

Ratio Correction Factor and Phase Displacement at Arbitrary Burdens in Instrument Transformers

Jae Kap Jung[†], Kyu-Tae Kim* and Young Seob Lee**

Abstract – Ratio correction factor and phase displacement of instrument transformers vary with the values of the external burden connected to the secondary of the transformers. Using the values measured at two burdens of the instrument transformers, the ratio correction factor and phase displacement at arbitrary burdens are theoretically obtained without any additional measurement. This is based on a theoretical analysis of the equivalent circuits of the instrument transformers. The validity of the methods was verified by comparing the theoretical value with measured value for several instrument transformers with different accuracy.

Keywords: Instrument transformer, Ratio error, Ratio correction factor, Phase displacement, Burden, Equivalent circuit, Expanded uncertainty

1. Introduction

Voltage transformers (VTs) and current transformers (CTs) are normally used in the power industry for high voltage, heavy current, and power loss measurements [1-3]. The method most widely used to calibrate the transformers is to compare the transformer under test with a reference transformer that has the same nominal ratio and higher accuracy [4, 5]. According to the International Electrotechnical Commission (IEC) [6] and American National Standard Requirements for Instrument Transformers (ANSI) [7], the ratio correction factor and phase displacement of an instrument transformer under test should be measured by connecting an external burden to the secondary of the transformer under test. The measurements of ratio correction factor and phase displacement of the instrument transformers at two different burdens are required. However, the values of burden required in IEC are different from that in ANSI.

The users in industry are usually using their instrument transformers at the different burden conditions compared with the burdens calibrated according to requirement of IEC or ANSI. Therefore, it is very useful that the ratio correction factor and phase displacement of instrument transformer are obtained at the real burden complying with the environment of industry without any additional measurements.

In this study, we have developed the methods for obtaining the ratio correction factor and phase displacement at arbitrary any burdens without any additional accuracy

measurement, from the ratio correction factor and phase displacement of instrument transformer measured at two different burdens according to IEC or ANSI. This burden effects are based on a theoretical analysis of the equivalent circuits of the VT and CT. The validity of this method was verified by comparing the theoretical value for several instrument transformers with measured value.

2. Burden Effects on VT

2.1 Calculation of ratio correction factor and phase displacement at arbitrary burdens

An equivalent circuit for a VT with a zero burden is shown in Fig. 1 [8]. Z_0 in Fig. 1 is the leakage output impedance of the secondary of the VT:

$$Z_0 = R_0 + jX_0. \quad (1)$$

The complex ratio of the primary voltage vector (V_p) to the secondary voltage vector (V_s) of the VT with high accuracy at a zero burden is given by [8, 9].

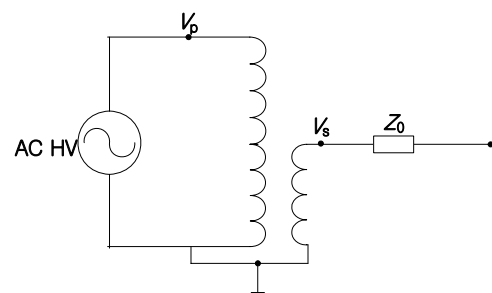


Fig. 1. Equivalent circuit for a VT with a zero burden

[†] Corresponding Author: Korea Research Institute of Standards and Science, Korea. (jkjung@kriss.re.kr)

* Korea Research Institute of Standards and Science, Korea. (ktkim@kriss.re.kr)

** Korea University of Science and Technology, Korea. (yshaha524@naver.com)

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$$\begin{aligned} \frac{V_p}{V_s} &= N_{VT} RCF_0 e^{-j\beta_0} \cong N_{VT} (1 - \alpha_0 - j\beta_0) \\ &= N_{VT} (RCF_0 - j\beta_0) \end{aligned} \quad (2)$$

In Eq. (2), N_{VT} is the rated transformation ratio of VT. α_0 is the ratio error at a zero burden, and β_0 is the phase displacement between the secondary voltage vector and the primary voltage vector at a zero burden, defined as $\beta_0 \equiv \beta_s - \beta_p$. The RCF_0 is the ratio correction factor at a zero burden, defined as the actual transformation ratio (N_a) divided by the rated transformation ratio (N_{VT}). The relationship between RCF_0 and α_0 is as follows;

$$RCF_0 \equiv 1 - \alpha_0, \quad (3)$$

An equivalent circuit for the VT with an external burden, Z_b , is shown in Fig. 2 [8]. The VT burden consists of a serial connection of the resistance and the inductor, expressed as:

$$Z_b = R_b + jX_b. \quad (4)$$

In a similar manner to Eq. (2), the complex ratio of the primary voltage vector (V_p) to the secondary voltage vector (V_b) of a VT with high accuracy in the presence of an external burden is:

$$\begin{aligned} \frac{V_p}{V_b} &= N_{VT} RCF_b e^{-j\beta_b} \cong N_{VT} (1 - \alpha_b - j\beta_b) \\ &= N_{VT} (RCF_b - j\beta_b), \end{aligned} \quad (5)$$

where α_b is the ratio error with the external burden, and β_b is the phase displacement between the secondary voltage vector and the primary voltage vector with the external burden. RCF_b is the ratio correction factor with the external burden, written as $RCF_b \equiv 1 - \alpha_b$. The ratio error and the phase displacement of the VT arise from the secondary burden, the leakage inductance of the primary and secondary, the winding resistance of the primary and secondary, the magnetizing current, and the core loss [10, 11].

Equating the currents passing through Z_0 and Z_b , as shown in Fig. 2, we obtain the following equation.

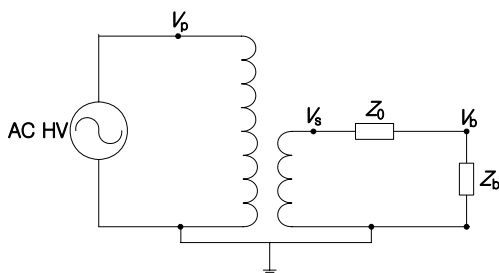


Fig. 2. Equivalent circuit for a VT with burden, Z_b

$$\frac{V_s - V_b}{Z_0} = \frac{V_b}{Z_b} \quad (6)$$

This can be rewritten as:

$$\frac{V_p}{V_b} = \frac{V_p}{V_s} \left(1 + \frac{Z_0}{Z_b} \right). \quad (7)$$

Eq. (7) can be changed into Eq. (8) using Eqs. (1), (2), (4) and (5) as:

$$RCF_b - j\beta_b = (RCF_0 - j\beta_0) \left(1 + \frac{R_0 + jX_0}{R_b + jX_b} \right). \quad (8)$$

By taking the real part of Eq. (8), we can obtain the ratio correction factor with the external burden as:

$$RCF_b = RCF_0 (1 + G_b R_0 - B_b X_0) + \beta_0 (G_b X_0 + B_b R_0), \quad (9)$$

where G_b and B_b are defined as follows.

$$G_b \equiv \frac{R_b}{R_b^2 + X_b^2} : \text{conductance of the VT burden}$$

$$B_b \equiv -\frac{X_b}{R_b^2 + X_b^2} : \text{susceptance of the VT burden}$$

In a similar manner to Eq. (9), we can obtain the phase displacement with the external burden by taking the imaginary part of Eq. (8):

$$\beta_b = \beta_0 - RCF_0 (G_b X_0 + B_b R_0) + \beta_0 (G_b R_0 - B_b X_0) \quad (10)$$

The leakage output impedance, Z_0 , of the secondary of the VT is written by substituting subscript t for b in Eq. (7) as follows;

$$Z_0 = Z_t \left(\frac{V_p / V_t}{V_p / V_s} - 1 \right) = Z_t \left[\frac{RCF_t e^{-j(\beta_t - \beta_0)} - RCF_0}{RCF_0} \right] \quad (11)$$

β_t and β_0 is less than 10^{-3} order in Eq. (11), thus the quadratic and higher order terms in the exponential expansion of $e^{-j(\beta_t - \beta_0)}$ are less than 1×10^{-6} , which is neglected. Therefore, the resistance (R_0) and reactance (X_0) of Z_0 are given by as follows;

$$R_0 = \left[\frac{(RCF_t - RCF_0) R_t + RCF_t (\beta_t - \beta_0) X_t}{RCF_0} \right] \quad (12)$$

$$X_0 = \left[\frac{-RCF_t (\beta_t - \beta_0) R_t + (RCF_t - RCF_0) X_t}{RCF_0} \right] \quad (13)$$

By measuring the ratio correction factor/phase

displacement at the zero, t burden and impedance of t burden, we can obtain both R_0 and X_0 according to eqs. (12) and (13), respectively. Using values of R_0 and X_0 , the ratio correction factor and phase displacement at arbitrary b burden could be theoretically obtained without any additional accuracy experiment according to eqs. (9) and (10), respectively.

2.2 Comparison between calculated and measured values for ratio correction factor and phase displacement at an arbitrary burden

For study of burden effects, the ratio correction factor and phase displacement at four different burdens (zero, t, b and b' burden) including zero burden are measured for three different types of VTs (VT 1, VT 2, and VT 3) with different accuracy. The VT 1, VT 2 and VT 3 have the accuracy of 0.005 %, 0.02 % and 0.2 %, respectively. The values of resistance/reactance of t, b and b' burden are summarized in table 1. Here t, b and b' burden correspond to 4.87 VA with unity power factor, 5.05 VA with 0.80 lagging power factor and 15.02 VA with 0.80 lagging power factor, respectively.

The measurement results of ratio correction factor/phase

Table 1. The values of resistance/reactance of t, b and b' burdens

Burden	Parameters	Value
T burden	R_t	2483 Ω
	X_t	0 Ω
b burden	R_b	1917.2 Ω
	X_b	1437.9 Ω
B' burden	$R_{b'}$	645.4 Ω
	$X_{b'}$	481.9 Ω

Table 2. Comparison between calculated and measured values of ratio correction factor/phase displacement for the voltage ratio of 3300 V/110 V in three different type of VTs

Burden	Parameters	VT type		
		VT 1	VT 2	VT 3
zero burden*	RCF_0	0.999 890	0.999 752	0.998 114
	β_0 [rad]	-0.000 006	-0.000 012	0.000 227
t burden*	RCF_t	1.000 007	0.999 835	0.998 742
	β_t [rad]	-0.000 047	-0.000 099	0.000 020
b burden*	RCF_b	1.000 014	0.999 873	0.998 762
	β_b [rad]	0.000 032	-0.000 032	0.000 448
b burden ⁺	RCF_b	1.000 012	0.999 875	0.998 763
	β_b [rad]	0.000 033	-0.000 033	0.000 446
difference	ΔRCF_b	0.000 002	-0.000 002	-0.000 001
	$\Delta\beta_b$ [rad]	-0.000 001	0.000 001	0.000 002
b' burden*	$RCF_{b'}$	1.000 259	1.000 116	1.000 034
	$\beta_{b'}$ [rad]	0.000 105	-0.000 073	0.000 887
b' burden ⁺	$RCF_{b'}$	1.000 255	1.000 117	1.000 045
	$\beta_{b'}$ [rad]	0.000 108	-0.000 074	0.000 876
difference	$\Delta RCF_{b'}$	0.000 004	-0.000 001	-0.000 011
	$\Delta\beta_{b'}$ [rad]	-0.000 003	0.000 001	0.000 011

* : measured value ⁺ : calculated value

displacement at zero, t and b burdens for three different types of VTs are represented in the second, third and fourth row of table 2, respectively. From the errors measured at zero/t burdens and the impedance values of t burden, the values of R_0 and X_0 for three different types of VTs using eqs. (12) and (13), respectively, are calculated as follows ;

$$\begin{aligned}
 R_0 &= 0.29 \Omega, X_0 = 0.10 \Omega \text{ for VT 1} \\
 R_0 &= 0.21 \Omega, X_0 = 0.22 \Omega \text{ for VT 2} \\
 R_0 &= 1.56 \Omega, X_0 = 0.51 \Omega \text{ for VT 3}
 \end{aligned}$$

The ratio correction factor and phase displacement at arbitrary b burden are calculated using eqs. (9) and (10), respectively, as shown in the fifth row of table 2. The differences between calculated and measured values at arbitrary b burden are represented in the sixth row of table 2, which are less than 2×10^{-6} and shows good consistency. Meanwhile, the ratio correction factor and phase displacement are measured at arbitrary b' burden for three VTs, as shown in the seventh row of table 2. The ratio correction factor and phase displacement at arbitrary b' burden according to eqs. (9) and (10) are calculated using R_0 and X_0 obtained already at zero and t burdens, as shown in the eighth row of table 2. The differences between calculated and measured values at arbitrary b' burden are represented in the last row of table 2, which are less than 11×10^{-6} . The expanded uncertainty ($k = 2$) for the errors of the VTs was estimated to be within 30×10^{-6} in ratio and 30 microrad in phase [12]. This implies that the measured values at arbitrary any burdens for VTs with different accuracy are good consistent with calculated value within the expanded uncertainty.

3. Burden Effects on CT

3.1 Calculation of ratio correction factor and phase displacement at arbitrary burdens

An equivalent circuit for a CT with an external burden, Z_b , is shown in Fig. 3 [13-14]. The parameters shown in figure 3 are defined as follows:

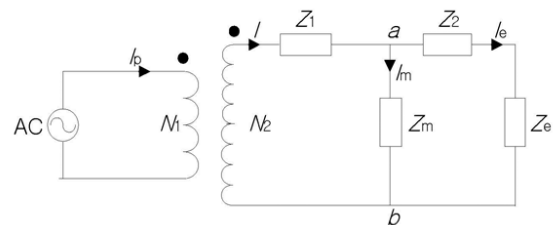


Fig. 3. Equivalent circuit for a CT with external burden, Z_e .

$$\begin{aligned}
 Z_m &= R_m + jX_m : \text{magnetizing impedance.} \\
 Z_1 &= R_1 + jX_1 : \text{primary leakage impedance.} \\
 Z_2 &= R_2 + jX_2 : \text{secondary leakage impedance.}
 \end{aligned}$$

- $Z_e = R_e + jX_e$: impedance of external burden.
- N_1 : number of primary windings.
- N_2 : number of secondary windings.
- I_p : actual primary current.
- I_e : actual secondary current with an external burden.
- I : ideal current with infinite magnetization impedance.
- I_m : magnetization current.

The complex ratio of the primary current vector (I_p) to the secondary current vector (I_e) in a CT with an external burden is given by [13].

$$\frac{I_p}{I_e} = N_{CT} \left(1 + \frac{Z_2 + Z_e}{Z_m} \right) \cong N_{CT} (1 - \varepsilon_e - j\delta_e) \quad (14)$$

$$= N_{CT} (RCF_e - j\delta_e),$$

where N_{CT} is the rated transformation ratio of CT. ε_e is the ratio error with the external burden and δ_e is the phase displacement between the secondary current vector and the primary current vector with the external burden. RCF_e is the ratio correction factor with the external burden, defined as $RCF_e \cong 1 - \varepsilon_e$.

By taking the real and imaginary parts of $(Z_2 + Z_e)/Z_m$ in Eq. (14), we obtain the ratio correction factor (RCF_e) and the phase displacement (δ_e), respectively, with the external burden as follows:

$$RCF_e = 1 + G_m(R_2 + R_e) - B_m(X_2 + X_e), \quad (15)$$

$$\delta_e = -B_m(R_2 + R_e) - G_m(X_2 + X_e), \quad (16)$$

where $G_m = \frac{R_m}{R_m^2 + X_m^2}$ is the conductive component of

the excitation admittance, and $B_m = -\frac{X_m}{R_m^2 + X_m^2}$ is the susceptive component of the excitation admittance.

When a non-reactive resistor with an AC–DC difference less than 10^{-5} [15], i. e., $(X_e/R_e) < 10^{-5}$, is used as the external burden of the CT under test, then Eqs. (15) and (16) become:

$$RCF_e = 1 + (G_m R_2 - B_m X_2 + G_m R_e) = const. + G_m R_e \quad (17)$$

$$\delta_e = -B_m R_2 - G_m X_2 - B_m R_e = const. - B_m R_e, \quad (18)$$

Both the ratio correction factor (RCF_e) and the phase displacement (δ_e) of the CT under test in Eqs. (17) and (18) are proportional to the resistance of external burden, R_e , because of the constant values of G_m , B_m , R_2 , and X_2 for a fixed secondary current. By measuring RCF_e and δ_e at two resistive burdens, the slopes in Eqs. (17) and (18) give G_m and B_m , respectively. From values of G_m and B_m obtained from measurements of two resistive burdens, the ratio correction factor and phase displacement at arbitrary any e burden can be calculated according to Eqs. (15) and

(16), respectively, without any additional accuracy measurement.

3.2 Comparison between calculated and measured values for ratio correction factor and phase displacement at an arbitrary burden

The ratio correction factor and phase displacement at four different burdens are measured for three different types of CTs (CT 1, CT 2, and CT 3) with different accuracy. The CT 1, CT 2 and CT 3 have the accuracy of 0.001 %, 0.01 % and 0.2 %, respectively. The values of resistance/reactance of R_a , R_b , e and e' burden and secondary winding resistance (R_2) for three different types of CT are summarized in table 3. R_a and R_b indicate resistive burden with unity power factor. The e and e' indicate burden composing as a serial connection of a resistance and inductance. In general, the primary leakage reactance (X_1) in a CT is much larger than secondary leakage reactance (X_2), and the secondary windings are next to the core in a single layer. Therefore, it is reasonable to neglect X_2 entirely [10, 16].

The measurement results of ratio correction factor/phase displacement at R_a and R_b resistive burdens for three types of CTs are represented in the second and third row of Table 4, respectively. From the ratio correction factor/phase displacement obtained at R_a and R_b resistive burdens, the values of G_m and B_m are calculated using eqs. (17) and (18), respectively. The calculated values of G_m and B_m for three different types of CTs are presented as follows ;

$$G_m = 0.000\ 001\ \text{S}, B_m = 0.000\ 001\ \text{S for CT 1}$$

$$G_m = 0.000\ 036\ \text{S}, B_m = -0.000\ 114\ \text{S for CT 2}$$

$$G_m = 0.000\ 659\ \text{S}, B_m = -0.000\ 657\ \text{S for CT 3}$$

The ratio correction factor and phase displacement are measured at arbitrary e burden for three CTs, as shown in the fourth row of table 4. The ratio correction factor and phase displacement at arbitrary e burdens are calculated

Table 3. Resistance/reactance at four burdens (R_a , R_b , e and e' burden) and secondary winding resistance (R_2) for three different types of CTs.

Burden	Parameters	CT type (current ratio)		
		CT 1 (100 A/1 A)	CT 2 (100 A/5 A)	CT 3 (100 A/5 A)
R_a burden	R_a	0.184 Ω	0.184 Ω	0.184 Ω
R_b burden	R_b	1.082 Ω	0.682 Ω	0.682 Ω
e burden	R_e	0.192 Ω	0.192 Ω	0.192 Ω
	X_e	0.056 Ω	0.056 Ω	0.056 Ω
e' burden	$R_{e'}$	0.555 Ω	0.555 Ω	0.555 Ω
	$X_{e'}$	0.368 Ω	0.368 Ω	0.368 Ω
	R_2	3.200 Ω	0.367 Ω	0.210 Ω

CT 1 : 5 kA Tettex company CT, accuracy : 0.001 %, rated burden : 5 VA
 CT 2 : 2 kA Cte-tech company CT, accuracy : 0.01 %, rated burden : 5 VA
 CT 3 : 1.5 kA Yokogawa company CT, accuracy : 0.2 %, rated burden : 15 VA

Table 4. Comparison between calculated and measured values for ratio correction factor/ phase displacement for the current ratio of 100 A/5 A and 100 A/1 A in three different type of CTs.

Burden	Parameters	CT type (current ratio)		
		CT 1 (100 A/1 A)	CT 2 (100 A/5 A)	CT 3 (100 A/5 A)
R _a burden*	RCF_a	0.999 997	1.000 024	1.000 298
	δ_a [rad]	-0.000 001	0.000 077	0.000 340
R _b burden*	RCF_b	0.999 998	1.000 042	1.000 626
	δ_b [rad]	-0.000 002	0.000 134	0.000 667
e burden*	RCF_e	0.999 997	1.000 032	1.000 351
	δ_e [rad]	-0.000 001	0.000 076	0.000 311
e burden ⁺	RCF_e	1.000 003	1.000 027	1.000 302
	δ_e [rad]	-0.000 003	0.000 062	0.000 227
difference	ΔRCF_e	-0.000 006	0.000 005	0.000 049
	$\Delta \beta_e$ [rad]	0.000 002	0.000 014	0.000 084
e' burden*	$RCF_{e'}$	0.999 997	1.000 082	1.000 792
	$\delta_{e'}$ [rad]	-0.000 001	0.000 106	0.000 335
e' burden ⁺	$RCF_{e'}$	1.000 003	1.000 075	1.000 746
	$\delta_{e'}$ [rad]	-0.000 004	0.000 092	0.000 260
difference	$\Delta RCF_{e'}$	-0.000 006	0.000 007	0.000 046
	$\Delta \delta_{e'}$ [rad]	0.000 003	0.000 014	0.000 075

* : measured value + : calculated value

using eqs. (15) and (16), respectively. The calculated ratio correction factor and phase displacement at arbitrary e burden are presented in the fifth row of table 4. The differences between calculated and measured values at arbitrary e burden for three CTs are shown in the sixth row of table 4, which are less than 14×10^{-6} for CT 1, CT 2 and 84×10^{-6} for CT 3. Meanwhile, the ratio correction factor and phase displacement are measured at arbitrary e' burden for three CTs, as shown in the seventh row of table 4. The ratio correction factor and phase displacement calculated at arbitrary e' burden using eqs. (15) and (16), respectively, are presented in the eighth row of table 4. The differences between calculated and measured values at arbitrary e' burden for three CTs are shown in the last row of table 4, which are less than 14×10^{-6} for CT 1, CT 2 and 75×10^{-6} for CT 3.

The expanded uncertainty ($k = 2$) for the errors of the CTs was estimated to be within 30×10^{-6} in ratio and 30 microrad in phase for the case of CT with higher accuracy [17]. This implies that the measured values at arbitrary any burdens for CT 1 and CT 2 are good consistent with calculated value within the expanded uncertainty. However, the relative large difference between calculated and measured values for CT 3 implies CT 3 with lower accuracy of 0.2 % has larger measurement uncertainty than CT 1 and CT 2.

4. Conclusions

From the ratio correction factor and phase displacement measured at two different burdens, we have developed the

methods for obtaining the ratio correction factor and phase displacement of instrument transformers at arbitrary any burdens without any additional accuracy measurement. The methods were applied the three VTs with the accuracy of 0.005 % to 0.2 % and three CTs with the accuracy of 0.001 % to 0.2 %. The validity of these methods was verified by comparing the theoretical with experimental values. The calculated values for the several instrument transformers are consistent with measured values within the expanded uncertainty. For additional accuracy measurement of transformer under test in industry, they need a reference transformer with higher accuracy, which is only located in National Measurement Institute. Thus, it is more difficult to get the accuracy data precisely without reference transformer in industry itself. The proposed method could be possible it obtain the accuracy data at any arbitrary burden without the reference transformer in industry. This is also the merit of the proposed method. Consequently, this paper is a small contribution to understanding such burden effects on instrument transformers.

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Kyu-Tae Kim received the B.S. degree in applied physics from Inha University, Incheon, South Korea, in 1983 and the M.S. and Ph.D. degree in physics from Korea Advanced Institute of Science and Technology (KAIST), Seoul, in 1985 and 1989, respectively. Since 1989, he has been with the Korea Research Institute of Standards and Science (KRISS), Daejeon where he has been working on the establishment of Josephson voltage standard, DC voltage ratio standard, ELF E-field calibration system, and DC high voltage/high current standard. He has been the leader in the field of Electricity and Magnetism at KRISS for 16 years, received the Presidential Citation from Korean government, in 2004, and the local technical program chair of the CPEM 2010, Daejeon.



Young Seob Lee was born in 1988 in Korea. He received the B.S. degree in Kwangwoon University in Seoul. He is currently participating in the high voltage/high current research works in Korea Research Institute of Standards and Science (KRISS), Daejeon under M.S degree course with University of Science and Technology (UST).



Jae Kap Jung He received the B.S. degree in physics and the M.S. and Ph.D. degrees in solid-state physics from Korea University, Seoul, Korea. He joined the Korea Research Institute of Standards and Science (KRISS), Daejeon, Korea, in 2001. He is currently a Principal Researcher with the Center for Energy Materials Metrology.