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The Effect of Burden on the Accuracy of Instrument Transformers – A Case Analysis

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Abstract**:** *This paper presents an analysis with regard to the effect of connected burden, on accuracy of measuring current transformer (CT) as well as potential transformer (PT). The analysis is carried out as a case study, with experiments performed on spare CT & PT, which are meant for measuring application on line side of 11kV, 93.333MVA hydro generator of Chhukha Hydropower Plant, Bhutan. The effect on accuracies of these instruments transformers are established based on real time experiment made for current/voltage ratio errors and their corresponding phase displacements, for increasing burden (VA/Ohms) connected to their secondary. The paper in totality presents some general findings with regard to their burden and also its influence on the current/voltage ratio errors & phase displacements, that being the ultimate factors defining their accuracies. The multifunctional primary injection kit CPC 100 from omicron, Austria is utilized for current/voltage injection and corresponding measurements during the experimental analysis.*

Keywords: *Current transformer (CT), Potential transformer (PT), Phase displacement, Ratio error*

1. Introduction

Instrument transformers viz. current transformers and potential transformers are of paramount importance in any electrical network. They are applied both for measuring as well as protection functions, whereby their names are indicative of them being used for current and voltage applications respectively [1]. These instrument transformers are manufactured with certain technical specifications & various standard accuracy classes, unique to each. Every electrical network comprises of numerous instrument transformers and having several accuracy classes, that are opted, mostly depending on their application area and the standard system requirement. The correct choice of their accuracy class for a particular measuring or protection application is very important in any electrical network. IEC 60044-1 and 60044-2 respectively defines their accuracy classes based on the allowable limits of percentage current or voltage ratio error (±) and their corresponding current or voltage phase displacement (±) in minutes. These allowable limits of ratio as well as phase displacement further are defined to be valid only for certain standard burden ranges for each accuracy class [2] [3]. The burden therefore also play a very crucial role in defining and guaranteeing the measuring and protection accuracy of these instrument transformers. The paper in overall therefore aims to look into the significance and the effect of the connected burden on the accuracy of these instrument transformers.

2. Case Description

This study on the effect of varying burden on instrument transformers was carried out as a part of the investigation done to establish the cause of the high auxiliary transformation losses for the year 2016 at one of the hydropower plant viz. Chhukha Hydropower Plant (CHP) in Bhutan [4]. CHP has four generating units of 93.333MVA each, generating at 11kV voltage level. The generated voltage is either stepped up or down for transmission at 220 kV & 66kV levels and to further meet the local auxiliary consumption at 11kV & 415V levels [5]. These transformations at different voltage level to meet the auxiliary consumption of the plant has an allowable limit of transformation losses, which seemed exceeded in 2016. CHP had the entire protection devices of the electromechanical type that got entirely replaced with the numerical type in 2015 – 2016. One area therefore taken up for investigation was on the accuracy of the instrument transformers, with an anticipation that their effective connected burden got lowered owing to them being now feeding the numerical type protection relays in place of earlier high burden electromechanical type. It was in turn anticipated that this lowering of the effective burden resulted into compromised measuring accuracy (% ratio error & phase displacement) beyond IEC permissible limits for measuring instrument transformers, thereby requiring an in-depth investigation [6].

3. Test Specimen And Experiment

A spare each of potential and current transformers applied for the measuring function with CHP generators were considered as test specimen for the experimental analysis. The basic technical name plate specifications of these instrument transformers are enlisted in Table I.

TABLE I: Technical Name Plate Specifications of Test Specimen

Particulars	Specifications	
	Current Transformer	Potential Transformer
Type	Toroidal	2-Winding
Phases	1	1
Application	Metering	Metering
No. of Cores	1	13
$I_{Primary}$ / $V_{Primary}$	6000 A	11000/√3 V
$I_{Secondary}$ / $V_{Secondary}$	5 A	110/√3 V
Accuracy Class	0.5	0.5
Rated Burden	150 VA	150 VA
Rated Voltage Factor	N.A	1.2 Cont. / 1.9, 30 s

$I_{Primary}$ = CT primary current, $I_{Secondary}$ = CT secondary current, $V_{Primary}$ = PT primary voltage, $V_{Secondary}$ = PT secondary voltage, A = ampere, V = volt, VA = volt-ampere, s = second.

The experimental setup was arranged in the laboratory environment, where a multifunctional primary injection kit CPC 100™ from Omicron, Austria was utilized in injecting and measuring the test signals (current / voltage) and inferring the corresponding results. The kit with its multifunctional features allows for automated testing of various power system primary equipment, including instrument transformers. It has inbuilt capability to inject, measure and generate results in compliance to any standard industry best practice and international standards. The kit's capability to inject or measure AC voltages up to 2000V and AC currents up to 2000A are utilized in performing the measurements and analysis on the test specimen [7].

The analysis comprised of basic experiments on the instrument transformers, wherein their % current/voltage ratio error and the corresponding phase displacements were measured, and each time varying the effective burden connected to them. The eventual motive was to establish the effect of varying the burden on the accuracy of measuring instrument transformers. The burden for the experimental purpose were purely resistive, wherein linear type slide rheostats were used. An overall experimental setup as arranged is shown in Fig.1.

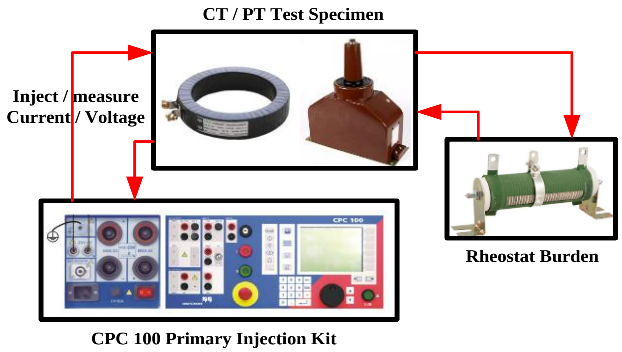

Fig. 1 Overall experimental setup

4. Experimental Measurements

A series of ratio and the phase displacement errors were measured, individually for the CT & PT test specimens, each time varying the burden connected to them. Depending on whether the rheostat (Ohms) is connected to CT or PT, the multifunctional kit automatically calculates and displays the effective Volt-Ampere (VA) burden, as seen by these instrument transformers, during each measurement. The total effective VA burden thus applied and measured during the experiment varied from 0.0VA to 427.9VA in case of PT and 0.0VA to 2700VA in case of CT.

The ratio and phase displacement errors as measured for the PT test specimen is tabulated in Table II and that for CT test specimen in Table III. The measurements are for the respective VA burden as seen by them at respective percentages of primary values (voltage / current) applied to their primary windings in each measurement set.

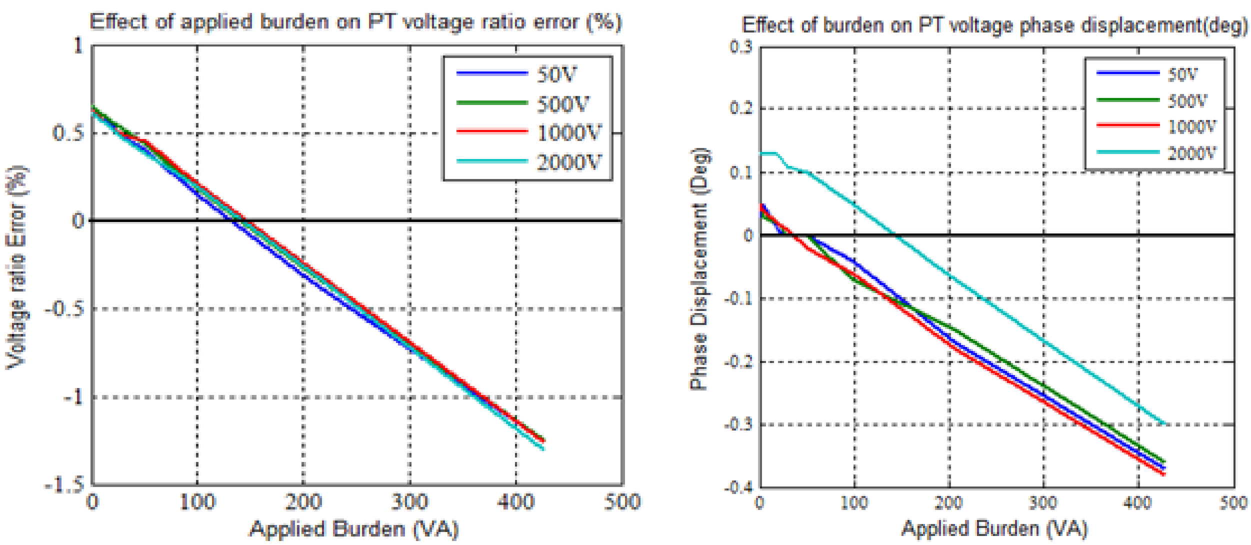

Fig. 2: Dependency of PT voltage ratio error and phase displacement on the applied burden

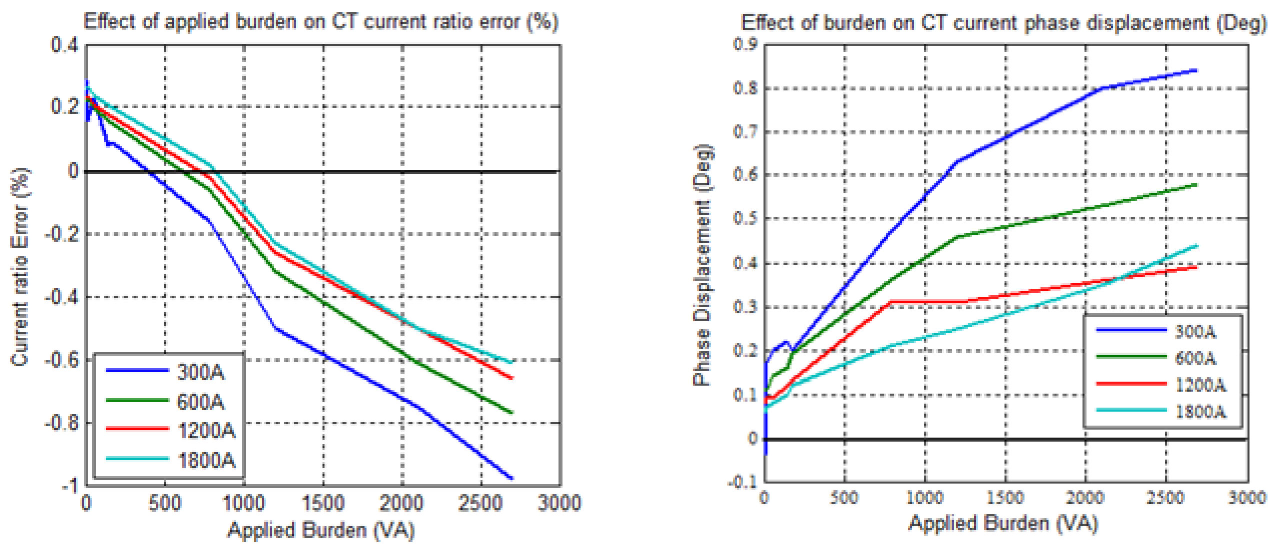

Fig. 3: Dependency of CT current ratio error and phase displacement on the applied burden

TABLE II: Error Measurement with PT Test Specimen

Applied Primary Voltage (V)		50		500		1000		2000	
Burden		Ratio Error (%)	Ph. Disp. (Deg.)	Ratio Error (%)	Ph. Disp. (Deg.)	Ratio Error (%)	Ph. Disp. (Deg.)	Ratio Error (%)	Ph. Disp. (Deg.)
Volt-ampere (VA)	Ohms (Ω)								
0.0	0.0	0.61	0.05	0.65	0.05	0.62	0.05	0.61	0.13
1.98	2000.0	0.61	0.03	0.65	0.04	0.61	0.04	0.60	0.13
4.06	1000.0	0.59	0.05	0.63	0.03	0.60	0.04	0.59	0.13
18.28	220.80	0.55	0.01	0.57	0.02	0.53	0.02	0.53	0.13
28.5	140.80	0.48	0.00	0.52	0.00	0.49	0.01	0.47	0.11
51.41	78.00	0.40	0.00	0.43	0.00	0.45	-0.02	0.38	0.10
98.7	40.00	0.15	-0.04	0.18	-0.07	0.21	-0.06	0.19	0.05
207.05	19.50	-0.34	-0.17	-0.30	-0.15	-0.27	-0.18	-0.29	-0.07
427.9	9.30	-1.25	-0.37	-1.25	-0.36	-1.26	-0.38	-1.31	-0.30

% = percentage, Deg. = degree, Ph. Disp. = phase displacement

TABLE III: Error Measurement with CT Test Specimen

Applied Primary Current (A)		300 (5%)		600 (10%)		1200 (20%)		1800 (30%)	
Burden		Ratio Error (%)	Ph. Disp. (Deg.)	Ratio Error (%)	Ph. Disp. (Deg.)	Ratio Error (%)	Ph. Disp. (Deg.)	Ratio Error (%)	Ph. Disp. (Deg.)
Volt-ampere (VA)	Ohms (Ω)								
0.0	0.0	0.29	-0.04	0.22	0.11	0.23	0.08	0.26	0.06
12.68	0.6	0.16	0.17	0.23	0.11	0.24	0.09	0.27	0.07
58.51	2.5	0.23	0.20	0.20	0.14	0.21	0.09	0.24	0.08
146.96	5.8	0.08	0.22	0.16	0.16	0.18	0.12	0.21	0.10
177.37	7.2	0.09	0.20	0.15	0.19	0.17	0.13	0.20	0.12
783.41	31.5	-0.16	0.47	-0.06	0.36	-0.02	0.31	0.02	0.21
1200.00	50.0	-0.5	0.63	-0.32	0.46	-0.26	0.31	-0.23	0.25
2100.00	86.0	-0.75	0.80	-0.61	0.53	-0.50	0.36	-0.50	0.35
2700.00	110.0	-0.98	0.84	-0.77	0.58	-0.66	0.39	-0.61	0.44

% = percentage, Deg. = degree, Ph. Disp. = phase displacement

This variation of the measured ratio and the phase displacement with burden variation is illustrated better by way of their plots [8] in Fig.2 and Fig.3, respectively for PT & CT. All the measurements were made in line with the requirements stated in IEC 60044-1 & 60044-2.

5. General Experimental Findings

Some general observation and findings were made from the experiments performed on the CT & PT specimens, with regard to the burden connected to them. The findings are based on the results and plots above.

1) The actual VA burden as seen by PT is based on the actual ohms (R) connected to its secondary and the rated secondary voltage of the PT ($V_{sec} = \sqrt{110}$) under test, irrespective of the applied primary voltage during the test. It is directly based on the relationship given in (1) and is inversely related to the actual ohms (R) connected to its secondary.

$$VA_{PT} = \frac{V_{sec}^2}{R} \tag{1}$$

2) The actual VA burden as seen by CT is based on the actual ohms (R) connected to its secondary and the transformed CT secondary current ($I_{sec} = K_n * I_{Pri}$) for a given CT primary current (I_{Pri}) during the test. It is directly based on the relationship given in (2) and is directly related to the actual ohms (R) connected to its secondary.

$$VA_{CT} = I_{sec}^2 * R \tag{2}$$

3) From (1) & (2) and the measurements, it is observed that, while actual VA burden as seen by PT remains same irrespective of the voltage available at its primary, in case of CT, it varies with the actual current flowing in its primary (transformed secondary current) as in Table IV.

TABLE IV: Dependency of CT's VA Burden on its Actual Primary Current

Actual test current on CT primary (A)		300	600	1200	1800
Test Burden		Actual VA burden as seen by CT for transformed secondary current, corresponding to the test current applied on primary			
VA	Ω				
0.0	0.0	0.00	0.00	0.00	0.00
12.68	0.6	0.037	0.150	0.600	1.350
58.51	2.5	0.156	0.625	2.500	5.625
146.96	5.8	0.363	1.450	5.800	13.05
177.37	7.2	0.450	1.800	7.200	16.20
783.41	31.5	1.970	7.875	31.50	70.875
1200.00	50.0	3.125	12.50	50.00	112.50
2100.00	86.0	5.375	21.50	86.00	193.50
2700.00	110.0	6.875	27.50	110.0	247.50

It is therefore concluded from Table.4 that, as long as the value of primary current in CT is comparatively lower than rated, the actual VA seen by CT is also low [eg: 6.875 VA corresponding to a connected burden of 2700VA (110 Ohms), for 300A applied in the primary]. It therefore follows and increases with the value of the primary current flowing. Correspondingly for a rated current of 6000 A (5A in the CT secondary) in the CT primary, a value of only about 6.0 Ohms connected to its secondary, corresponds to its rated burden of 150 VA, beyond which CT should saturate and result into ratio error beyond permissible limits.

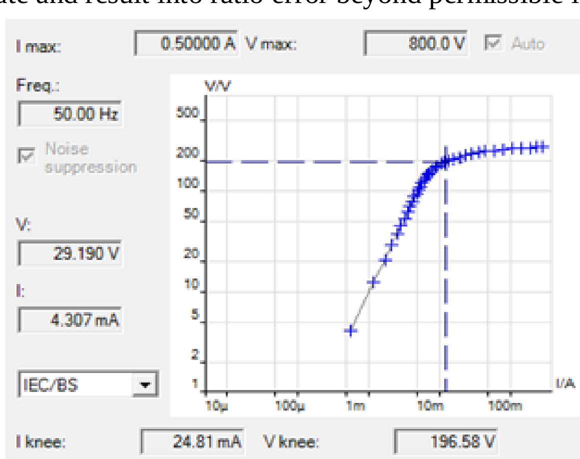

Fig. 4: Saturation plot measured for the CT specimen

A typical CT saturation plot measured for the CT specimen is shown in Fig.4. The saturation plot indicates that the CT would enter into saturation beyond the measured knee-point resulting into higher ratio error. CTs at its rated current normally operate far below this point to maintain the error at the least possible, provided the burden connected to it is at its optimum value corresponding to its rating.

6. Effect of Burden on Voltage Ratio Error and Phase Displacement

From the measurements and plots in case of Potential Transformers:

1) The % voltage ratio error increases as the burden is either low or high. As per IEC 60044-2, the measuring accuracy of the PTs do not get guaranteed when the total connected burden is not within 25-100% of the rated burden. The same is illustrated from the experiment & plots, where it is seen that the % ratio error is all the time within the allowable limits when the burden connected to the PT is between 25 - 100 % of the rated burden (i.e between 50 to 200VA)
2) The ratio error in case of PT is seen to gradually vary from the extreme positive value initially when connected to low burden to the negative values with increased burden. The error finally is seen to go beyond permissible limits in both the cases, burden either lower than 25% (50 VA) or beyond 100% (200VA). It is further established that the % ratio error is least if the connected burden is optimally maintained between 50 to 100 % of rated value.
3) The error being positive, the voltage readings therefore will be read higher than the actual when the actual connected burden to the PT is very low and vice-versa.
4) The same is observed in case of voltage phase displacement too (Fig.3 (a)), where it also is varying from the extreme positive values at low burden to the negative values as the burden gets increased. It also is seen to be least displaced if the connected burden is optimally maintained between 50 to 100 % of rated value.

7. Effect of Burden on Current Ratio Error and Phase Displacement

From the measurements and plots in case of Current Transformers:

1) The % current ratio error increases as the burden is either low or high. As per IEC 60044-1, the measuring accuracy of the CTs also do not get guaranteed when the total connected burden is not within 25-100% of the rated burden. The same is illustrated from the experiment & plots for CT specimen, where it is seen that the % ratio current error is all the time within the allowable limits when the actual effective burden (corresponding to the actual transformed secondary current) connected to the CT is between 25 - 100 % of the rated burden (i.e. between 37.0 to 150VA).
2) The ratio error in case of CT is also seen to gradually vary from positive value initially when connected to very low burden to the negative values with increased burden. The error finally is seen to go beyond permissible limits in case the actual burden seen by CT for its corresponding secondary current goes beyond the rated burden. However unlike the case of PTs the error exceeding the allowable values is seen only towards the negative error side when the effective connected burden far exceeds the rated burden. It is further established that the % ratio error is least as in case of PT, if the connected burden is optimally maintained between 50 to 100 % of rated value.
3) The current readings therefore will be read lower than the actual value, when the actual connected burden to the CT is very high and vice-versa.
4) The current phase displacement on the other hand is seen to mostly vary only on the positive side with the displacement gradually getting more positive as the burden is increased from 0 VA towards the rated VA and beyond. Unlike the case of PTs, the current displacement is measured least when the connected burden is also least (Fig.3 (b)) and goes beyond allowable limits as the burden goes beyond rated VA.

8. Conclusion

Overall, it is established from the experiment and the corresponding analysis on the CT & PT specimens that, their measuring accuracy definitely gets affected with the effective connected burden being either too low or beyond rated values. The errors in both the instrument being positive for the lower burden and negative for higher burden.

The case under investigation with regard to CHP however is the case of considerable lowering of the connected burden, that have resulted due to replacement of the entire electromechanical type protection relays with the modern low burden numerical relays. From the general facts and the experimental analysis it is therefore established that, the errors in the measurement in case of CHP can be attributed mostly to the low burden connected (far below rated), especially to the PT secondary, whereby the PTs are operating at an error beyond permissible positive limits of 0.5. It is moreover due to the fact established that the effective VA burden connected to the PTs are dependent on the connected resistance and the rated PT secondary voltage, irrespective of its primary voltage.

The VA burden however for the CTs as measured are seen to be not so low to effect the current measurements. Moreover, the effective VA burden unlike PTs as established from the analysis are dependent on the connected resistance and actual primary current of the CTs, which if maintained low would result into burden maintained within its rated values, to affect the measuring accuracy.

It is therefore concluded that the case of low PT burden and the associated higher voltage reading (positive error), therefore is applicable in case of PTs for CHP's units, thereby resulting into a voltage higher than actual in the measuring/metering devices. This is therefore seen as one of the factors contributing to higher reading in the energy metering devices recording CHP's auxiliary consumption.

In general, following few options are concluded as a measure to overcome the cases similar to CHP, for any such upgrades in the electrical system:

1) Adequate compensation of the lowered burdens during such upgrades in the system, to match the rated burden of instrument transformers, especially PTs, as they are seen to contribute more to the measurement errors.
2) Replacing the associated instrument transformers with adequate burden rating, to match the actual low burden imposed by numerical relays.
3) Match the accuracy class of the instrument transformers to that of the corresponding energy meter accuracy class, for more precise measurement.

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