Exploring The Impact Of Inductive Current Transformers On Harmonic Emission Measurements For South African Grid Code Compliance

2024 32nd Southern African Universities Power Engineering Conference (SAUPEC) | 979-8-3503-7134-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/SAUPEC60914.2024.10445104

Ruan Murray
School of Electrical and Electronic Engineering
North-West University and Hatch
Johannesburg, South Africa
Oricd ID 0000-0003-3416-8007

Jan A. de Kock
School of Electrical and Electronic Engineering
North-West University
Potchefstroom, South Africa
jan.dekock@nwu.ac.za and Orcid ID 0000-0002-5485-0647

***Abstract*—There have been various revisions of the South African Grid Code for Renewable Power Plants. This paper specifically focuses on the harmonic emissions component of the Grid Code, and how inductive current transformers (commonly used in outdoor substations) can impact the accuracy of these measurements. This paper considers inductive burden and harmonic current amplitude as two components to consider. An increased ratio error is introduced when lower current harmonic amplitudes are measured, typically below 0.5 A. An even greater ratio error is experienced when inductive burdens are connected to the secondary circuit of the current transformers. Conducting measurements and quantify the burden at each site is of importance, while also determining its influence on measurements when conducting harmonic current analysis for Grid Code compliance. Once quantified, these errors can be compensated for to improve the accuracy of these harmonic current measurements.**

Keywords— burden, grid code compliance, harmonic currents, independent power producers, current transformers, power quality.

I. Introduction

With increasing renewable power penetration, power quality (PQ) measurements become of great importance [1]. Accuracy of these measurements becomes a relevant subject when it comes to Grid Code compliance evaluations. Not complying with limits can result in non-conformance, having a financial impact on Renewable Energy Independent Power Producers (REIPPs).

In the South African context, there have been various versions of the South African Grid Code for Renewable Power Plants (SAGCRPP), with changes relating to harmonic emission assessments in these versions. In this paper the focus will be on evaluating the influence measurement errors from inductive current transformers (CTs) might have in this context, especially when burdens are involved as per the IEC standard (IEC 61869-2).

Recent literature evaluated the impact of inductive and resistive burdens and how these influence harmonic current measurements when current transformers (CTs) are used [2]. The measurement error can be up to 90%, for higher-order harmonics. This paper will further develop this work and link the results to the impact on harmonic emissions assessments for Grid Code compliance in South Africa.

This will be done by first discussing the literature and history of the Grid Code requirements concerning harmonic emission assessment. A test setup and measurement results are presented for two outdoor 132 kV 200/1 and 400/1 CTs, which are then discussed, focussing on the impact ratio errors might have on the assessment of harmonic emissions for Grid Code compliance.

II. Grid Code on Harmonic Measurements

A. *Review of Grid Code Versions*

The first official SAGCRPP was introduced in November 2012 as version 2.6 [3]. There were however versions published for comments before this one. Since the 2012 version, there have been various updates resulting in versions 2.8 [4], 2.9 [5], 3.0 [6] and the latest version 3.1 [7].

Versions 2.6 and 2.8 were similar from a harmonic current and voltage perspective. Limited details are provided as to the limits to be set by the NSP, and no reference is made to NRS 048 series or IEC 61000 series in these two versions.

Version 2.9 (published in 2016) included additions concerning harmonic limits. This was the first version which allows current harmonic limits to be exceeded by 50% for individual harmonics, as long harmonic distortion (HD) limits for the four bands are met. NRS 048 and IEC 61000 were referenced and used as guidelines for emission limits. It was also specified that 30% of the NRS 048:4 limit must be used as default, where these are not specified for individual harmonics. The focus was also more on voltage harmonics, if compared to the latest two versions (3.0 and 3.1). Some other additions include Appendix 13 as a PQ guideline, which includes a detailed assessment process which was focused on simulations and measurements to verify compliance, with exception periods for different phases. There was also an addition in this version (2.9) which stated that 0.1 A (primary current) must be used as the lower limit for emission limits for current harmonics, owing to constraints on current transformers and PQ equipment for measuring lower amplitude harmonic currents – this was removed in the latest version (3.1).

Version 3.0 was mostly a copy of version 2.9 from a PQ perspective. It did however include an additional Appendix 14, which focused on compensation for errors in simulations.

The latest version of the SAGCRPP was published in 2022, and there were some notable changes made. The first is the removal of the 0.1 A minimum limit for current harmonics. The other difference is that there was a shift of focus from simulations to measurements. There are no more requirements for simulations as part of the assessment process for power quality compliance in the latest version of this Grid Code. Emission limits for inverters were added to Appendix 13, with total harmonic current distortion (THDi) (up to the 50th harmonic) for inverters to be below 5%. Other notable changes included the addition of measurement uncertainty estimation as part of the measurement process, as well as the consideration of the IPP to absorb harmonics at the point of connection (POC) and therefore the direction of harmonic emissions becomes important.

Since the inception of the SAGCRPP, there have been several changes relating to harmonic emission limits and assessment. This was briefly touched on in the previous paragraphs. Table I shows some of these changes that are linked to harmonic emissions, comparing the various versions. The following have been tracked in the table presented:

1. Band limits for harmonic emissions,
2. allowance for 50% limit exceedance if 1. is complied with,
3. NRS 048 and IEC 61000 specified as guidance for setting emission limits,
4. limit for the minimum current amplitude of 0.1 A,
5. inverter emission limits.

TABLE I. SOUTH AFRICAN RENEWABLE GRID CODE HISTORY ON HARMONIC EMISSIONS

Version	**Year**	**Compliance**	**1**	**2**	**3**	**4**	**5**
2.6	2012	S & M	X	X	X	X	X
2.8	2014	S & M	X	X	X	X	X
2.9	2016	S & M	✓	✓	✓	✓	X
3.0	2019	S & M	✓	✓	✓	✓	X
3.1	2022	M	✓	✓	✓	R	✓

M – measurements, S – simulation, ✓ - included, X – not included

R - removed

The two main items considered in this paper, are the minimum measurable harmonic amplitude as well as the influence on the error of measurement when the burden is connected to CTs.

B. Harmonic emission assessment

To prove compliance with the Grid Code and emission limits set by the Network Service Provider (NSP), a power quality measuring instrument (IEC 61000-4-30 Class A) must be installed at the POC to measure voltage and current (bi-directional). This instrument must measure 10-minute aggregated values. The measurements for emission analysis shall be recorded for a minimum of 7 days, to represent the production cycle of the plant. Voltage and current harmonics up to the 50th harmonic order must be recorded.

As discussed, allowance is made for current harmonics to exceed the limit by up to 50%. This is only if the harmonic distortion (HD) is still within limits for the four bands, where h is the harmonic order:

Band 1: $2 \leqslant h \leqslant 13$,

Band 2: $14 \leqslant h \leqslant 25$,

Band 3: $26 \leqslant h \leqslant 39$,

Band 4: $40 \leqslant h \leqslant 50$.

The equations (1) and (2) below are applied to each band to prove compliance. Note that the actual primary current (in A) and not percentage are used. In these equations, I is the limit or measured current and h is the harmonic order.

$$HD_{IlimitGi} = \sqrt{\sum_{h=bottomhlimit}^{tophlimit} I_{limit}(h)^2} \qquad (1)$$

$$HD_{ImeasuredGi} = \sqrt{\sum_{h=bottomhlimit}^{tophlimit} I_{measured}(h)^2} \qquad (2)$$

For Grid Code compliance $HD_{ImeasuredGi}$ must be less than $HD_{IlimitGi}$. Where i represents the band (1, 2, 3 or 4) for which the calculation is done.

III. Current Transformers and Harmonic Measurements

Accuracy of current transformers for harmonic measurements have been investigated in literature - [8], [9], [10], [11], [12], [13], [14] and [15]. IEC/TR 61869-103 has also been developed, with a focus on power quality measurements in general [16]. Mention is made of a non-linear frequency response in literature, for lower odd harmonics – this is in most cases however with low resistive burdens.

The burden has an influence on both the fundamental current, as well as the harmonic current measurement accuracies [2] [8] [17]. The impedance of the burden (Z_{BURDEN}) includes cabling (Z_c) and measuring devices (Z_{md}) (refer to Fig. 1). When a low (below 2% of rated) mostly resistive burden is connected to CTs, it does not affect the accuracy of the harmonic measurements, where more inductive burdens however do seem to increase the harmonic current ratio errors [2] [17].

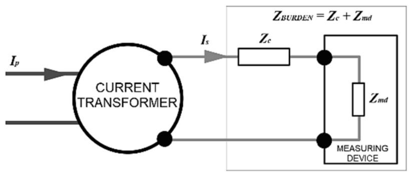

Fig. 1. Typical CT burden (Z_{BURDEN}) components

The IEC and IEEE standards specify burden limitations for which current transformers must prove compliance to the nameplate accuracy class. Both of these standards specify accuracies at a lagging power factor, where the IEC requires a power factor of 0.8 [18] and the IEEE 0.9 [19].

Table II shows the standard IEC burdens [18].

TABLE II. STANDARD IEC BURDENS

Class	**Burden Range (%)**	**Current amplitude (%)**	**Error - Ratio (%)**	**Error - Phase (min.)**
0.1	25 - 100[a]	I ≤ 5	0.4	15

Class	Burden Range (%)	Current amplitude (%)	Error - Ratio (%)	Error - Phase (min.)
		5 < I ≤ 20	0.2	8
		20 < I ≤ 120	0.1	5
0.2	25 - 100[a]	I ≤ 5	0.75	30
		5 < I ≤ 20	0.35	15
		20 < I ≤ 120	0.2	10
0.5	25 - 100[a]	I ≤ 5	1.5	90
		5 < I ≤ 20	0.75	45
		20 < I ≤ 120	0.5	30

a. For a rated burden of below 5 VA the power factor should be unity, otherwise 0.8 (lagging).

The burden connected to a CT can include various components. In indoor substation applications, metering will likely be the main component making up the burden. While for outdoor substation applications cabling might be the greater components of the burden. Components that typically add to the CT burden include the main energy meters, check energy meters, other meters (PQ), cables (between 0.3 VA and 2 VA for 5-200m cable lengths, at the rated current - 1 A), protection relay devices and current transducers [20].

In literature and standards, the focus is mostly on the impact on power frequency measurement, when burden is connected and varied. There is however some research references which also considers the influence that burden can have on the accuracy of harmonic measurements.

In [2] a literature review was presented with limited literature available on the impact of burden on CTs for current harmonic measurements. An analysis is conducted on the influence of burden on harmonic current measurements in [2], indicating a significant increase in ratio error. This is especially true when more inductive burdens are present in the secondary CT circuit – in some instances resulting in an error of up to 90% for higher order harmonics.

Some research has also been conducted on voltage transformers (VTs). It should however be noted that the mode of operation for CTs and VTs differ, specifically also the range of operation and also the design. In [21], the impact of capacitive and resistive burdens on VTs were evaluated. In doing this the authors also considered the impact of external factors like operating temperature, while varying the burden and primary voltage magnitude. Results presented indicate that resistive burden can increase the ratio error up to 12%, for harmonics up to 3 kHz. When a capacitive component is added the results seems to show a further increase in ratio error up to 50% at higher-order voltage harmonics.

IV. TEST SETUP

The test setup used enables the injection of a test signal to the test CTs primary circuit, while varying the fundamental and harmonic current amplitudes. This is repeated for various burden scenarios. The harmonic components (amplitude and phase) are measured and recorder using the DFT from the Power Analyzer, results are then used to compare the secondary and primary measurements.

The test waveform is represented by equation (3), where i(t) is the time domain current. The fundamental current is I_f, while I_h represents the harmonic current amplitude. A fundamental frequency (f) of 50 Hz is applied, with a superimposed harmonic component with frequency f_h.

$$i(t) = I_f \sin(2\pi f \cdot t) + I_h \sin(2\pi f_h \cdot t) \quad (3)$$

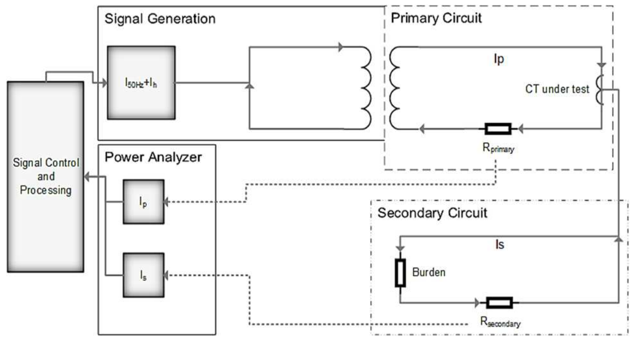

Fig. 2. Measuring circuit (test setup)

A layout of the test setup is presented in Fig. 2. [2], which was based on the information presented in [12]. This test setup includes:

- A signal generator – which generates the signal as per equation **Error! Reference source not found.**),
- interposing step-down transformer – for higher current transformation,
- test current transformer,
- high accuracy resistive shunt – able to measure high order harmonic currents (up to 1 Mhz), and
- power analyser (PPA) - for logging both the primary and secondary current measurements.

More detail on each component is discussed in [2].

Type A uncertainty was used to evaluate the uncertainty of the measuring circuit in [22]. An uncertainty of below 0.02% over the entire frequency range from 100 Hz to 3 kHz was determined in [12].

V. RATIO ERROR CALCULATION

IEC 61869 makes use of the ratio error (equation (4)) and phase error to determine the metrological performances of CTs [18]. In equation (4), h is the harmonic order, K the current transformer ratio, I_p the amplitude of the primary current and I_s the amplitude of the secondary current.

$$\varepsilon^h = \frac{KI_s - I_p}{I_p} \times 100\% \quad (4)$$

VI. MEASUREMENT RESULTS

Tests were conducted on two 132 kV outdoor, hairpin design current transformers. Both of these were manufactured locally in South Africa, which generally supplies outdoor-type CTs to the utility. The ratio, accuracy class and burden rating for these units are shown in Table III. 132 kV was specifically choses as the CT voltage, as it is commonly used at the point of connection (POC) for REIPPs.

Several variables were considered and varied during the measurements: Burden (VA) – 25% to 100%, power factor

(0.8 as per IEC), fundamental current amplitude as well as harmonic current amplitude (0-10 A on the primary current). Harmonics evaluation was done from the 2nd up to the 60th (3 kHz), although the Grid Code only requires measurements up to the 50th order. The reason for this is that the switching frequency of power electronic equipment used in a REIPP environment is usually between the 50th and 60th harmonic.

TABLE III. TEST UNITS (CTS)

Test CT No.	Accuracy Class	Voltage Rating	Current Ratio	Burden VA
1	1	132 kV	200/1	10
2	0.2	132 kV	400/1	10

A. Fundamental Current Ratio Error

For each one of the CTs tests were conducted as per IEC 61869, to determine the ratio error compliance based on the CT class. At 1.25 VA and 2.50 VA unity power factor is applied, while the larger burden is at 0.8 lagging. Results can be seen in Fig. 3 and Fig. 4, where I is the applied current amplitude and I_{pn} is the rated current.

The results indicate that the accuracy of the CTs complies with the class specified on the nameplate. For the Class 0.2 CT, a burden increase results in a decrease in ratio error. The opposite is true for the Class 1.0 CT, where an increase in burden results in an increase in ratio error.

As touched on in previous sections the focus of the IEEE and IEC tests is for accuracies at fundamental frequency, i.e. 50 Hz in South Africa. In the following sections, the focus will be on the harmonic current ratio errors.

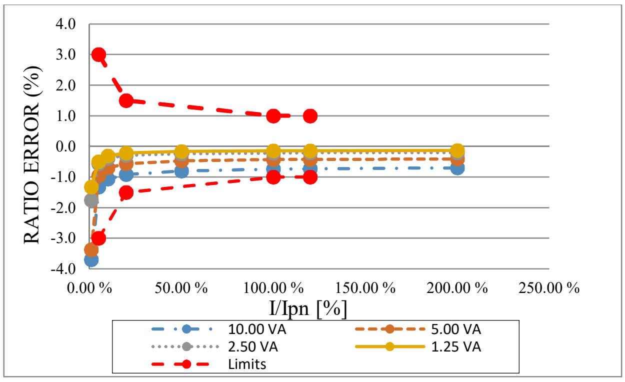

Fig. 3. CT No. 1 Ratio error for fundamental current amplitude

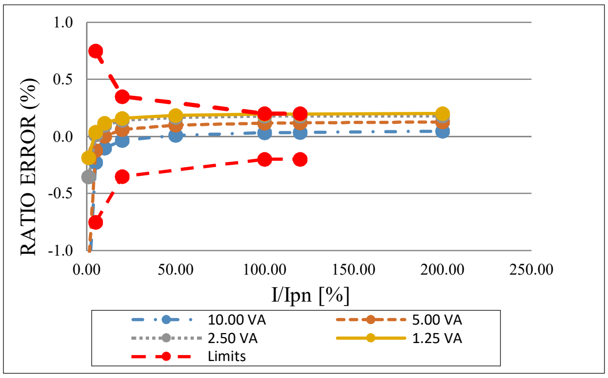

Fig. 4. CT No. 2 Ratio error for fundamental current amplitude

B. Minimum Harmonic Current Amplitude Analysis

As part of the Grid Code compliance, the IPP needs to comply with harmonic emission limits set by the NSP at the POC. Table IV shows an example of actual limits at a 132 kV POC for a specific REIPP plant in South Africa. In this specific case, all harmonic limits were below 1 A in primary current, with harmonics above the 14th order having a limit of 440 mA in primary current.

TABLE IV. EXAMPLE OF EMISSION LIMITS AT 132 KV FOR REIPP

Harmonic Order	Voltage Limit (%)	Current Limit (A in primary current)	HD Limit (A)
2	0.1	0.76	2.11
3	0.12	0.61	
4	0.1	0.44	
5	0.33	0.99	
6	0.1	0.44	
7	0.33	0.71	
8	0.1	0.44	
9	0.33	0.55	
10	0.1	0.44	
11	0.48	0.67	
12	0.1	0.44	
13	0.48	0.56	
14-50	0.1	0.44	-

These limits can be exceeded by more than 50%, so in essence 150% of the limit indicated in table IV. But it will then be required that the limit for the HD of the band should still be within the defined limit. For this specific case, the lower-order band had an HD limit of 2.11 A. The other three bands have limits of 1.52 A, 1.65 A and 1.46 A respectively.

As the CT forms part of the measurement chain, it is important to know what the accuracy of the CT is at lower harmonic amplitudes. This becomes relevant as harmonic limits can generally be below 1 A, as shown in Table IV.

An analysis was conducted for the two CTs considered in Table III. This was done by comparing the ratio error to the harmonic amplitude that was applied. In both Fig. 5 and Fig. 6 the accuracy class limits are indicated to evaluate at which harmonic current amplitude the accuracy class is exceeded. In these figures, the legend indicates the fundamental current amplitude applied. For the measurements, the only burden connected to the CT was the power analyser (PPA).

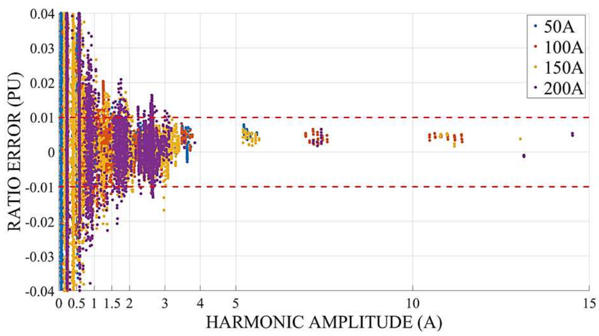

Fig. 5. CT No. 1 Ratio error vs Harmonic amplitude

For both CTs (Fig. 5 and Fig. 6), the ratio errors increase exponentially as the harmonic current amplitude decreases. Above 0.5 A the ratio error improves exponentially, as below that a lot of noise might be measured. A conclusion can be drawn that the error experienced for lower amplitude measurements would typically be below 6%. This might not be significant if a 50% exceedance allowance for individual harmonics is allowed. However, the band measurements would experience a larger ratio error, owing to the formula used (equation (2)).

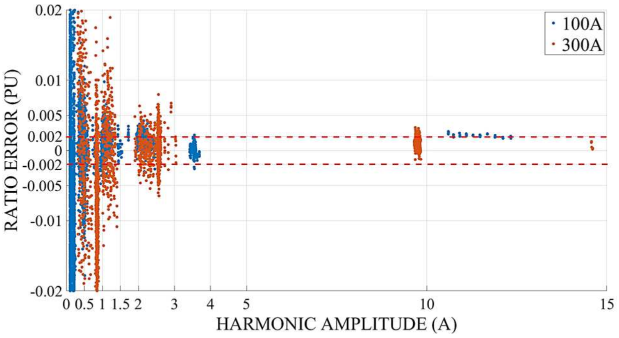

Fig. 6. CT No. 2 Ratio error vs Harmonic amplitude

C. Harmonic Ratio Error with Inductive Burden

The IEC specifies accuracy in measurement when inductive burden (0.8 power factor) is connected to a CT. In this section, the effect on harmonic current measurements will be explored. Typically, low burden (like when the power analyser is connected) as well as resistive burden has less of an effect on accuracy in measurements [2] and is therefore not discussed in detail.

For unity power factor the ratio error increases up to 8% [2]. An increase in harmonic order also results in an increase in ratio error, most likely owing to a low inductive component within the circuit.

Fig. 7 and Fig. 9 shows the results for tests for the fundamental current with a superimposed harmonic component (0.1% to 5% of the fundamental current). Various burden scenarios were tested, with a burden varying between 25% and 100%. A power factor of 0.8 lagging was applied. From the results presented in these figures it is clear that the inductive burden component would result in a significant increase in current ratio error - up to 90% for the Class 1 CT and up to around 40% for the Class 0.2 CT. The ratio error increases exponentially over the harmonic frequency spectrum, which would be expected as the inductive reactance changes with an increased frequency. It is also clear that the ratio error is more dependent on the burden and not influenced significantly by the variation of the applied fundamental current amplitude.

To link this ratio error results to the effect on HD band measurements, equation (5) is derived from equations (1) and (2). It should be noted that a 5th band was added, to account for harmonics up to 60th order – as measurements were conducted up to the 60th harmonic.

$$HDE_{measured} = \sqrt{\sum_{h=bottomhlimit}^{tophlimit} RatioError_{measured}(h)^2} \quad (5)$$

This equation is then used to determine the error per band, as presented in Fig. 8 and Fig. 10, for CT No. 1 and CT No. 2 respectively. The results show that an increased error per band is experienced and again increases exponentially – as would be expected from the results in Fig. 7 and Fig. 9.

For the HD band measurements, this can result in an error exceeding 50% for the third and fourth bands that are defined in the SAGCRPP. The result is however dependent on the actual power factor and VA of the burden.

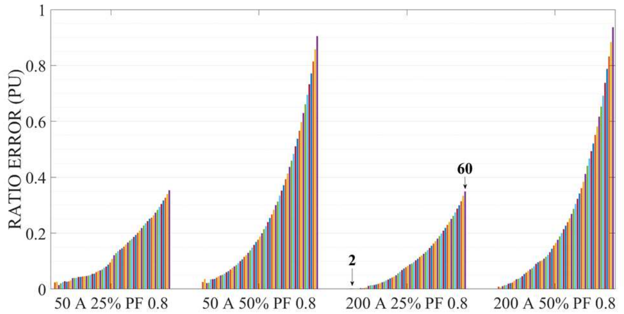

Fig. 7. 50 A and 200 A Fundamental, 200/1, 25%-50% Burden

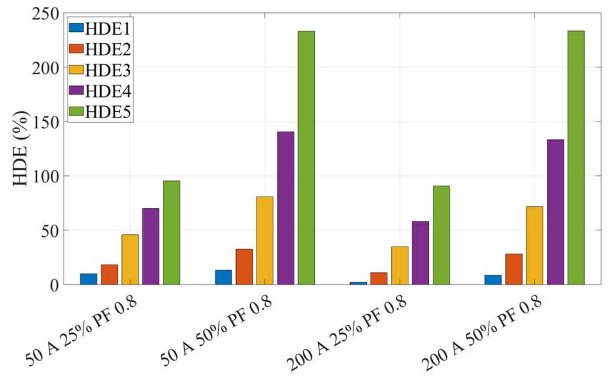

Fig. 8. CT No. 1 Harmonic distortion error per band

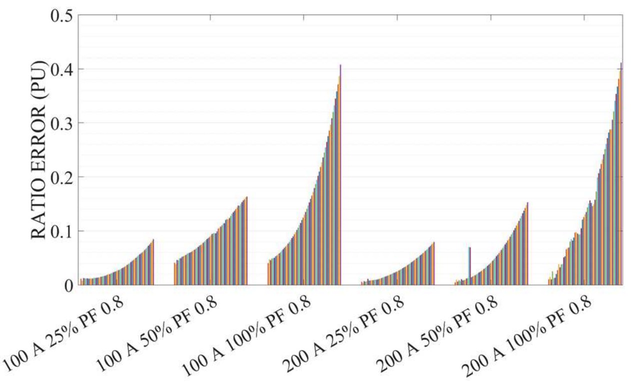

Fig. 9. 100 A and 200 A Fundamental, 400/1, 25%-100% Burden

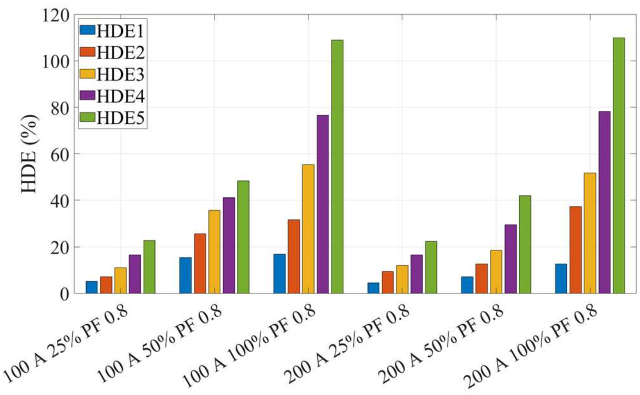

Fig. 10. CT No. 2 Harmonic distortion error per band

This becomes important to consider for band measurements especially when the 50% exceedance is applicable for individual harmonics, which in some cases might be less or more – based on individual harmonic ratio errors shown in Fig. 7 and Fig. 9. The results indicate that the error of the band measurements also needs to be considered as that becomes the secondary defence once individual harmonics limits are exceeded. It is especially important to consider for higher-order harmonics, i.e. above the 26th order.

VII. Conclusion

This paper considered the effect that current transformers (and their connected burden) can have on current harmonic measurements, specifically if used for Grid Code compliance assessments. There are two important factors considered, the first being the minimum current amplitude that can be accurately measured. The second factor is the burden impact on ratio error and specifically the effect on the HD band errors.

For the first, the results seem to indicate that harmonic amplitudes below 3 A would have some measurements exceeding the CT accuracy class, with a larger noise/error below 0.5 A. This exceedance of the class increases exponentially as the amplitude decreases and can lead to ratio errors of up to around 6%. This might become important if harmonics are within 6% of the 150% emission limit, for limits below 0.5 A. These errors will also have to be considered when determining the uncertainty in measurement relating to harmonics.

On the second (the burden), it is clear from the results that the burden influence on these measurements cannot be disregarded. Especially when a CT has an inductive burden component, which results in significantly higher harmonic ratio errors - 40% to 90% depending on the harmonic order, burden, power factor and accuracy class of the CT. The inductive reactance varies with frequency and therefore increases for higher-order harmonics.

This paper showed that both the burden and harmonic amplitude could result in increased ratio errors, which could become important when emission limits are exceeded for REIPPs. It is however still important for the utility that the measurements are representative of the actual power quality conditions, whether limits are exceeded or not.

From a SAGCRPP perspective, there will be an impact on the accuracy of the individual and band HD emission measurements. To compensate for this ratio error, the actual CT burden must be measured and then compensated for in the HD equation presented. This will be the focus of future work.

References

[1] R. Murray and J. de Kock, "Instrument transformers influence on harmonic measurements for grid code compliance," in *GEMCCON 2018*, Stellenbosch, 2018.

[2] R. Murray and J. de Kock, "Evaluating varying burden when inductive current transformers are used for harmonic current measurements," in *IEEE AMPS*, Bern, Switzerland, 2023.

[3] NERSA, *Grid Connection code for renewable power plants (RPPs) connected to the electricity transmission system (TS) or the distribution system (DS) in South Africa (Version 2.6),* 2012.

[4] NERSA, *Grid Connection code for renewable power plants (RPPs) connected to the electricity transmission system (TS) or the distribution system (DS) in South Africa (Version 2.8),* 2014.

[5] NERSA, *Grid Connection code for renewable power plants (RPPs) connected to the electricity transmission system (TS) or the distribution system (DS) in South Africa (Version 2.9),* 2016.

[6] NERSA, *Grid Connection code for renewable power plants (RPPs) connected to the electricity transmission system (TS) or the distribution system (DS) in South Africa (Version 3.0),* 2019.

[7] NERSA, *Grid Connection code for renewable power plants (RPPs) connected to the electricity transmission system (TS) or the distribution system (DS) in South Africa (Version 3.1),* 2022.

[8] A. Cataliotti, D. Di Cara, A. E. Emanuel and S. Nuccio, "A novel approach to current transformer characterization in the presence of harmonic distortion," *IEEE Transactions on Instrumentation and measurement,* vol. 58, p. 1446–1453, 2009.

[9] C. Laurano, S. Toscanil and M. Zanoni, "Improving the accuracy of current transformers through harmonic distortion compensation," *IEEE Instrumentation and Measurement Society,* 2019.

[10] C. Laurano, S. Toscani and M. Zanoni, "A Simple Method for Compensating Harmonic Distortion in Current Transformers: Experimental Validation," *Sensors,* vol. 21, p. 2907, 2021.

[11] M. Faifer, C. Laurano, R. Ottoboni and S. Toscani, "Adaptive Polynomial Harmonic Distortion Compensation in Current and Voltage Transformers Through Iteratively Updated QR Factorization," *IEEE Transactions on Instrumentation and Measurement,* 2023.

[12] R. Murray and J. de Kock, "A proposed method for evaluating the frequency response of 22 kV outdoor current transformers for harmonic measurements in renewable energy plant applications," in *AMPS 2019 - 2019 10th IEEE International Workshop on Applied Measurements for Power Systems, Proceedings*, Aachen, Germany, 2019.

[13] M. Kaczmarek, "Inductive current transformer accuracy of transformation for the PQ measurements," *Electric Power Systems Research,* vol. 150, p. 169–176, 2017.

[14] M. Kaczmarek and E. Stano, "Proposal for extension of routine tests of the inductive current transformers to evaluation of transformation accuracy of higher harmonics," *Electrical Power and Energy Systems,* vol. 113, pp. 842-849, 2019.

[15] G. Crotti, G. D'Avanzo, C. Landi, P. S. Letizia, M. Luiso, F. Muñoz and H. van den Brom, "Instrument Transformers for Power Quality Measurements: a Review of Literature and Standards," in *2021 IEEE 11th International Workshop on Applied Measurements for Power Systems (AMPS)*, Cagliari, Italy, 2021.

[16] *Instrument transformers - The use of instrument transformers for power quality measurement,* IEC TR 61869-103, 2012.

[17] T. Pfajfar, J. Meyer, P. Schegner and I. Papič, "Influence of instrument transformers on harmonic distortion assessment," in *Power and Energy Society General Meeting, 2012 IEEE*, 2012.

[18] *Instrument transformers - Part 2: Additional requirements for current transformers,* IEC 61869-2, 2012.

[19] *Standard Requirements for Instrument Transformers,* IEEE C57.13 , 2016.

[20] R. Mullikin, "Instrument Transformers," in *Electric Power Transformer Engineering*, CRC Press LLC, 2004, pp. 128-160.

[21] R. Stiegler and J. Meyer, "Impact of external influences on the frequency dependent transfer ratio of resin cast MV voltage instrument transformers," in *20th International Conference on Harmonics & Quality of Power (ICHQP)*, 2022.

[22] *Uncertainty of Measurement Part 3: Guide to the expression of uncertainty in measurement (GUM : 1995),* ISO/IEC Guide 98-3, 2009.