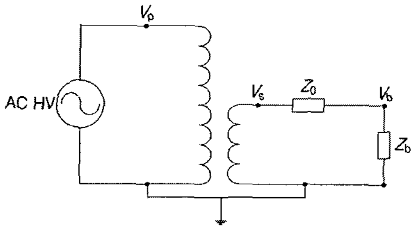

Fig. 2. An equivalent circuit for a PT with a burden, Z_b.

In the case of the normal PT within 0.1 class, the both values of β_b and β_0 were less than 0.15 crad. Thus the quadratic and higher order terms in the exponential series of eq. (5) were neglected. Eq. (5) can then be converted into eq. (6) as:

$$\begin{aligned}&(1-\alpha_b)(1-j\beta_b)\\&=(1-\alpha_0)(1-j\beta_0)\left(1+\frac{R_0+jX_0}{R_b+jX_b}\right)\end{aligned} \tag{6}$$

By taking the real part of eq. (6), we can obtain the ratio error with the external burden as follows.

$$\begin{aligned}\alpha_b &= \alpha_0 + (\alpha_0 - 1)\left(\frac{R_bR_0 + X_bX_0}{R_b^2 + X_b^2}\right)\\&+(\alpha_0 - 1)\beta_0\left(\frac{R_bX_0 - X_bR_0}{R_b^2 + X_b^2}\right)\end{aligned} \tag{7}$$

We obtain the phase displacement having the external burden by taking the imaginary part of eq. (6), as follows.

$$\begin{aligned}\beta_b &= k\beta_0 - k\left(\frac{R_bX_0 - X_bR_0}{R_b^2 + X_b^2}\right)\\&+k\beta_0\left(\frac{R_bR_0 + X_bX_0}{R_b^2 + X_b^2}\right),\end{aligned} \quad k = \left(\frac{1-\alpha_0}{1-\alpha_b}\right) \cong 1. \tag{8}$$

3. Calibration Method of Pt in Hvcb System

The calibration of the PT using the HVCB comprises two step processes [1]. The bridge is the first used to establish the ratio between LV capacitor (C_L) and HV capacitor (C_H) under a few hundred voltages. In the first step, C_L and C_H were connected to N_x and N_s windings of bridge, respectively. The second step of the process is to exchange the connections of the two capacitors to the bridge windings and apply the two voltages whose ratio is to be determined to the appropriate capacitors. The details of the processes and measurement principle are well described in the previous papers [6, 8, 9].

In the calibration of the PT by the HVCB, the complex ratio of the actual primary voltage for actual secondary voltage of the PT in two step processes is given by

$$\begin{aligned}\frac{V_p}{V_s} &= \left(\frac{C_L}{C_H}\right)_1\left(\frac{N_s}{N_x}\right)_2(1-jD)\\&= N\cdot RCF(1-j\beta) = N(1-\alpha)(1-j\beta)\end{aligned} \tag{9}$$

D is the dissipation dial setting value of capacitor under test corresponding to the phase displacement (β) of a PT under test. $(C_L/C_H)_1$ and $(N_s/N_x)_2$ are ratio dial setting values obtained from the first and the second step of measurements, respectively. $(C_L/C_H)_1(N_s/N_x)_2$ corresponds the actual measured transformation ratio, N_a, of transformer under test. The *RCF* is the ratio correction factor defined as the actual transformation ratio divided by the rated transformation ratio. Therefore ratio error and phase displacement of the PT under test are obtained from the two step measurements in the HVCB.

4. Uncertainty Evaluation

The individual contributions of the uncertainty factors affecting in the measurements of the errors of the PT using the HVCB system are calculated as follows.

4.1 Repeated Measurement

The A-type uncertainty due the repeated measurements is given $u_A = \sqrt{\frac{\sum(\delta_i - \bar{\delta})^2}{n(n-1)}}$, where δ_i is the measured ratio error or phase displacement, $\bar{\delta}$ is the average value, and n is the measurement number.

4.2 Linearity of HVCB Dial

A linearity of the HVCB dial can be checked by employing the non-reactive PT burdens. We use the non-reactive burdens with the negligible AC-DC difference less than 10^{-5} (X_b=0). The value of β_0 in PT under test is 0.74 mrad and then last terms in eqs. (7) and (8) are neglected. Thus, the eqs. (7) and (8) can be written, respectively, as follows.

$$\alpha_b \cong \alpha_0 + (\alpha_0 - 1)\cdot R_0 \cdot (\frac{1}{R_b}) \tag{10}$$

$$\beta_b \cong \beta_0 - X_0 \cdot (\frac{1}{R_b}) \tag{11}$$

where the values of α_0, β_0, R_0 and X_0 are constant at a fixed voltage. Both the ratio error and phase displacement with the external burden are then proportional to reciprocal of the resistance of the non-reactive burden, ($1/R_b$). Consequently, by plotting α_b and β_b as a function of $1/R_b$, we can evaluate the linearity of ratio error and phase displacement measured in the HVCB dial. The experimental results of burden effects on ratio error is shown in Fig. 3. Fig. 3 is measured results for the rated transformation ratio of 3300 V : 110 V at the secondary voltage of 85 V. The inset of Fig. 3 is measured results for the rated transformation ratio of 550 V : 110 V at the secondary voltage of 30 V. The two solid lines fitted by eq. (10) in Fig. 3 show good consistency with the measurement results within 10 × 10^{-6} for the ratio error ranges of -329 × 10^{-6} ~ -66 × 10^{-6} and 334 × 10^{-6} ~ 1888 × 10^{-6}.

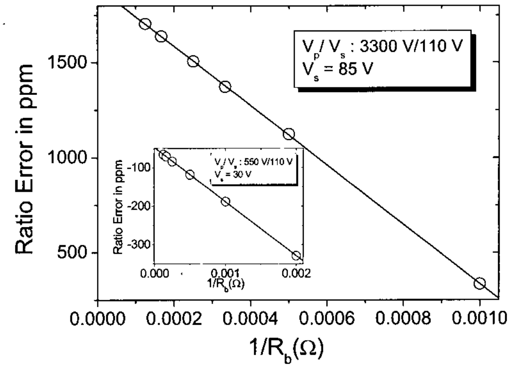

Fig. 3. A change of ratio error as a function of resistance of non-reactive burden.

The external burden effects on phase displacement are represented in Fig. 4. Fig. 4 is measured results for the rated transformation ratio of 3300 V : 110 V at the secondary voltage of 85 V. The solid line fitted by eq. (11) in Fig. 4 shows good consistency with measurement results within 10 μrad for the phase displacement range of -280 μrad ~ 160 μrad. Therefore, the uncertainty due to a linearity of HVCB dial is written as $u_{B1} = (10\times10^{-6})/\sqrt{3} = 5.8\times10^{-6}$.

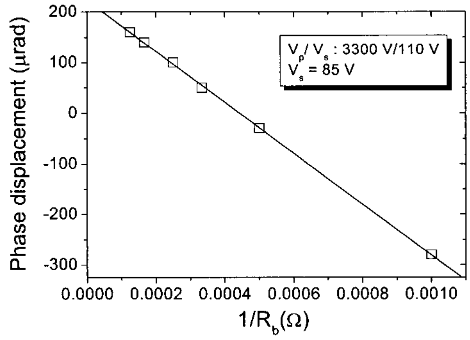

Fig. 4. A change of phase displacement as a function of resistance of non-reactive burden.

4.3 Change of the PT Burden

As shown in eqs. (7) and (8), both the ratio error and the phase displacement of the PT depend directly on the conductance and the susceptance of the PT burden. Thus, an error of 1 % in the measurement of the PT burden causes the uncertainty of 1 % in both ratio and phase. This means the uncertainty (u_{B2}) of the PT due to the burden error is given as $u_{B2} = (1\times10^{-6})/\sqrt{3} = 0.6\times10^{-6}$ in the case of 0.01 % class PT.

4.4 HVCB Calibration

The ratio dial settings in the HVCB were calibrated by comparison with a scale of loss-less gas dielectric capacitors which were trimmed to exact ratios using a self-validating build-up technique [12]. The dissipation dial settings were checked by injecting a calibrated quadrature current into the bridge in parallel with that from a 1000 pF capacitor at 1/1 ratio. The uncertainty ($u_{B3,\,r}$) in the ratio dial measurements was less than 5 × 10^{-6} up to ×1000 ratio. The uncertainty ($u_{B3,\,p}$) in the dissipation factor dial measurements was not more than ±0.25 % of the dial indication.

4.5 Voltage Coefficient (VC) of HV Capacitor

High voltage capacitor of compressed gas type have a voltage dependence of its capacitance due to the displacement of the electrodes and the pressure-vessel effect [13]. We have measured a VC of 1000 pF capacitor of 30 kV rated voltage against a reference 100 pF capacitor of 200 kV rated voltage having a negligible VC. Fig. 5 shows the voltage dependence for 1000 pF capacitor. The change in the capacitance of compressed gas capacitor increases exponentially with the applied voltage. The solid line in Fig. 5 is fitted as $\frac{\Delta C_x}{C_x} = aV^b$, with $a = 2.77 \times 10^{-12}$ and $b = 1.63$. The standard uncertainty (u_{B4}) due to the VC of high voltage capacitor is then given as $u_{B4} = (2.77 \times 10^{-12} V^{1.63}) / \sqrt{3}$.

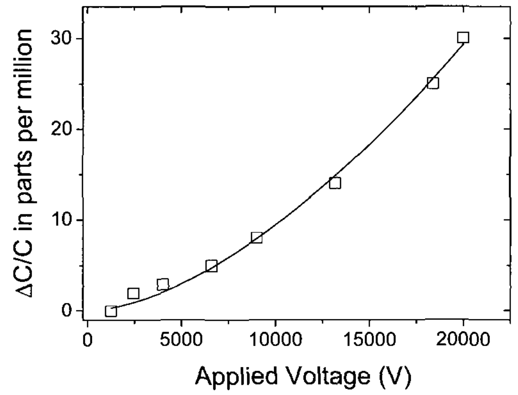

Fig. 5. Relative capacitance variation with the change of the applied voltage.

4.6 Resolution of HVCB Dial

The resolution of the HVCB is 10^{-6} in both ratio and phase measurement. The uncertainty (u_{B5}) due to the resolution is then written as $u_{B5} = 10^{-6} / 2\sqrt{3} = 0.29 \times 10^{-6}$ by considering probably a rectangular distribution.

4.7 Change of Secondary Voltage of PT Under Test

The uncertainty (u_{B6}) due to an error of 1 % of the rated secondary voltage can be written as $u_{B6} = \left[\frac{\delta_2 - \delta_1}{V_2 - V_1} \times \frac{V_s}{100} \right] \times \frac{1}{\sqrt{3}}$, where δ_1 is the ratio error or phase displacement at first secondary voltage, δ_2 is the ratio error or phase displacement at second secondary voltage, V_1 is the first secondary voltage, V_2 is the second secondary voltage, and V_s is the rated secondary voltage.

4.8 Change of Applied Frequency at 60 Hz

The uncertainty (u_{B7}) due to an error of 1 % at 60 Hz can be given as $u_{B7} = \left[\frac{\delta_2 - \delta_1}{f_2 - f_1} \times \frac{60}{100} \right] \times \frac{1}{\sqrt{3}}$, where δ_1 is the ratio error or phase displacement at first frequency, δ_2 is the ratio error or phase displacement at second frequency, f_1 is the first frequency, and f_2 is the second frequency.

4.9 Change of Temperature of Capacitors

The temperature coefficients of the two capacitors was not more than 30 × 10^{-6}/℃ according to the manufacturer's specification. We assume the change of the temperature during the measurements is within ±0.5 ℃ and the uncertainty (u_{B8}) due to the change of temperature is then obtained by considering probably a rectangular distribution as $u_{B8} = (15 \times 10^{-6}) / \sqrt{3} = 8.7 \times 10^{-6}$.

The individual uncertainty contributions obtained from the uncertainty analysis for the case of V_p/V_s = 6600 V/110 V

Table 1. Summary of significant factors contributing to the uncertainty in the PT calibration for the case of V_p/V_s = 6600 V/110 V.

Source of uncertainty	α (parts in 10^{-6})	β (μrad)
Repeated measurement, u_A	3.0	3.0
Linearity of HVCB dial, u_{B1}	5.8	5.8
Change of PT burden, u_{B2}	0.6	0.6
HVCB calibration, u_{B3}	5.0	5.0
VC of HV capacitor, u_{B4}	0.8	0.8
Resolution of HVCB, u_{B5}	0.3	0.3
Change of secondary voltage, u_{B6}	0.3	0.2
Change of applied frequency, u_{B7}	0.4	0.4
Change of temp. of capacitors, u_{B8}	8.7	8.7
Combined standard uncertainty, u_c	12	12
Expanded uncertainty (k =2)	24	24

are summarized in Table 1. The combined standard uncertainty (u_c) is represented as a root sum of squares of the individual uncertainty. The expanded uncertainties were obtained by assuming a normal distribution and multiplying the combined standard uncertainty by a coverage factor of $k = 2$. The expanded uncertainty up to the primary voltage of $V_p = 22$ kV is estimated to be not more than 30×10^{-6} for ratio and 30 μrad for phase.

5. Intercomparisons between NMIs

To check the validity in HVCB system, the measured results of the PT in our system are compared those in two NMIs for same PTs. Table 2 is represented the comparison of measured results for same PT between KRISS and NMIA. According to NMIA calibration certificate, the uncertainties of the PTs are not more than 30×10^{-6} for ratio 20 μrad for phase. Meanwhile table 3 is represented the comparison of measured results for same PT between KRISS and PTB. The uncertainties of the PT in PTB are 30×10^{-6} for ratio and 30 μrad for phase. Consequently, the two intercomparison results for KRISS-NMIA and KRISS-PTB show the consistency with each other within the corresponding uncertainties.

Table 2. Comparison of measurement results for same PT between KRISS and NMIA (0 VA, 60 Hz)

Rated Transformation ratio	Secondary Voltage (%)	Ratio error (%)			Phase displacement (*crad*)		
		KRISS	NMIA	KRISS-NMIA	KRISS	NMIA	KRISS-NMIA
220 V:110 V	27	-0.006	-0.005	-0.001	+0.001	+0.004	-0.003
	100	-0.006	-0.005	-0.001	+0.002	+0.002	+0.000
440 V:110 V	27	-0.003	-0.005	+0.002	+0.001	+0.003	-0.002
	100	-0.004	-0.004	+0.000	+0.000	+0.001	-0.001
550 V:110 V	27	-0.003	-0.005	+0.002	+0.000	+0.003	-0.003
	100	-0.003	-0.004	+0.001	+0.000	+0.001	-0.001
1100 V:110 V	27	+0.003	+0.005	-0.002	+0.008	+0.006	+0.002
	100	+0.009	+0.010	-0.001	+0.004	+0.003	+0.001
2200 V:110 V	27	+0.013	+0.012	+0.001	+0.001	-0.001	+0.002
	100	+0.017	+0.016	+0.001	-0.001	-0.002	+0.001
3300 V:110 V	27	+0.013	+0.013	+0.000	-0.003	-0.004	+0.001
	100	+0.017	+0.016	+0.001	-0.004	-0.004	+0.000
6600 V:110 V	27	+0.010	+0.008	+0.002	-0.003	-0.004	+0.001
	100	+0.014	+0.013	+0.001	-0.005	-0.004	-0.001
11000 V:110 V	27	+0.012	+0.013	-0.001	+0.002	+0.004	-0.002
	100	+0.023	+0.024	-0.001	-0.003	-0.002	-0.001
13200 V:110 V	27	+0.013	+0.012	+0.001	+0.000	+0.001	-0.001
	100	+0.023	+0.023	+0.000	-0.005	-0.004	-0.001
22000 V:110 V	27	+0.015	+0.013	+0.002	-0.005	-0.003	-0.002
	100	+0.019	+0.019	+0.000	-0.005	-0.003	-0.002

6. Conclusion

Two systems for calibrating the PT up to 200 kV have been successfully set up recently in KRISS. One is composed as the HVCB and capacitive divider, as studied already in present paper. The other is a commercial semi-automatic system, which is composed as a standard PT and a transformer comparator. The commercial system is mainly used for calibrating the PTs belonging to industry. In order to establish the traceability chain to the national standard, the "absolute errors" of the standard PT in the commercial system are obtained by employing the HVCB system.

The measurement uncertainty in the HVCB system was evaluated by considering the overall factors affecting during the calibration of PT under test. The expanded uncertainties are found to be not more than 30×10^{-6} for ratio error and 30 μrad for phase displacement. The measured values for a PT using the bridge are well coincide with those in NMIs within the corresponding uncertainties for same PT.

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[1] W. J. M. Moore and P. N. Miljanic, "The current comparator", Peter Peregrinus Ltd., London, United Kingdom, 1988.

Table 3 . Comparison of measurement results for same PT between KRISS and PTB(5 VA, cosβ = 1, 60 Hz)

Rated transformation ratio	Secondary Voltage (%)	Ratio error (%)			Phase displacement (*crad*)		
		KRISS	PTB	KRISS-PTB	KRISS	PTB	KRISS-PTB
110 V:110 V	80	-0.003	-0.004	+0.001	-0.009	-0.009	+0.000
	100	-0.002	-0.003	+0.001	-0.010	-0.009	-0.001
220 V:110 V	80	-0.002	-0.002	+0.000	-0.007	-0.009	+0.002
	110	-0.001	-0.002	+0.001	-0.008	-0.009	+0.001
380 V:110 V	80	+0.000	+0.000	+0.000	-0.007	-0.006	-0.001
	100	+0.000	+0.000	+0.000	-0.007	-0.009	+0.002
440 V:110 V	80	+0.000	+0.000	+0.000	-0.006	-0.006	+0.000
	100	+0.000	+0.000	+0.000	-0.007	-0.006	-0.001
550 V:110 V	80	+0.000	+0.000	+0.000	-0.006	-0.006	+0.000
	100	+0.001	+0.000	+0.001	-0.006	-0.006	+0.000
1100 V:110 V	80	-0.001	+0.000	-0.001	-0.005	-0.006	+0.001
	100	+0.000	+0.000	+0.000	-0.006	-0.006	+0.000
2200 V:110 V	80	-0.001	-0.001	+0.000	-0.005	-0.006	+0.001
	100	+0.000	-0.001	+0.001	-0.005	-0.006	+0.001
3300 V:110 V	80	-0.001	-0.001	+0.000	-0.004	-0.003	-0.001
	100	-0.001	+0.000	-0.001	-0.004	-0.003	-0.001

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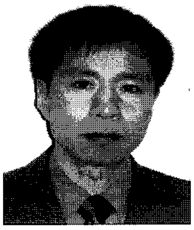

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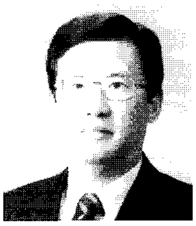

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