

## CONTRIBUTION TO EXPERIMENTAL INVESTIGATION OF FITTING THE CURRENT TRANSFORMERS' CALIBRATION CURVES

### PRIOLOG EKSPERIMENTALNOM ISTRAŽIVANJU FITOVANJA KALIBRACIONIH KRIVIH STRUJNIH MERNIH TRANSFORMATORA

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#### ABSTRACT

*The paper experimentally investigates the problem of fitting calibration curves of current transformers (CTs). An efficient fitting algorithm enables precise and accurate electronic real-time correction of CT errors and thus effective improvement of their accuracy class. The paper presents the results of a novel algorithm that allows correcting the transformers' current ratio error from 0.25% to within 0.004%, based on 8 key calibration points in the range 1% to 200% of the CT's nominal primary current, in line with the new IEEE Standard.*

**Keywords:** curve fitting, calibration curve, accuracy class, current transformer.

#### REZIME

*U radu se eksperimentalno istražuje problem fitovanja kalibracionih krivih strujnih mernih transformatora (SMT). Efikasan algoritam fitovanja omogućuje preciznu i tačnu elektronsku korekciju grešaka SMT u realnom vremenu i time efektivno unapređenje njihove klase tačnosti. U radu se daju rezultati jednog takvog algoritma koji u 8 kalibracionih tačaka u opsegu 1% - 200% nominalne primarne struje SMT koriguje grešku prenosnog odnosa do nivoa 0,004% u skladu sa novim IEEE Standardom..*

**Ključne reči:** fitovanje krive, kalibraciona kriva, klasa tačnosti, strujni merni transformator.

#### INTRODUCTION

Measurement of large currents, especially those at the highest voltage levels is done with the help of CT. At these voltage levels, the flow of electrical power and energy is the highest, so precise and accurate measurement of current is of the greatest possible importance. CTs have been in use for more than a century. Some authors (Emanuel, Orr, 2007) have predicted the end of their era due to significant pollution of the grid with higher harmonics content. However, CT manufacturers have always found ways to meet these challenges. Today, their answer to this challenge is the application of high-quality nanomaterials for CT cores (Naumovic Vukovic, et al, 2019). These high-tech solutions are very costly and only large, very advanced entities can implement them (Emanuel, 2004). Small entities are trying to use standard CTs and improve the methodology, thus solving this problem in a cost-effective way. This paper fulfills the necessary condition for an efficient methodological solution for a precise and accurate real-time measurement of large currents with CTs whose cores are made of classic ferromagnetic materials.

#### Problem statement

Current transformers are very robust devices, with stable characteristics. Their purpose is to reduce the large primary currents to small secondary currents, suitable for measuring with measuring instruments: ammeters, watt-meters, power meters, etc. (Schlabbach, Rofalski, 2008).

Today, measuring instruments are primarily digital electronic instruments. The development of digital electronic measuring technology has come a long way in terms of speed, precision and accuracy.

However, the critical element in the measuring chain remains - the CT - and increasing its precision and accuracy is crucial.

Due to the increase of dynamics in the electric distribution network, the appropriate IEEE C 57 standard has been changed (SASO IEEE C 57:2018, IEEE C 57:2013), (IEEE Std C57.13.7™-2018). Now the declared class must be guaranteed in the range of 1% to 200% of the nominal primary current (Naumovic Vukovic et al, 2019). The previous definition required a class guarantee of 5% to 120%. In addition to the standard requirement for greater precision and accuracy, the above change in standards has put CT manufacturers in front of major problems. Today, large manufacturers solve these problems by applying modern nanomaterials for the core (Swieboda, et al, 2019), so they solve the problem technologically. These solutions are expensive for small producers and users, whose investment funds are limited, hence they must look for methodological solutions to the problems discussed above.

Due to the nonlinearity of the magnetization curves and losses in both iron and copper, the current ratio error ( $\varepsilon$ ) and the phase shift ( $\Delta\phi$ ) error are nonlinear curves. The nonlinearity of the calibration curve is especially pronounced as a knee at small values of primary current - below 5% of its nominal value. The usual way of using CTs neglects this nonlinearity at a low range and treats CTs as linear elements (reducers) in the range of 5% to 120%. Improving the accuracy class, for example from 0.5% to 0.15%, and extending the declaration to the range of 1% to 200% of the primary current, requires detailed analysis and precise correction of the calibration curves.

#### Standard approach to ct calibration curve fitting

The first step in defining the method is to investigate the numerical algorithm of accurate real-time precision correction, by measuring the primary current based on measuring the secondary current. The basis for this is a suitable analytical formula for the amplitude and the phase error of a given CT.

The authors analysed three commercially available CTs from the same production batch, with a current ratio of 20A / 5A and accuracy class 0.5 in the range of 5% - 120%. The CTs have practically identical characteristics, so all the presented work is based on one of them. The goal is to formulate a method that would electronically correct the amplitude and the phase error in order to improve the accuracy to 0.15S measuring class (SASO IEEE C 57:2018, IEEE C 57:2013). Analyzing the experimental calibration curves obtained from the producer of the CTs, the authors observed that the nonlinearities were most pronounced at the lowest load level of 1.25 VA. Hence this load level was chosen as a candidate for the largest possible improvements.

The black line in Figure 1 shows the measured current ratio error ( $\varepsilon[\%]$ ) curve whereas in Figure 2 it shows the phase displacement error ( $\Delta\phi[\text{min}]$ ) of the given CT, both as a function of a percentage of the nominal primary current ( $I_n[\%]$ ) at 1.25 VA load. Table 1 gives the 8 calibration points in the range of 1% to 200% of the primary current, given by the CT manufacturer.

Table 1:  $\varepsilon$  and  $\Delta\phi$  calibration points – factory data

$I(\%)$	$\varepsilon(\%)$	$\Delta\phi(\text{min})$
1	-0.1404	46.9347
5	0.0805	17.6860
10	0.1431	12.6545
20	0.1897	9.3827
50	0.2320	6.6591
100	0.2541	5.1985
120	0.2587	4.8480
200	0.2680	3.9360

## Second-order polynomial regression

The orange lines in Figures 1 and 2 show the 2<sup>nd</sup> order polynomial regression curves, obtained by the standard least square regression algorithm (Ling et al, 2020). This regression method is a standardized polynomial approach, using the equations:

$$\varepsilon = \sum_{i=0}^2 c_i \cdot I^i \quad (1)$$

$$\Delta\phi = \sum_{i=0}^2 d_i \cdot I^i \quad (2)$$

where  $I$  is the percentage of nominal current and  $c_i$  and  $d_i$  are coefficients for  $\varepsilon$  and  $\Delta\phi$ , respectively. The obtained coefficients  $c_i$  and  $d_i$  are given in Table 2.

Table 2: 2<sup>nd</sup> order polynomial regression coefficients

$c_0$	$c_1$	$c_2$
0.12182	0.00222	-8.01702E-06
$d_0$	$d_1$	$d_2$
15.12274	-0.16838	0.00061

After applying these 2<sup>nd</sup> order standard regression curves, there will still be some residual errors, for both the magnitude (Figure 3) and the phase angle (Figure 4). It can be seen that the 2<sup>nd</sup> order polynomial regression works well in general, reducing the errors approximately 5 times in most of the range. However, this is not the case in the range of 1% to 5% (the so-called "knee" area), which is important since the adoption of the new IEEE Standard.

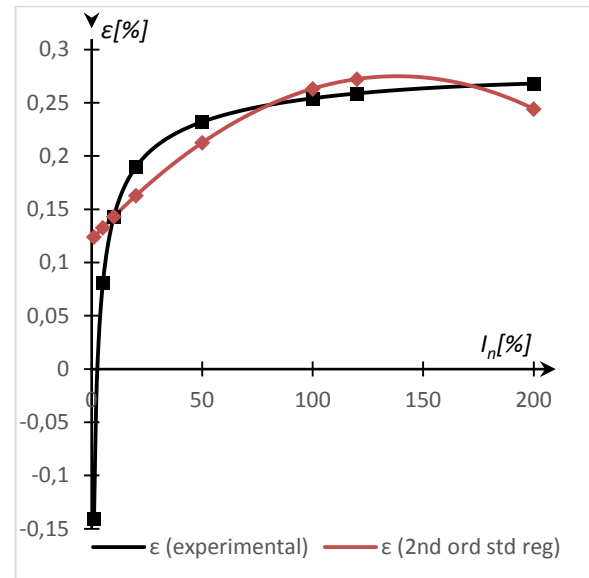


Fig. 1. Current ratio error  $\varepsilon$ : experimental and 2<sup>nd</sup> order regression

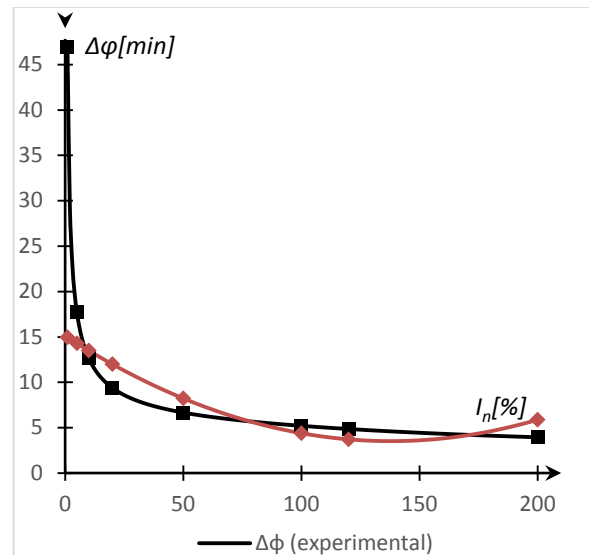


Fig. 2. Phase shift error  $\Delta\phi$ : experimental and 2<sup>nd</sup> order regression

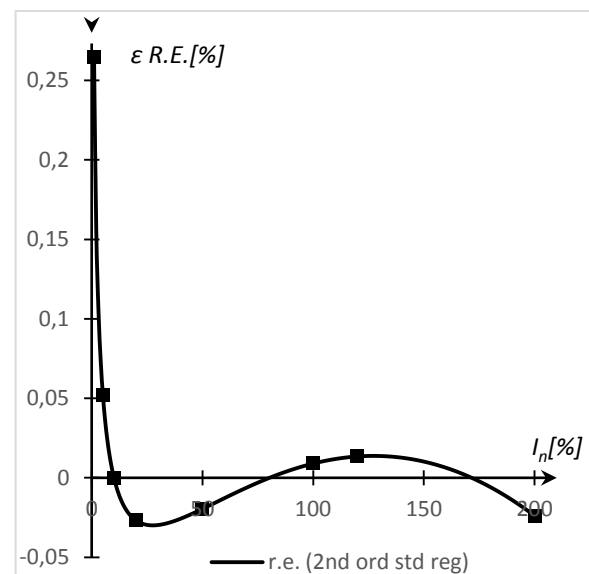


Fig. 3. Residual error of  $\varepsilon$  after 2<sup>nd</sup> order regression

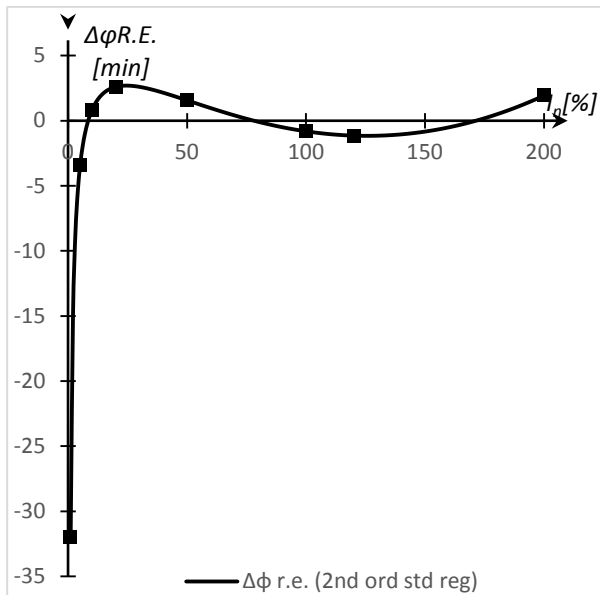


Fig. 4. Residual error of  $\Delta\phi$  after 2<sup>nd</sup> order regression

### Fourth-order polynomial regression

In order to obtain better results, the 4<sup>th</sup> order polynomial regression was applied. The formulas for regression curves of  $\varepsilon$  and  $\Delta\phi$  are given in equations (3) and (4) whereas Table 3 shows the new set of regression coefficients, specific for the analyzed CTs.

$$\varepsilon = \sum_{i=0}^4 c_i \cdot I^i \quad (3)$$

$$\Delta\phi = \sum_{i=0}^4 d_i \cdot I^i \quad (4)$$

Table 3: 4<sup>th</sup> order polynomial regression coefficients

$c_0$	0.03309	$d_0$	23.13032
$c_1$	0.00905	$d_1$	-0.79271
$c_2$	-0.00013	$d_2$	0.01216
$c_3$	8.13841E-07	$d_3$	-7.61949E-05
$c_4$	-1.74139E-09	$d_4$	1.65149E-07

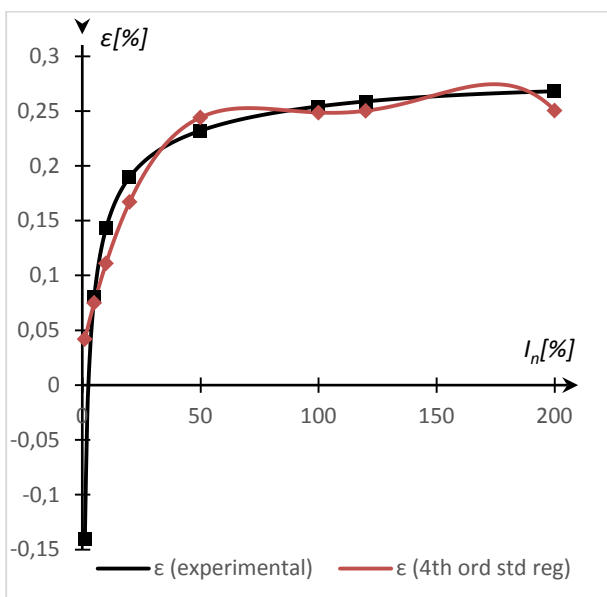


Fig. 5. Current ratio error  $\varepsilon$ : experimental and 4<sup>th</sup> order regression

The corresponding diagrams for the standardized 4<sup>th</sup> order polynomial regression of  $\varepsilon$  and  $\Delta\phi$  are shown in Figure 5 and Figure 6, whereas the residual errors are in Figure 7 and Figure 8.

Again, there is a significant improvement in the interval of 5% - 200%, but insufficient in the interval of the "knee" (1% - 5%). For classical polynomial regression analysis, therefore, the "knee" is a big problem if the aim is a fast and efficient procedure of real-time correction of both errors, in order to improve the class of the given CT from a 0.5 S to 0.2 S.

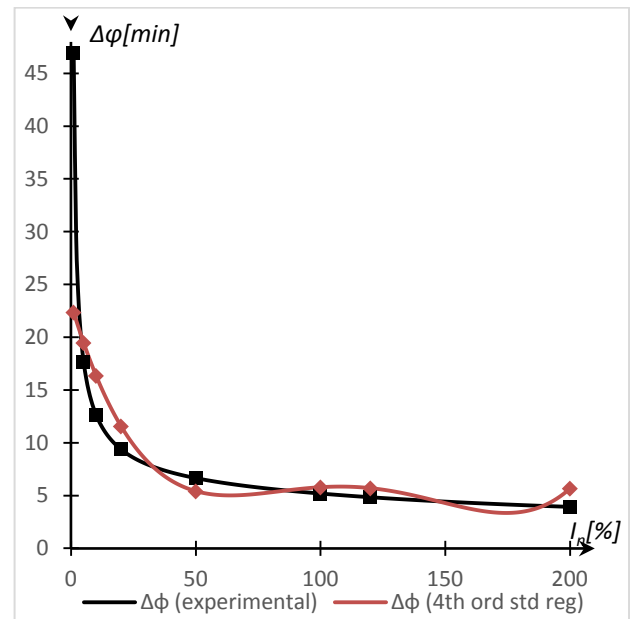


Fig. 6. Phase shift error  $\Delta\phi$ : experimental and 4<sup>th</sup> order regression

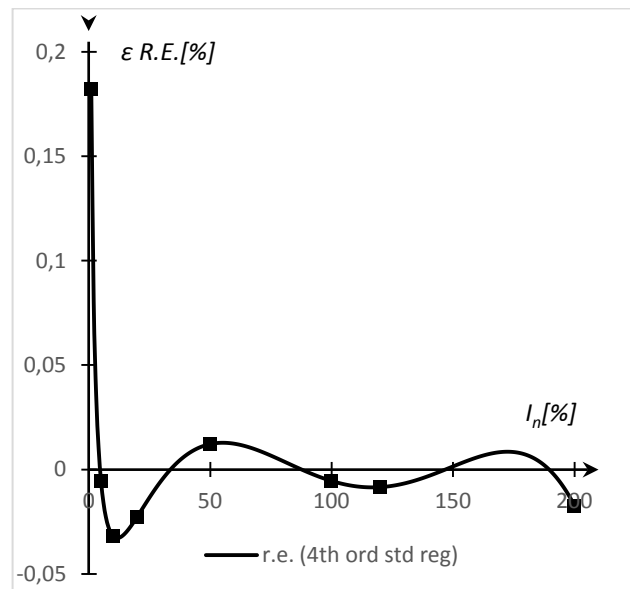


Fig. 7. Residual error of  $\varepsilon$  after 4<sup>th</sup> order regression

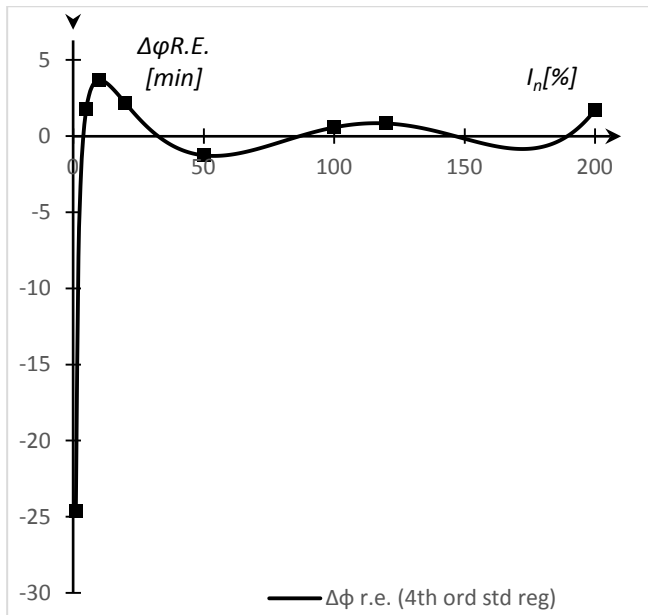


Fig. 8. Residual error of  $\Delta\phi$  after 4<sup>th</sup> order regression

### Conclusion on standard method results

Figures 3, 4, 7 and 8 indicate that a weak correction of the CT accuracy class is obtained in the knee area by utilizing standard polynomial regression, even if the polynomial is of the 4<sup>th</sup> order. The authors concluded that the standard approach, described in this section, is not good enough and that an alternative approach should be sought.

### Proposed solution for improvement

The authors propose a novel regression model to reduce the errors in the knee area.

Given the very steep drop in the  $\varepsilon$  and  $\Delta\phi$  calibration curves as the current is reduced from 5% to 1%, we started exploring a significantly different approach. Equations (1) to (4) are now extended with the negative exponents of the calibration arguments, so we propose equations (5) and (6) for the 2<sup>nd</sup> order:

$$\varepsilon = \sum_{i=-2}^2 e_i \cdot I^i \quad (5)$$

$$\Delta\phi = \sum_{i=-2}^2 f_i \cdot I^i \quad (6)$$

And equations (7) and (8) for the 3<sup>rd</sup> order new regression model of the calibration curves:

$$\varepsilon = \sum_{i=-3}^3 g_i \cdot I^i \quad (7)$$

$$\Delta\phi = \sum_{i=-3}^3 h_i \cdot I^i \quad (8)$$

The algorithm for obtaining the corresponding coefficients in (5) to (8) is exactly the same as in the standard polynomial regression method in equations (1) to (4), i.e. the least-squares error method is used.

The mathematical analysis and the scope of this method go beyond the frame of this paper and are the subject of detailed analytical and experimental research. This paper, as will be seen below, is a confirmation of its usability and efficiency.

The authors propose the name of their new method: the Integer Power Symmetrical Regression Method (IPSRM).

Note that in equations (5) and (6) the exponents range from -2 to +2, whereas in (7) and (8) the exponents are from -3 to +3. Hence the phrase: symmetrical.

### Application of ipsrm to the ct calibration curves

Table 4 shows the coefficients obtained for the analyzed CT, to be used in equations (5) to (8).

Table 4. 2<sup>nd</sup> and 3<sup>rd</sup> order IPSRM coefficients

$i$	$e_i$	$f_i$	$g_i$	$h_i$
-3	-	-	-0.59490	28.4358
-2	0.37358	-14.62106	1.16156	-52.4123
-1	-0.72286	54.00454	-0.92683	63.9070
0	0.21339	7.342303	0.21872	7.05526
1	6.99564E-04	-0.036783	8.32337E-04	-0.04193
2	-2.14132E-06	9.62968E-05	-4.83912E-06	2.1258E-04
3	-	-	1.02329E-08	-4.50331E-07

Figures 9 and 10 show the result of applying 2<sup>nd</sup> order IPSRM whereas Figures 11 and 12 illustrate the corresponding residual error diagrams.

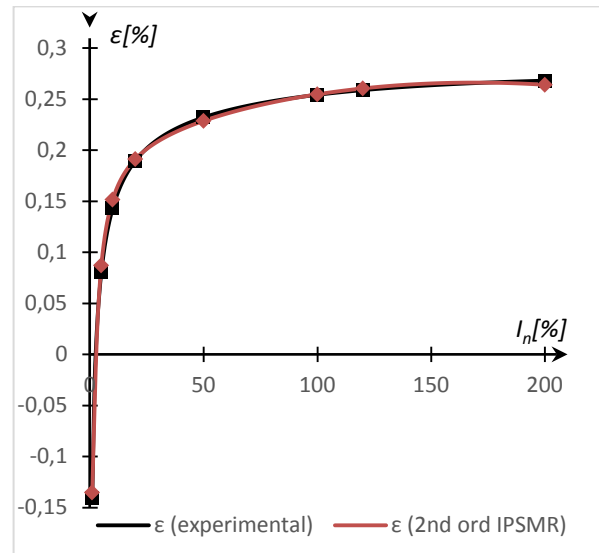


Fig. 9.  $\varepsilon$ : experimental and 2<sup>nd</sup> order IPSRM

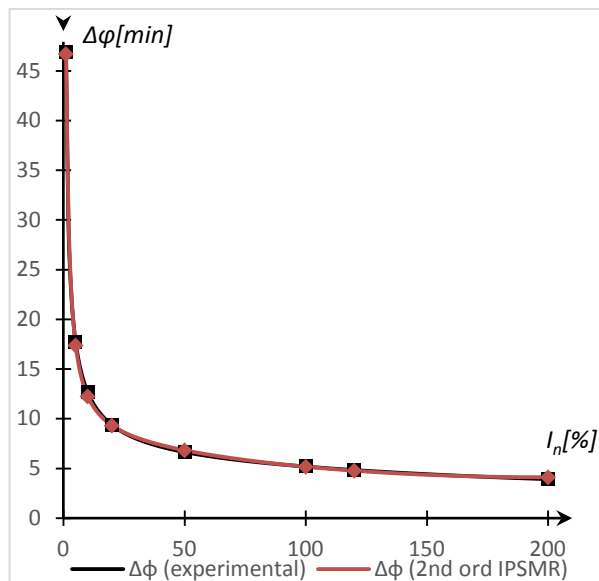
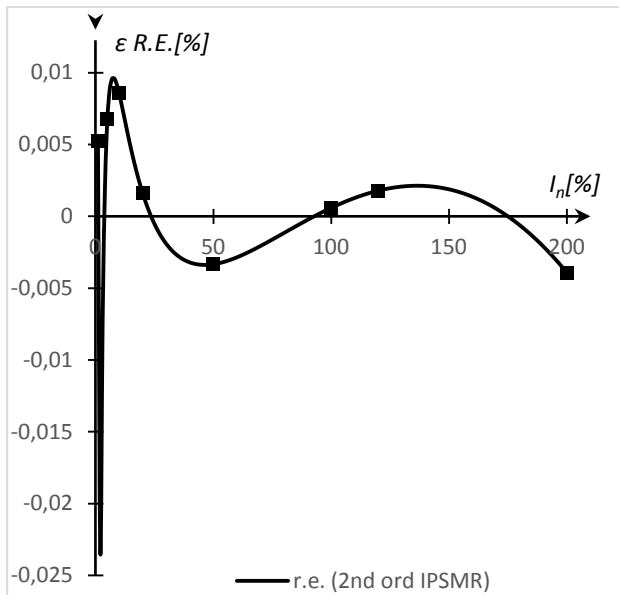
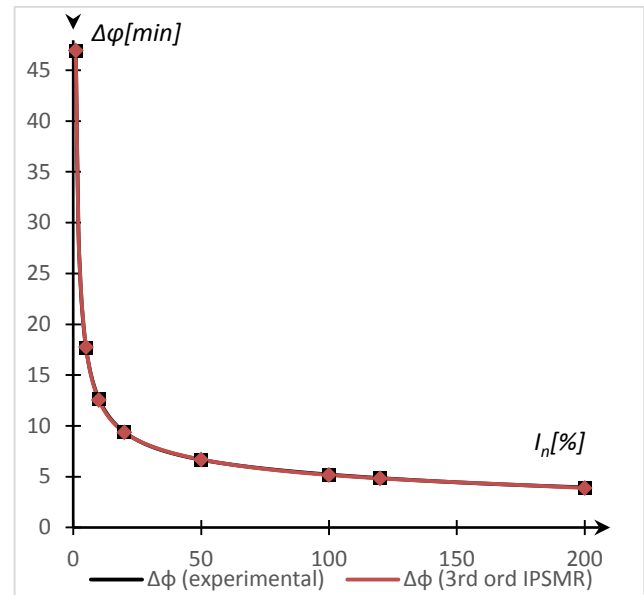
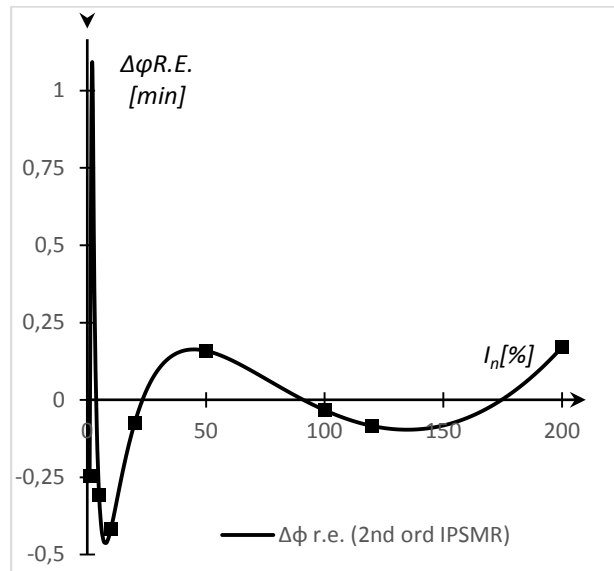
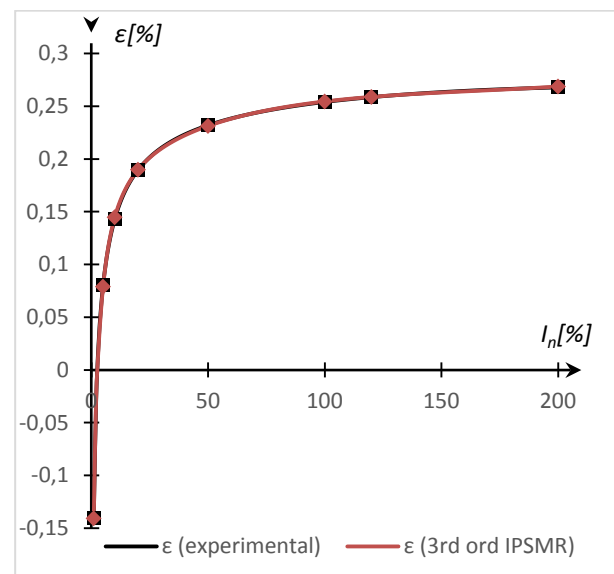
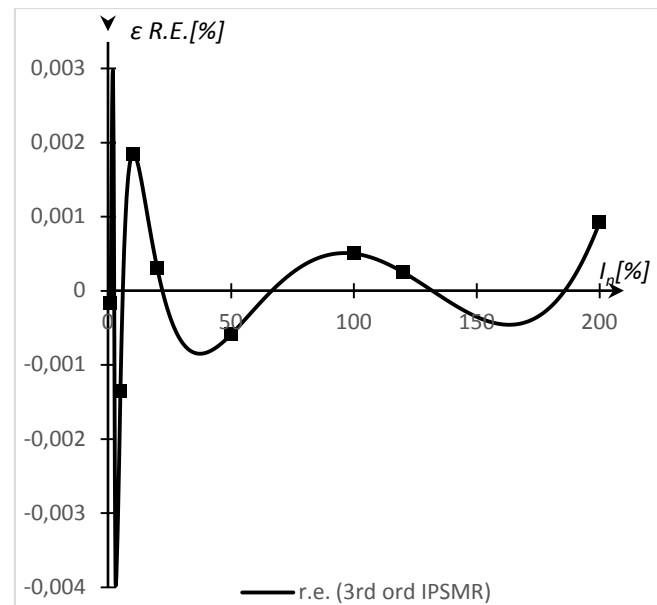


Fig. 10.  $\Delta\phi$ : experimental and 2<sup>nd</sup> order IPSRM


Fig. 11. Residual error of  $\varepsilon$  after 2<sup>nd</sup> order IPSRM

Fig. 14.  $\Delta\phi$ : experimental and 3<sup>rd</sup> order IPSRM

Fig. 12. Residual error of  $\Delta\phi$  after 2<sup>nd</sup> order IPSRM

Fig. 13.  $\varepsilon$ : experimental and 3<sup>rd</sup> order IPSRM

The corresponding diagrams of the residual error after applying the new 3<sup>rd</sup> order IPSRM are given in Figure 15 and Figure 16.

Application of the 2<sup>nd</sup> order IPSRM yields a significant reduction in the residual errors, especially in the knee area – almost by an order of magnitude smaller than those obtained by standard regression methods. This fact encouraged the authors to perform the 3<sup>rd</sup> order IPSRM on the same set of calibration points. The corresponding diagrams of Figure 13 and Figure 14 show an almost perfect match between the calibration curves and the regression curves.


Fig. 15. Residual error of  $\varepsilon$  after 3<sup>rd</sup> order IPSRM

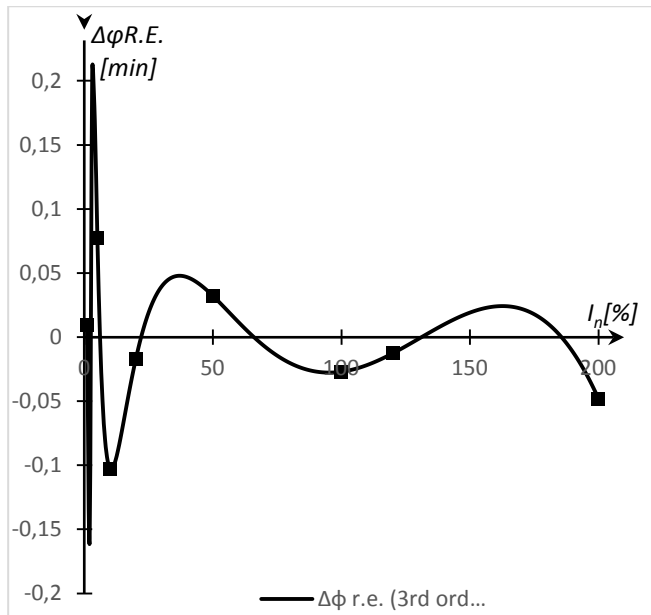


Fig. 16. Residual error of  $\Delta\phi$  after 3<sup>rd</sup> order IPSRM

### IPSRM results

Comparison of the y-axes values of Figures 11 and 15 indicates that the residual error after implementing the 3<sup>rd</sup> order IPSRM is further reduced by another order of magnitude with respect to the 2<sup>nd</sup> order IPSRM. Overall, the 3<sup>rd</sup> order IPSRM reduced the maximum error of the measured current ratio error ( $\varepsilon$ [%]) by up to  $0.268\%/0.004\% = 67$  times and the maximum phase displacement error ( $\Delta\phi$ ) by up to  $46.93/0.2 = 235$  times. Therefore the authors believe that the primary goal of improving the accuracy was satisfactorily met.

An efficient and economical physical real-time realization of CT error correctors should now follow. This is a complex optimization and engineering problem, which will need to be solved separately for each particular CT, and is beyond the scope of this paper.

### DISCUSSION

Considering the maximum residual error as the key criterion, it can be seen that the 2<sup>nd</sup> and 3<sup>rd</sup> order IPSRM gives significantly better results than the 2<sup>nd</sup> and 4<sup>th</sup> order classical polynomial regression method. This is validated on the given set of 8 calibration points in the range of 1% to 200% of rated current, which give curves typical for a standard-construction of CTs. Figures 3, 4, 7, 8, 11, 12, 15 and 16 clearly show the error reductions, especially in the critical low-current (knee) area. The current ratio error  $\varepsilon$  is about four times (235/67 times) harder to correct than the phase error  $\Delta\phi$ .

The IPSRM fits the calibration curves independently of the ordinate values of the calibration curves. This means that IPSRM is an applicable method to CT of any arbitrary class.

### CONCLUSION

The paper experimentally investigated the problem of optimal fitting of CT calibration curves. Simple and accurate analytical expressions for the CT calibration curves, for amplitude and for phase, will enable efficient real-time electronic correction of CT errors in digital instruments.

This study also showed that the proposed IPSRM gives significantly better results than the standard polynomial regression method in the case of calibration curves for given CTs.

The research showed that the amplitude error correction is about four times lower than the phase shift error correction, especially in the CT's knee area, so further calibration research will be concentrated on that critical aspect.

The authors are confident, that in further research based on this paper, they can show that this method is applicable to any CT, even those at the highest voltage, current and power levels. In order for the principle to be applied in those cases, calibration equipment for the highest voltage levels must be available.

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