

Article

Power Measurement Errors Using Current and Voltage Transformers in the Extended WB2 Optional Accuracy Class

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Abstract

Modern power systems increasingly operate under distorted waveform conditions caused by distributed generation, renewable energy sources, and power-electronic loads. In medium- and high-voltage networks, power measurement accuracy depends on voltage and current transformers, whose ratio and phase displacement errors vary with frequency. This paper investigates how these errors propagate into indirect measurements of active, reactive, and apparent power. The analysis considers the conventional 0.2 accuracy class at 50 Hz and the extended 0.2 WB2 optional accuracy class for individual higher harmonic components up to the 400th order. Analytical expressions are derived for power measurement errors, and the results are presented as deterministic error envelopes. In addition, 16 global sign scenarios are evaluated to determine how different combinations of transformer error signs affect total power measurement. The results show that apparent power errors are mainly determined by ratio errors, whereas active and reactive power errors are additionally influenced by differential phase displacement errors. For higher harmonics, the WB2 frequency band limits produce step changes in the error envelopes, and relative errors may become large when the reference active or reactive power of a harmonic component is small. The proposed method extends conventional power error propagation analysis by linking harmonic power components with the frequency band limits of the IEC 61869 WB2 optional accuracy class and by introducing deterministic error envelopes and global sign scenarios for worst-case-oriented assessment under nonsinusoidal operating conditions.

Keywords: instrument transformers; voltage transformers; current transformers; power measurement error; harmonic power; power quality; wideband accuracy class; WB2; IEC 61869; deterministic error envelope

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1. Introduction

Modern electrical power distribution networks have undergone a profound transformation due to the large-scale integration of distributed generation (DG), renewable energy sources (RESs) such as solar photovoltaic (PV) and wind systems, and the widespread adoption of nonlinear power electronic loads [1–4]. While these technologies improve overall energy efficiency and support global decarbonization efforts, their inherently nonlinear characteristics and high-frequency switching operations may deteriorate the power quality (PQ) of the grid [2,3,5]. The increasing use of power electronic interfaces has shifted the paradigm of waveform distortions from classical low-order harmonics (up

to 2 kHz) to a broader spectrum, introducing the phenomena of supraharmonics in the frequency range of 2–150 kHz [4,6–8]. These high-frequency components cause numerous adverse effects, including increased thermal stress, premature aging of dielectric materials, spurious tripping of protection devices, and severe interference with power line communications (PLC) [4–6]. Consequently, accurate monitoring of PQ and precise quantification of harmonic power flows have become crucial for grid stability, efficient operation, and equitable responsibility assignment among network participants [9,10].

Harmonic and supraharmonic disturbances can be introduced into distribution networks through several mechanisms associated with distributed generation and modern power electronic equipment [1–4,6–8,11]. Grid-connected photovoltaic inverters, wind turbine converters, battery energy storage systems, electric vehicle chargers, and variable-speed drives may generate nonsinusoidal current components due to semiconductor switching, pulse-width modulation, control interactions, and the operation of input and output filters [1–4,11]. In addition, nonlinear loads, such as switched-mode power supplies, rectifiers, LED lighting systems, and industrial converter-fed equipment, draw distorted currents from the network and may inject low-order harmonics into the point of common coupling [4,6,11,12]. The interaction between converter control systems, grid impedance, filter resonances, and cable or transformer parasitic parameters may further amplify selected harmonic or supraharmonic components [4,6–8]. Therefore, harmonic distortion in renewable-rich distribution networks is not produced by a single source, but results from the combined effect of converter-based generation, nonlinear consumption, network resonance conditions, and the frequency-dependent behavior of the grid impedance.

Recent studies on renewable-rich distribution networks confirm that the increasing penetration of renewable energy sources changes not only the operating conditions of distribution systems, but also the requirements for planning, monitoring, and control. A recent study proposed a joint planning framework for transportable and flexible resources in distribution systems, showing that renewable integration increases operational uncertainty and requires additional flexibility- and resilience-oriented solutions [13]. In particular, mobile energy storage systems and soft open points were used to improve renewable energy utilization, reduce load curtailment, and enhance post-event restoration capability. These results indicate that modern distribution systems increasingly depend on advanced planning and operational strategies supported by reliable measurement data. In parallel, power quality monitoring and harmonic assessment are becoming increasingly important in distribution grids with inverter-based distributed generation. Another recent study proposed a physics-aware neural network approach for harmonic state estimation in distribution grids, using synchronized measurements and network-aware modeling to estimate harmonic quantities at unmeasured locations [14]. This confirms that power quality state estimation can support harmonic monitoring in distribution systems with limited measurement infrastructure. However, the accuracy of such monitoring and estimation methods depends on the reliability of the measurement chain. In medium- and high-voltage networks, voltage and current transformers remain essential elements of this chain. Therefore, the propagation of their wideband ratio and phase displacement errors into active, reactive, and apparent-power measurements represents an important complementary problem to system-level power quality monitoring and harmonic state estimation.

The presence of harmonic and supraharmonic components significantly complicates the measurement of electrical power and energy. Traditional power theories and revenue metering systems were primarily designed for ideal, sinusoidal conditions at fundamental frequencies [12]. Under nonsinusoidal regimes, the measurement of complex power—encompassing active, reactive, and apparent power—must account for the contribution of individual voltage–current harmonic pairs and for the definition of reactive and apparent

power adopted under nonsinusoidal conditions [1,15,16]. Ignoring these harmonic power terms can lead to substantial errors in total energy estimation, directly impacting the financial accuracy of electricity billing and increasing grid losses [12,17,18]. Experimental studies have demonstrated that voltage and current distortions affect the performance of revenue meters, often leading to unpredictable variations in the registered electrical quantities depending on the harmonic profile of the loads [18]. In industrial facilities and electrified railways, failing to accurately measure non-fundamental apparent power and harmonic active power not only obscures the true energy consumption but also prevents the correct identification of the disturbing loads responsible for injecting harmonic pollution into the point of common coupling (PCC) [1,12].

At medium voltage (MV) and high voltage (HV) levels, PQ monitoring and energy metering rely entirely on instrument transformers (ITs)—namely, voltage transformers (VTs) and current transformers (CTs)—to scale down primary grid signals to levels suitable for measurement devices [5,11,19]. While conventional inductive ITs offer galvanic isolation, high reliability, and excellent accuracy at the fundamental frequency, their metrological performance degrades dramatically when subjected to distorted, harmonic-rich waveforms [5,19,20]. The transformation accuracy of inductive CTs and VTs is compromised by the nonlinear behavior of their ferromagnetic cores, such as hysteresis and saturation effects, as well as by internal parasitic parameters like stray capacitances and leakage inductances [5,20–22]. Extensive experimental evaluations have shown that these nonlinearities not only attenuate the magnitudes of higher-order harmonics but also introduce spurious intermodulation components and significant phase displacement errors between the primary and secondary waveforms [5,22]. Consequently, ITs may represent a significant source of uncertainty in the PQ measurement chain, transferring a highly distorted replica of the original signal to the secondary side and introducing complex uncertainties into the measurements [19,20]. To address the urgent need for reliable measurements in harmonically polluted networks, international standardization bodies have recently updated their regulations. Recognizing that traditional accuracy classes, defined strictly for power frequencies (50/60 Hz), are inadequate for modern PQ assessments, the International Electrotechnical Commission (IEC) introduced the revised IEC 61869-1:2023 standard [23]. This standard establishes a unified framework by defining optional wideband (WB) accuracy classes for ITs, ranging from WB0 to WB4, which specify permissible limits for ratio and phase displacement errors over extended frequency ranges up to 500 kHz [23,24]. Specifically, the WB2 optional accuracy class covers frequency bands up to 20 kHz, which corresponds approximately to the 400th harmonic order in a 50 Hz system. The establishment of these wideband classes paves the way for standardizing PQ measurements and certifying reference high-voltage sensing chains capable of accurately resolving high-frequency disturbances [24]. Despite the introduction of these wideband accuracy limits for individual voltage and current measurements, a critical research gap remains regarding the propagation of these frequency-dependent IT errors into the indirect calculation of complex power quantities. In practical power assessments under distorted conditions, the final error in active, reactive, and apparent power is not simply a direct reflection of individual magnitude deviations. It is profoundly influenced by the differential phase displacement between the voltage and current measurement channels. For example, the relative active power error becomes exceptionally sensitive to phase displacement errors at low harmonic displacement power factors. Conversely, the relative reactive power error escalates dramatically when the reference harmonic reactive power approaches zero. Therefore, assessing the worst-case scenario of power measurement accuracy requires a comprehensive analysis of how the maximal permissible ratio and phase errors of the WB classes dynamically interact under various load conditions.

To bridge this gap, this paper aims to quantify the maximum possible errors in active, reactive, and apparent power measurements when utilizing VTs and CTs compliant with the extended WB2 optional accuracy class. By performing a deterministic global sign scenario analysis, this study systematically evaluates the worst-case power measurement errors resulting from the maximum permissible ratio and phase displacement limits specified by the WB2 standard for higher harmonic components up to the 400th order. The findings highlight the complex interactions between amplitude and angular inaccuracies, providing essential insights for the reliable deployment of instrument transformers and the precise assessment of harmonic power flows in modern, distortion-rich power grids. The methodological novelty of this work is not limited to applying the WB2 limits to standard power-error formulas. Existing studies usually analyze either the frequency response of voltage and current transformers or the influence of harmonics on power and energy measurements as separate problems. In contrast, this paper combines the frequency band accuracy limits of the IEC 61869 WB2 optional class with an analytical power-error propagation model for individual harmonic components and for a distorted multi-harmonic waveform.

The main contributions of this paper are as follows:

- Analytical expressions are formulated for the relative errors of harmonic apparent, active, and reactive powers, explicitly separating the influence of ratio errors and differential phase displacement errors of voltage and current transformers;
- The frequency bands of the 0.2 WB2 optional accuracy class are converted into harmonic order ranges for a 50 Hz power system, enabling the assessment of power measurement errors up to the 400th harmonic order;
- Deterministic lower and upper error envelopes are determined for individual harmonic power components, which makes it possible to identify the limiting influence of WB2 ratio and phase displacement errors;
- A global sign scenario approach is introduced to evaluate how systematic positive or negative signs of voltage and current transformer errors affect the total active, reactive, and apparent power of a distorted waveform;
- The analysis distinguishes between the error behavior of dominant low-order harmonics and higher-frequency harmonic components, showing that large relative errors may occur when the corresponding reference harmonic active or reactive power is small.

This approach provides a deterministic worst-case-oriented framework for evaluating power measurement uncertainty introduced by instrument transformers under non-sinusoidal operating conditions.

2. Calculation Method

The purpose of this section is to define the accuracy limits and calculation assumptions used to determine the maximum possible errors of active, reactive, and apparent power measurements. The analysis considers indirect power measurement performed using voltage and current transformers. In this case, the measured power is affected by both ratio errors and phase displacement errors introduced by the instrument transformers. Two operating cases were considered. The first case concerns sinusoidal voltage and current at the fundamental frequency of 50 Hz. This case was used as a reference for the conventional accuracy class 0.2 of current and voltage transformers. The second case concerns individual higher harmonic components transformed by instrument transformers assigned to the extended WB2 optional accuracy class. This case was used to evaluate how the permissible errors defined for higher-frequency components may affect the measurement of harmonic active, reactive, and apparent powers. The accuracy limits for current

transformers during sinusoidal current transformation are given in Table 1. These limits depend on the percentage of the rated primary current. Therefore, in the 50 Hz case, the permissible current transformer ratio and phase displacement errors vary with the primary current level. The voltage transformer limits for sinusoidal voltage transformation are given in Table 2. In this case, the ratio and phase displacement errors are assigned directly to the considered voltage transformer accuracy class.

Table 1. Limits of accuracy classes for CTs during transformation sinusoidal current in accordance with the standard IEC 61869-2 [25].

Accuracy Class	5% of Rated Current		20% of Rated Current		100% of Rated Current		120% of Rated Current	
	Ratio Error [%]	Phase Error [°]	Ratio Error [%]	Phase Error [°]	Ratio Error [%]	Phase Error [°]	Ratio Error [%]	Phase Error [°]
0.1	±0.4	±0.25	±0.2	±0.13	±0.1	±0.083	±0.1	±0.083
0.2	±0.75	±0.5	±0.35	±0.25	±0.2	±0.167	±0.2	±0.167
0.5	±1.5	±1.5	±0.75	±0.75	±0.5	±0.5	±0.5	±0.5
1	±3	±3	±1.5	±1.5	±1	±1	±1	±1

Table 2. Limits of accuracy classes for VTs during transformation sinusoidal voltage in accordance with the standard IEC 61869-3 [26].

Accuracy Class	Voltage Transformer Error	
	Ratio Error [%]	Phase Error [°]
0.1	±0.1	±0.083
0.2	±0.2	±0.167
0.5	±0.5	±0.33
1	±1	±0.667

Tables 3 and 4 summarize the optional accuracy limits for instrument transformers used for distorted signals and higher-frequency components. The WB0 class is defined for selected harmonic ranges, whereas the WB1–WB4 classes are defined using frequency bands. In this study, particular attention was paid to the WB2 optional accuracy class.

Thus, the WB2 frequency bands can be directly converted into harmonic-order ranges. Frequencies up to 5 kHz correspond to harmonic orders up to $h = 100$, frequencies from 5 kHz to 10 kHz correspond approximately to harmonic orders from $h = 101$ to $h = 200$, and frequencies from 10 kHz to 20 kHz correspond approximately to harmonic orders from $h = 201$ to $h = 400$.

Table 3. Limits of accuracy classes for ITs during transformation harmonics of distorted current/voltage in accordance with the WB0 optional accuracy class defined in the standard IEC 61869-1 [23].

WB0	Accuracy class	Freq. harm. from 2nd to 4th		Freq. harm. from 5th to 6th		Freq. harm. from 7th to 8th		Freq. harm. from 9th to 13th	
		Ratio	Phase	Ratio	Phase	Ratio	Phase	Ratio	Phase
		error [%]	error [°]	error [%]	error [°]	error [%]	error [°]	error [%]	error [°]
	0.1	±1	±1	±2	±2	±4	±4	±8	±8
	0.2–0.2 S	±2	±2	±4	±4	±8	±8	±16	±16
	0.5–0.5 S	±5	±5	±10	±10	±20	±20	±20	±20
	1	±10	±10	±20	±20	±20	±20	±20	±20

Table 4. Limits of accuracy classes for ITs during transformation harmonics distorted signals or higher frequency signals in accordance with the WB1–WB4 optional accuracy class in accordance with the standard IEC 61869-1 [23].

	Accuracy class	Freq. to 1 kHz		Freq. from 1 kHz to 1.5 kHz		Freq. from 1.5 kHz to 3 kHz	
		Ratio	Phase	Ratio	Phase	Ratio	Phase
		error [%]	error [°]	error [%]	error [°]	error [%]	error [°]
WB1	0.1	±1	±1	±2	±2	±5	±5
	0.2–0.2 S	±2	±2	±4	±4	±5	±5
	0.5–0.5 S	±5	±5	±10	±10	±10	±20
	1	±10	±20	±20	±10	±20	±20
	Accuracy class	Freq. to 5 kHz		Freq. from 5 kHz to 10 kHz		Freq. from 10 kHz to 20 kHz	
		Ratio	Phase	Ratio	Phase	Ratio	Phase
		error [%]	error [°]	error [%]	error [°]	error [%]	error [°]
WB2	0.1	±1	±1	±2	±2	±5	±5
	0.2–0.2 S	±2	±2	±4	±4	±5	±5
	0.5–0.5 S	±5	±5	±10	±10	±10	±20
	1	±10	±20	±20	±10	±20	±20
	Accuracy class	Freq. to 20 kHz		Freq. from 20 kHz to 50 kHz		Freq. from 50 kHz to 150 kHz	
		Ratio	Phase	Ratio	Phase	Ratio	Phase
		error [%]	error [°]	error [%]	error [°]	error [%]	error [°]
WB3	0.1	±1	±1	±2	±2	±5	±5
	0.2–0.2 S	±2	±2	±4	±4	±5	±5
	0.5–0.5 S	±5	±5	±10	±10	±10	±20
	1	±10	±20	±20	±10	±20	±20
	Accuracy class	Freq. to 50 kHz		Freq. from 50 kHz to 150 kHz		Freq. from 150 kHz to 500 kHz	
		Ratio	Phase	Ratio	Phase	Ratio	Phase
		error [%]	error [°]	error [%]	error [°]	error [%]	error [°]
WB4	0.1	±1	±1	±2	±2	±5	±5
	0.2–0.2 S	±2	±2	±4	±4	±5	±5
	0.5–0.5 S	±5	±5	±10	±10	±10	±20
	1	±10	±20	±20	±10	±20	±20

Under nonsinusoidal periodic conditions, the definitions of active, reactive, and apparent power must be specified explicitly. In this study, the power quantities are evaluated in the frequency domain using the RMS values and phase displacement angles of individual voltage–current harmonic pairs. The adopted calculation approach is consistent with the general framework of IEEE Std. 1459-2025 [27], which defines electric power quantities under sinusoidal and nonsinusoidal conditions. For the h th harmonic component, the apparent, active, and quadrature reactive power components are defined as follows:

$$\begin{aligned}
 S_h &= U_h I_h \\
 P_h &= U_h I_h \cos \varphi_h \\
 Q_h &= U_h I_h \sin \varphi_h
 \end{aligned}
 \tag{1}$$

where

U_h and I_h are the RMS values of the h th voltage and current harmonic components, respectively, and φ_h is the phase displacement angle between these components.

For a nonsinusoidal waveform containing several harmonic components, the total active power is calculated as the sum of the active power components of individual voltage–current harmonic pairs:

$$P = \sum_h U_h I_h \cos \varphi_h \quad (2)$$

In this paper, the reactive power-related quantity reported for the distorted waveform is calculated as the algebraic sum of the quadrature harmonic components:

$$Q = \sum_h U_h I_h \sin \varphi_h \quad (3)$$

This quantity is used as a scalar measure of the quadrature contribution of the voltage–current harmonic pairs. It should be interpreted as a Budeanu-type or harmonic quadrature reactive power quantity and should not be confused with the nonactive power defined in IEEE Std. 1459-2025 [27].

The total apparent power of the nonsinusoidal waveform is calculated from the RMS values of the complete voltage and current waveforms:

$$S = U_{rms} I_{rms}$$

where

$$\begin{aligned} U_{rms} &= \sqrt{\sum_h U_h^2} \\ I_{rms} &= \sqrt{\sum_h I_h^2} \end{aligned} \quad (4)$$

It should be emphasized that, under nonsinusoidal conditions, the total apparent power is not calculated as the arithmetic sum of the individual harmonic apparent powers S_h . The quantities S_h , P_h , and Q_h are used to analyze individual harmonic contributions, whereas the total apparent power is obtained from the RMS values of the complete distorted voltage and current waveforms.

The calculations were performed separately for each individual voltage–current harmonic pair. Therefore, the obtained results describe the error of the power component associated with one harmonic order h th, not the total power of a nonsinusoidal waveform containing several harmonic components simultaneously. This distinction is important because the permissible ratio and phase displacement errors depend on the frequency range of the considered harmonic. The transformer ratio errors were treated as independent bounded variables. For the h th harmonic, the relative ratio errors of the voltage and current transformers are denoted by ε_{Uh} and ε_{Ih} , respectively. The corresponding maximum permissible magnitudes are denoted by $\varepsilon_{Uh,max}$ and $\varepsilon_{Ih,max}$. The combined influence of the voltage and current ratio errors is described by the multiplicative factor k_h . This factor accounts for the simultaneous modification of the measured voltage and current RMS values. Since the two ratio errors are assumed to vary independently within their permissible limits, the minimum and maximum values of k_h are obtained by combining the corresponding negative and positive extreme values of the voltage and current ratio errors. In addition to ratio errors, voltage and current transformers introduce phase displacement errors. These errors are denoted by δ_{Uh} and δ_{Ih} respectively. All angular quantities used in the calculations are expressed in radians. The differential phase displacement error affecting the indirect power measurement is equal to the difference be-

tween the voltage transformer and current transformer phase displacement errors. As a result, the measured phase displacement between the voltage and current harmonic components may be either smaller or larger than the reference phase displacement. For each harmonic order, the reference apparent, active, and reactive powers are denoted by S_{0h} , P_{0h} , and Q_{0h} , respectively. The measured powers after transformation are denoted by S_{mh} , P_{mh} , and Q_{mh} . The apparent power is affected only by the ratio errors, whereas the active and reactive powers are affected by both ratio errors and the differential phase displacement error. The analysis was performed using deterministic error envelopes. This means that all permissible combinations of ratio and phase displacement errors within the considered accuracy limits were taken into account. The resulting lower and upper envelopes represent the limiting values of the possible power measurement error. They should not be interpreted as statistical confidence intervals or probability distributions. The relative errors of apparent, active, and reactive power were calculated with respect to the corresponding reference power components. For the apparent power, the exact relative error depends directly on the combined ratio error factor k_h . For the active and reactive powers, the exact errors also depend on the phase displacement angle of the considered harmonic. First-order approximations were additionally used to interpret the influence of the individual error components. These approximations show that the phase-related component of the active power error is proportional to $\tan(\varphi_h)$, whereas the phase-related component of the reactive power error is proportional to $\cot(\varphi_h)$. Consequently, the active power measurement error becomes more sensitive to phase displacement errors when the displacement power factor of the considered harmonic decreases. In contrast, the relative reactive power error becomes more sensitive when the reference reactive power approaches zero, i.e., when φ_h approaches zero and $\cos(\varphi_h)$ approaches unity. In such cases, the relative error may become very large even if the absolute error expressed in var remains limited.

To determine the limiting power measurement errors, the relative ratio errors of the voltage transformer and current transformer were treated as independent bounded variables:

$$\begin{aligned}\varepsilon_{Uh} &\in [-\varepsilon_{Uh,\max}, +\varepsilon_{Uh,\max}] \\ \varepsilon_{Ih} &\in [-\varepsilon_{Ih,\max}, +\varepsilon_{Ih,\max}]\end{aligned}\quad (5)$$

where

$\varepsilon_U/\varepsilon_I$ —the relative ratio errors of the voltage and current transformers, respectively, for the h th harmonic.

$\varepsilon_{U,\max}/\varepsilon_{I,\max}$ —the corresponding maximum permissible error magnitudes defined by the considered accuracy class. The ratio errors are expressed as dimensionless quantities.

The combined multiplicative factor describing the influence of both ratio errors on the apparent power associated with the h th harmonic is given by

$$k_h = (1 + \varepsilon_{Uh})(1 + \varepsilon_{Ih}) \quad (6)$$

The factor (k_h) accounts for the simultaneous modification of the measured voltage and current RMS values. Because the two ratio errors are assumed to vary independently within the intervals defined in Equation (5), the minimum and maximum possible values of (k_h) are

$$\begin{aligned}k_{h,\min} &= (1 - \varepsilon_{Uh,\max})(1 - \varepsilon_{Ih,\max}) \\ k_{h,\max} &= (1 + \varepsilon_{Uh,\max})(1 + \varepsilon_{Ih,\max})\end{aligned}\quad (7)$$

In addition to ratio errors, the voltage and current transformers introduce phase displacement errors. For the h th harmonic, these errors are represented by the following intervals:

$$\begin{aligned}\delta_{Uh} &\in [-\delta_{Uh,max}, +\delta_{Uh,max}] \\ \delta_{Ih} &\in [-\delta_{Ih,max}, +\delta_{Ih,max}]\end{aligned}\quad (8)$$

where

δ_{Uh}, δ_{Ih} — the phase displacement errors introduced by the voltage and current transformers, respectively. All phase displacement values used in the calculations are expressed in radians.

The phase displacement between the voltage and current components of the h th harmonic after transformation by the voltage and current transformers is defined as follows:

$$\varphi_{mh} = \varphi_h + \delta_{Uh} - \delta_{Ih} \quad (9)$$

Because the phase displacement errors of the two transformers may vary independently within their permissible intervals, the measured phase displacement is bounded by

$$\varphi_{mh} \in [\varphi_h - \delta_{Uh,max} - \delta_{Ih,max}, \varphi_h + \delta_{Uh,max} + \delta_{Ih,max}] \quad (10)$$

For the h th harmonic, after accounting for the ratio and phase displacement errors of both instrument transformers, the measured harmonic of each apparent, active, and reactive power is given by

$$\begin{aligned}S_{mh} &= S_{0h} k_h \\ P_{mh} &= S_{0h} k_h \cos(\varphi_h + \delta_{Uh} - \delta_{Ih}) \\ Q_{mh} &= S_{0h} k_h \sin(\varphi_h + \delta_{Uh} - \delta_{Ih})\end{aligned}\quad (11)$$

Equation (11) shows that the measured apparent power depends only on the ratio errors, whereas the measured active and reactive powers are affected by both the ratio errors and the differential phase displacement error.

For the distorted multi-harmonic waveform, the total measured active power, the total measured quadrature reactive power quantity, and the total measured apparent power are calculated as follows:

$$\begin{aligned}P_m &= \sum_h U_{mh} I_{mh} \cos(\varphi_{mh}) \\ Q_m &= \sum_h U_{mh} I_{mh} \sin(\varphi_{mh}) \\ S_m &= U_{mrms} I_{mrms} = \sqrt{\sum_h U_{mh}^2} \sqrt{\sum_h I_{mh}^2}\end{aligned}\quad (12)$$

where

$$\begin{aligned}U_{mh} &= U_h (1 + \varepsilon_{Uh}) \\ I_{mh} &= I_h (1 + \varepsilon_{Ih}) \\ \varphi_{mh} &= \varphi_h + \delta_{Uh} - \delta_{Ih}\end{aligned}\quad (13)$$

The total relative errors are then calculated with respect to the corresponding reference quantities P , Q , and S . This formulation ensures that the total apparent power of the distorted waveform is calculated from the RMS values of the complete measured voltage and current waveforms, not by summing the individual harmonic apparent powers.

The exact relative error of the apparent power associated with the h th harmonic is as follows:

$$\frac{\Delta S_h}{S_{0h}} = \frac{S_{mh} - S_{0h}}{S_{0h}} = k_h - 1$$

By expanding Equation (6), the multiplicative factor can be written as

$$k_h = 1 + \varepsilon_{Uh} + \varepsilon_{Ih} + \varepsilon_{Uh}\varepsilon_{Ih} \quad (14)$$

Consequently, the exact relative apparent power error is as follows:

$$\frac{\Delta S_h}{S_{0h}} = \varepsilon_{Uh} + \varepsilon_{Ih} + \varepsilon_{Uh}\varepsilon_{Ih}$$

The last term in Equation (14) represents the interaction between the voltage and current ratio errors. For sufficiently small ratio errors, the product $\varepsilon_{Uh}\varepsilon_{Ih}$ is substantially smaller than the first-order terms and may be neglected. The relative apparent power error can therefore be approximated as follows:

$$\frac{\Delta S_h}{S_{0h}} \approx \varepsilon_{Uh} + \varepsilon_{Ih} \quad (15)$$

The exact relative error of the active power associated with the h th harmonic is defined as follows:

$$\frac{\Delta P_h}{P_{0h}} = k_h \frac{\cos(\varphi_{mh})}{\cos(\varphi_h)} - 1$$

Using the expression for the measured phase displacement angle and the trigonometric identity:

$$\cos(\varphi_{mh}) = \cos(\varphi_h) \cos(\delta_{Uh} - \delta_{Ih}) - \sin(\varphi_h) \sin(\delta_{Uh} - \delta_{Ih}) \quad (16)$$

The exact relative active power error can be expressed as follows:

$$\frac{\Delta P_h}{P_{0h}} = k_h [\cos(\delta_{Uh} - \delta_{Ih}) - \tan(\varphi_h) \sin(\delta_{Uh} - \delta_{Ih})] - 1$$

For sufficiently small phase displacement errors expressed in radians, the following approximations may be applied:

$$\begin{aligned} \sin(\delta_{Uh} - \delta_{Ih}) &\approx \delta_{Uh} - \delta_{Ih} \\ \cos(\delta_{Uh} - \delta_{Ih}) &\approx 1 \end{aligned} \quad (17)$$

After substituting Equation (6) into Equation (16) and neglecting products of small ratios and phase displacement errors, the relative active power error is approximated by

$$\frac{\Delta P_h}{P_{0h}} \approx \varepsilon_{Uh} + \varepsilon_{Ih} - \tan(\varphi_h) (\delta_{Uh} - \delta_{Ih}) \quad (18)$$

Equation (18) separates the active power measurement error into an amplitude-related component and a phase-related component. The amplitude-related component is determined by the sum of the voltage and current ratio errors. The phase-related component is proportional to $\tan(\varphi_h)$ and to the differential phase displacement error. Therefore, the influence of instrument transformer phase displacement on the active power error increases as the displacement power factor $\cos(\varphi_h)$ decreases.

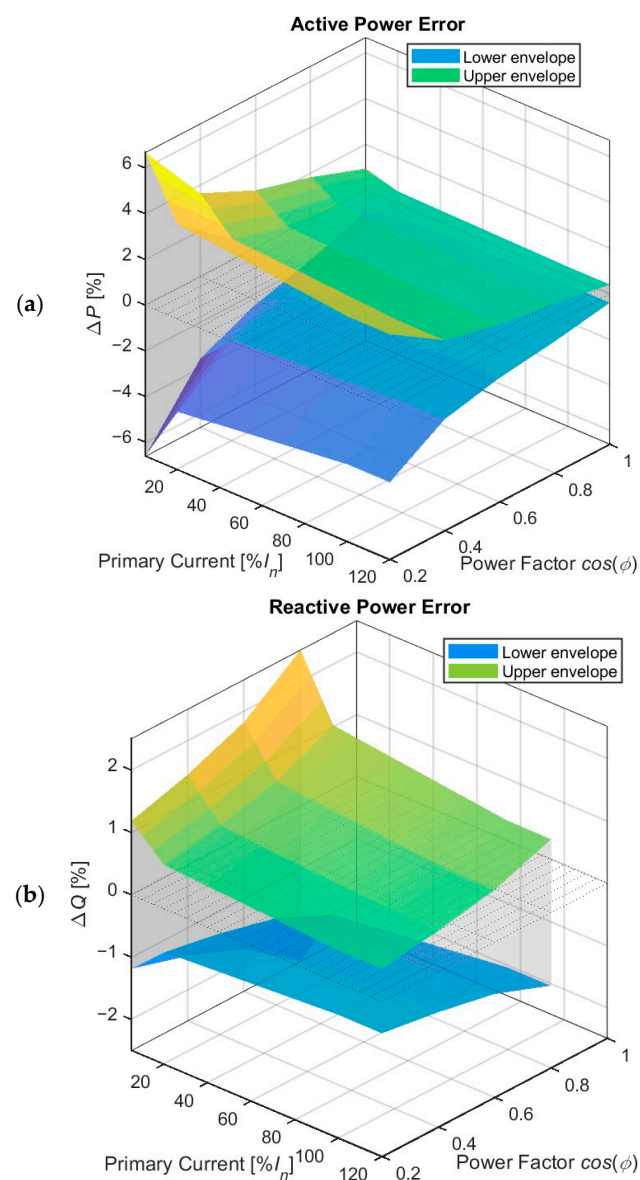
Following the same derivation as that used for the active power error, the relative error of the reactive power associated with the h th harmonic can be approximated as follows:

$$\frac{\Delta Q_h}{Q_{0h}} \approx \varepsilon_{Uh} + \varepsilon_{Ih} + \cot(\varphi_h) (\delta_{Uh} - \delta_{Ih}) \quad (19)$$

3. Calculation Results

The calculations were carried out in MATLAB R2024b, version 24.2.0.2863752, using the analytical model described in Section 2. The objective of the simulations was to determine the lower and upper envelopes of the relative power measurement error caused by

the maximum permissible ratio and phase displacement errors of the voltage and current transformers. The results are presented as deterministic error envelopes. Therefore, the plotted surfaces should not be interpreted as probability distributions, but as limiting error ranges resulting from the accuracy class under consideration. In the first stage, the calculations were performed for sinusoidal voltage and current at the fundamental frequency of 50 Hz. The voltage transformer and current transformer were assumed to meet accuracy class 0.2. The maximum permissible errors were selected according to the limits specified for sinusoidal voltage and current transformation. The primary current varied from low-current operating conditions up to 120% of the rated current, whereas the power factor ($\cos(\varphi_1)$) was varied over the considered operating range. The transformer secondary burden was assumed to remain within the range for which the declared accuracy class is valid. Figure 1 presents the calculated lower and upper envelopes of the relative errors of active, reactive, and apparent power for the 50 Hz component. The width of the envelopes depends mainly on the permissible ratio and phase displacement errors of the instrument transformers. At low values of primary current, the current transformer is allowed to have a larger ratio and phase displacement errors; therefore, the error envelopes are wider. As the primary current approaches the rated value, the permissible current transformer errors decrease, which leads to narrower power-error envelopes.



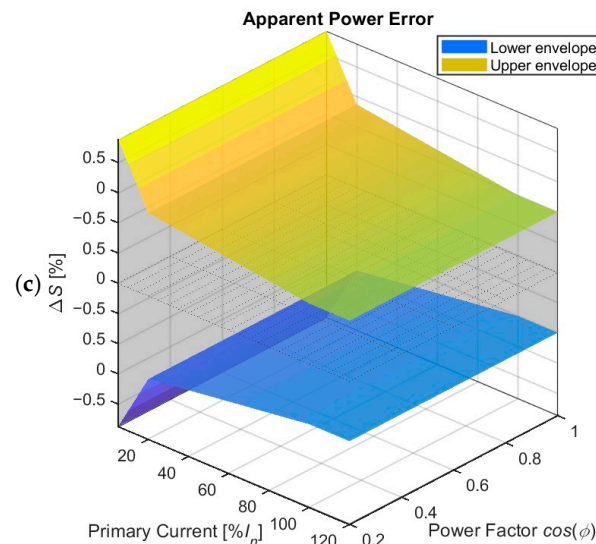


Figure 1. Relative power measurement error envelopes for sinusoidal voltage and current at 50 Hz for accuracy class 0.2: (a) active power error, (b) reactive power error, and (c) apparent power error.

In Figure 1, the surfaces represent the lower and upper deterministic error envelopes obtained from the maximum permissible ratio and phase displacement errors of the voltage and current transformers. For the apparent power, the relative error is determined only by the combined voltage and current ratio errors. As a result, the apparent power error surface is practically independent of the displacement power factor. Its variation with primary current is caused by the current-dependent accuracy limits of the current transformer. The largest apparent power error occurs at low primary current, where the permissible ratio error of the current transformer is the highest. The active power error is influenced by both the amplitude errors and the differential phase displacement error of the voltage and current transformers. The results show that the active power error becomes more sensitive to phase displacement errors as the displacement power factor decreases. This behavior is consistent with the analytical approximation in which the phase-related component of the active power error is proportional to $\tan(\varphi_1)$. Therefore, the widest active power error envelope is obtained for low power factor and low primary current. The reactive power error exhibits a different dependence on the displacement power factor. Its phase-related component is proportional to $\cot(\varphi_1)$, which means that the relative reactive power error increases when the phase angle approaches zero. Consequently, the relative error of reactive power becomes particularly high at high displacement power factor, where the reference reactive power is small. This effect does not necessarily imply a large absolute error in var; it mainly results from the normalization of the error by Q_1 , which approaches zero as $\cos(\varphi_1)$ approaches unity.

In the second stage, the analysis was extended to individual higher harmonic components transformed by voltage and current transformers assigned to the 0.2 WB2 optional accuracy class. Each harmonic was considered separately as one voltage–current harmonic pair of order h th. For a fundamental frequency of 50 Hz, the harmonic frequency was calculated as $f_h = h \cdot f_1$. Therefore, the WB2 frequency ranges correspond to harmonic orders up to $h = 100$, from $h = 101$ to $h = 200$, and from $h = 201$ to $h = 400$. The maximum permissible ratio and phase displacement errors were selected according to the WB2 limits for the corresponding frequency band. Figure 2 shows the calculated relative error envelopes for the individual harmonic components. The results clearly reflect the stepwise nature of the WB2 accuracy limits. Since the permissible ratio and phase displacement errors increase when the harmonic frequency enters the next WB2 band, the

error envelopes also exhibit step changes at the corresponding harmonic orders. These discontinuities are not numerical artifacts; they are a direct consequence of the frequency band structure of the WB2 optional accuracy class.

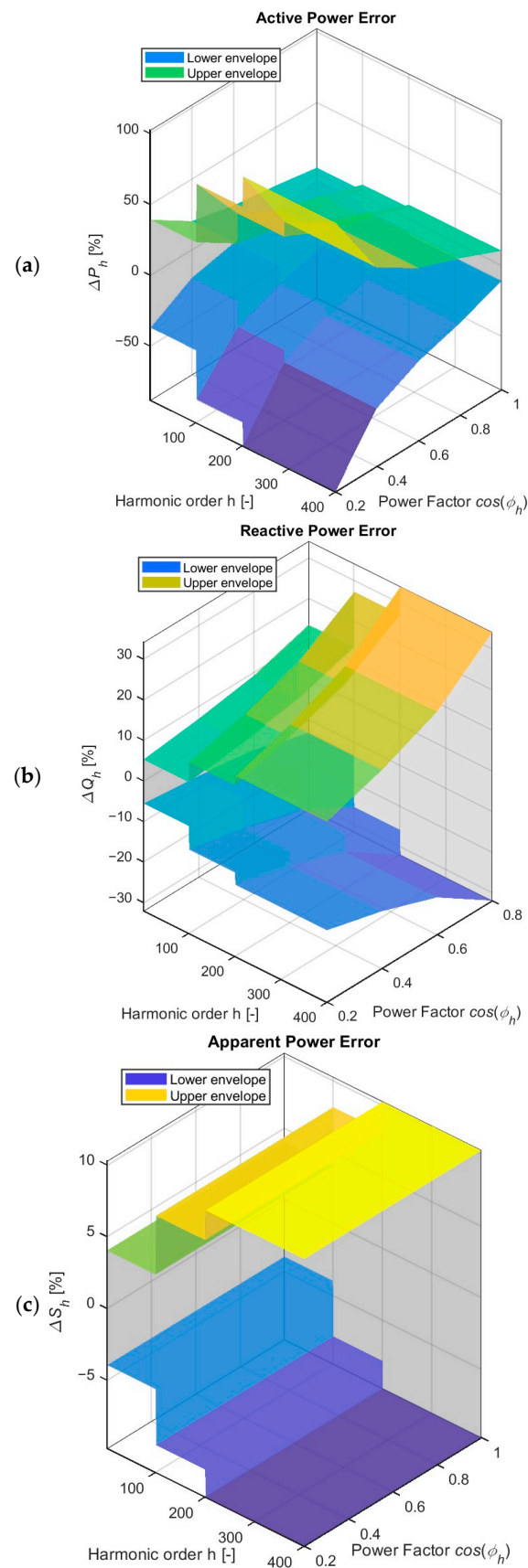


Figure 2. Relative power measurement error envelopes for individual higher harmonic components transformed according to the 0.2 WB2 optional accuracy class: (a) active power error, (b) reactive power error, and (c) apparent power error. The step changes along with the harmonic order axis result from the frequency band limits of the WB2 class.

According to Figure 2, the apparent power error of an individual harmonic depends only on the ratio errors of the voltage and current transformers. Therefore, the apparent power error does not depend on the harmonic displacement power factor. The surface changes only when the harmonic order enters a different WB2 frequency range. This confirms that, for apparent power, the main factor determining the error is the combined amplitude error of the transformed voltage and current harmonic components. The active power error of the individual harmonic components is much more sensitive to the phase displacement errors than in the 50 Hz case. This is caused by the larger permissible phase displacement errors in the WB2 class. The influence of the phase displacement error is especially visible at low values of $\cos(\varphi_h)$, where the phase-related term is proportional to $\tan(\varphi_h)$ becomes dominant. As a result, the largest relative active power errors are obtained for higher harmonic orders located in the upper WB2 frequency bands and for low harmonic displacement power factor. The reactive power error shows the opposite power factor sensitivity. The relative reactive power error increases when $\cos(\varphi_h)$ approaches unity, because the reference reactive power associated with the considered harmonic becomes small. In this region, even a limited phase displacement error may produce a large relative error. Therefore, when the harmonic reactive power is close to zero, the absolute error expressed in var should also be considered to avoid overinterpreting the relative error.

The comparison between Figures 1 and 2 indicates that the power measurement error may be significantly higher for higher harmonic components than for the 50 Hz component. This is mainly due to the larger permissible ratio and phase displacement errors assigned to the WB2 frequency bands. The results also show that the type of power component strongly influences the error sensitivity: apparent power is governed by amplitude errors, whereas active and reactive power are additionally affected by the differential phase displacement error.

Higher-order harmonics usually have lower RMS amplitudes than dominant low-order harmonics; however, their influence on power measurement accuracy cannot be neglected in harmonic-by-harmonic analysis. This is because the permissible ratio and phase displacement errors of instrument transformers increase in the higher WB2 frequency bands. Moreover, the reference active or reactive power associated with a high-order harmonic component may be small because of its low RMS amplitude or phase displacement angle. In such cases, even a limited absolute measurement error may result in a large relative error. Therefore, higher-order harmonics may have a smaller contribution to the total transferred power, but they remain important from the metrological point of view in wideband power quality and harmonic power measurements.

Dominant low-order harmonics, especially the 3rd, 5th, and 7th harmonic components, are usually the most important non-fundamental components from the point of view of total power measurement. Their RMS amplitudes are typically higher than those of higher-order harmonic components; therefore, their contribution to total active, reactive, and apparent power errors may be significant. For these harmonics, improving measurement accuracy requires accurate transformation of both RMS values and phase displacement angles, because active and reactive power errors depend not only on ratio errors but also on the differential phase displacement errors of voltage and current transformers. Higher-order harmonics usually have lower RMS amplitudes and may contribute less to the total transferred power. However, they remain important in harmonic-by-

harmonic power measurement and wideband power quality assessment. Their influence on measurement accuracy results mainly from the frequency-dependent WB2 limits. When the harmonic order enters a higher WB2 frequency band, the permissible ratio and phase displacement errors increase, which widens the deterministic error envelopes. Moreover, if the reference active or reactive power of an individual higher-order harmonic is small, even a limited absolute error may lead to a large relative error. Therefore, higher-order harmonics may have a smaller effect on total power than dominant low-order harmonics, but they can produce large relative errors in individual harmonic power components.

The main new observation obtained from the harmonic frequency analysis is that the influence of frequency on power measurement error is not gradual, but follows the frequency band structure of the WB2 optional accuracy class. As a result, the relative error envelopes exhibit step changes when the harmonic order enters the next WB2 band. This effect is especially visible for higher harmonic orders, where the permissible ratio and phase displacement errors of instrument transformers are larger. Another important observation is that apparent power errors are governed mainly by amplitude transformation errors and therefore follow the WB2 ratio error limits, whereas active and reactive power errors are additionally affected by the differential phase displacement error between the voltage and current channels. Consequently, the same harmonic frequency may lead to different error sensitivity depending on the harmonic displacement power factor. The analysis also shows that high relative errors may occur for harmonic components with small reference active or reactive power, even when their absolute contribution to the total transferred power is limited. Therefore, the impact of harmonic frequency on power measurement accuracy should be assessed not only through harmonic amplitude, but also through the corresponding WB2 frequency band, phase displacement angle, and type of calculated power quantity.

4. Power Measurement Errors Introduced by Instrument Transformers

In this section, the influence of voltage and current transformer errors on the measurement of power under distorted waveform conditions is analyzed. The calculations were performed for the extended 0.2 WB2 optional accuracy class. The RMS value of the fundamental voltage component was assumed to be 6 kV, and the RMS value of the fundamental current component was assumed to be 100 A. The power factor of the fundamental component was approximately equal to 0.94. The analyzed waveform contained the fundamental component and a set of higher harmonic components. The purpose of this waveform was to provide a representative distorted test signal for evaluating how the permissible ratio and phase displacement errors of instrument transformers propagate into the measurement of active, reactive, and apparent power. The harmonic components were first considered separately to determine the contribution of each voltage–current harmonic pair. For the distorted waveform, the total active power was calculated as the sum of the harmonic active power components. The reported reactive power-related quantity was calculated as the algebraic sum of the quadrature harmonic components. In contrast, the total apparent power was calculated from the RMS values of the complete distorted voltage and current waveforms, i.e., $S = U_{rms} I_{rms}$, and not as the arithmetic sum of the individual harmonic apparent powers. To evaluate the influence of the signs of transformer errors, a deterministic global sign scenario analysis was performed. Four independent error components were considered: the voltage transformer ratio error, the voltage transformer phase displacement error, the current transformer ratio error, and the current transformer phase displacement error. Each of these components was assigned to either its positive or negative limiting value. The selected sign of a given error component

was assumed to be the same for all harmonic orders. Therefore, the total number of analyzed global sign scenarios was equal to $2^4 = 16$.

Table 5 lists the 16 global sign scenarios used in the calculations. The signs shown in the table define whether a given transformer error component was assumed to take its positive or negative limiting value over the entire harmonic spectrum. The global sign assumption was adopted to represent systematic rather than randomly alternating transformer-error behavior over the analyzed harmonic spectrum. In practical instrument transformers, ratio and phase displacement errors are determined by the frequency response of the complete measuring chain, including the magnetic core, windings, leakage inductances, parasitic capacitances, burden, and secondary measuring equipment. Therefore, within a given frequency range, the error sign may remain consistent or change only gradually with frequency, rather than varying independently from one harmonic order to another. It should be emphasized that the 16 global sign scenarios do not represent the absolute worst case obtained by assigning independent signs to each error component at each harmonic order. If (h) harmonic components were considered and each voltage transformer ratio error, voltage transformer phase displacement error, current transformer ratio error, and current transformer phase displacement error were allowed to change sign independently for every harmonic order, the total number of sign combinations would be 2^{4h} . Such an approach would be extremely conservative and would not necessarily correspond to a realistic transformer frequency-response characteristic.

Consequently, the total power results obtained from the 16 scenarios should be interpreted as conditional deterministic worst-case results under the adopted global sign assumption. They indicate the limiting effect of systematic positive or negative transformer-error signs over the analyzed harmonic spectrum. The individual harmonic error envelopes, however, still describe the limiting error range for a single harmonic component under the corresponding WB2 accuracy limits.

Table 5. Global sign scenarios used to analyze the influence of voltage and current transformer errors on power measurement.

Scenario	VT Error Sign		CT Error Sign	
	Ratio Error	Phase Error	Ratio Error	Phase Error
S1	−	−	−	−
S2	−	−	−	+
S3	−	−	+	−
S4	−	−	+	+
S5	−	+	−	−
S6	−	+	−	+
S7	−	+	+	−
S8	−	+	+	+
S9	+	−	−	−
S10	+	−	−	+
S11	+	−	+	−
S12	+	−	+	+
S13	+	+	−	−
S14	+	+	−	+
S15	+	+	+	−
S16	+	+	+	+

Thus, Table 5 should be interpreted as a set of global systematic sign scenarios for the whole distorted waveform, not as a complete enumeration of all possible independent

sign combinations for every individual harmonic component. The scenarios listed in Table 5 represent all possible combinations of signs of the four considered error components. This approach makes it possible to determine how different combinations of transformer ratio and phase displacement errors may either compensate for each other or accumulate in the final power measurement result. It should be emphasized that the signs are treated globally; the sign of a selected error component does not change from one harmonic order to another within the same scenario.

To clarify the construction process of the distorted voltage and current waveforms used in the simulation, the harmonic content of the reference waveform is explicitly specified in Table 6. The analyzed waveform was defined as a model-based deterministic reference case in MATLAB R2024b, version 24.2.0.2863752. The reference spectrum was obtained by assigning RMS values to selected voltage and current harmonic components and by defining the phase displacement angle between the voltage and current components of each harmonic order. This approach provides a controlled test case in which the contribution of each voltage–current harmonic pair to the total active, reactive, and apparent powers can be directly determined. In Table 6, U_h and I_h denote the RMS values of the h th voltage and current harmonic components, respectively, whereas φ_h denotes the phase displacement angle between the voltage and current components of the same harmonic order. The fundamental RMS values were assumed to be $U_1 = 6$ kV and $I_1 = 100$ A. For the fundamental component, the phase displacement angle was equal to 20° , which corresponds to a displacement power factor of approximately 0.94. Based on the harmonic spectrum listed in Table 6, the total harmonic distortion values of the reference waveform were $THD_U = 4.00\%$ and $THD_I = 16.82\%$.

Table 6. Harmonic components used to construct the reference distorted voltage and current waveforms.

Harmonic Order h [-]	U_h [V]	I_h [A]	φ_h [°]
1	6000	100	20.00
3	60	4	47.52
5	180	12	61.21
7	120	8	68.57
9	24	3	73.02
10	9	1	74.64
11	60	5	75.98
12	6	0.8	77.10
13	48	4	78.07
15	18	2	79.62
20	9	1	82.18
25	7.2	0.8	83.73
30	6	0.6	84.77
35	4.8	0.5	85.51
40	4.2	0.45	86.07
45	3.6	0.4	86.51
50	3	0.35	86.85
55	2.7	0.32	87.14
60	2.4	0.3	87.38
65	2.28	0.28	87.58
70	2.16	0.26	87.75
75	2.04	0.24	87.90
80	1.92	0.22	88.03
85	1.8	0.2	88.15

90	1.68	0.18	88.25
95	1.56	0.16	88.34
100	1.5	0.15	88.43
120	1.2	0.12	88.69
160	1.08	0.11	89.02
180	0.96	0.1	89.13
200	0.9	0.09	89.21
220	0.84	0.08	89.28
240	0.78	0.075	89.34
250	0.75	0.07	89.37
260	0.72	0.065	89.39
280	0.66	0.06	89.44
300	0.6	0.055	89.48
320	0.57	0.05	89.51
340	0.54	0.045	89.54
360	0.51	0.04	89.56
380	0.48	0.035	89.59
400	0.45	0.03	89.61

Because the total power measurement error may depend on the adopted harmonic spectrum, distortion level, and phase displacement conditions, additional sensitivity cases were analyzed. These cases are summarized in Table 7. The reference case R corresponds to the harmonic spectrum listed in Table 6. Cases A1 and A2 were introduced to evaluate the influence of the distortion level by decreasing and increasing the amplitudes of all higher harmonic components, respectively. Case B1 was used to assess the contribution of dominant low-order harmonics by retaining only the harmonic components up to the 13th order. Finally, cases C1 and C2 were introduced to evaluate the influence of the load phase character. Case C1 represents a predominantly active load-character condition, whereas case C2 represents a capacitive load-character condition.

Table 7. Sensitivity cases used to evaluate the influence of the harmonic distortion level, spectral distribution, and phase displacement conditions on the total power measurement errors.

Case	Description	Modification	THD_u [%]	THD_l [%]	Power Factor [-]
R	Reference waveform	Original harmonic spectrum	4	16.82	0.929
A1	Low-distortion waveform	Higher harmonics multiplied by 0.5	2	8.41	0.937
A2	High-distortion waveform	Higher harmonics multiplied by 2.0	8	33.65	0.898
B1	Dominant low-order harmonics	Only harmonics up to ($h = 13$) retained	3.98	16.6	0.929
C1	Predominantly active load-character case	Voltage and current components in phase	4	16.82	0.992
C2	Capacitive load-character case	Phase displacement equal to (-40°)	4	16.82	0.756

To compare the influence of the analyzed harmonic spectra and phase-displacement conditions on the final total power measurement accuracy, the maximum total relative errors of active, reactive, and apparent power were determined for each sensitivity case. For each case, the extreme values were selected from the 16 global sign scenarios listed in Table 5. Table 8 summarizes the obtained maximum total power measurement errors.

Table 8. Maximum total power measurement errors obtained for the sensitivity cases.

Case	Max $\Delta P/P$ [%]	Scenario	Max $\Delta Q/Q$ [%]	Scenario	Max $\Delta S/S$ [%]	Scenario
R	0.667	S12	2.096	S15	0.453	S11
A1	0.626	S5	2.029	S15	0.414	S11
A2	0.832	S12	2.348	S15	0.597	S11
B1	0.666	S12	2.096	S15	0.452	S11
C1	0.426	S2	—	—	0.453	S11
C2	0.957	S15	1.138	S12	0.453	S11

The results presented in Table 8 show that the numerical values of the total power measurement errors depend on the assumed harmonic spectrum, distortion level, and phase displacement conditions. Increasing the amplitudes of higher harmonic components increases the maximum total power errors. For example, the maximum relative active power error increases from 0.626% in the low-distortion case A1 to 0.832% in the high-distortion case A2. Similarly, the maximum relative apparent power error increases from 0.414% to 0.597%. This confirms that the distortion level affects the final total power measurement error, even though the same WB2 accuracy limits and the same global sign scenarios are applied. The comparison between the reference case R and the dominant low-order harmonic case B1 shows very similar values of the total power measurement errors. This indicates that, for the assumed spectrum, the total power error is mainly determined by the dominant low-order harmonic components. The influence of higher-order harmonics on the total power error is limited because their amplitudes are relatively small. However, higher-order harmonics remain important for the assessment of individual harmonic power errors, since the permissible WB2 ratio and phase displacement limits increase in higher frequency bands. The dominant low-order harmonics, especially the 3rd, 5th, and 7th harmonic components, are particularly important for total power measurement because their RMS amplitudes are usually much higher than those of higher-order harmonic components. As a result, their contribution to the total active, reactive, and apparent powers is usually dominant. Improving power measurement accuracy for these harmonics requires not only the use of voltage and current transformers compliant with the appropriate wideband accuracy class, but also the application of harmonic-specific ratio and phase displacement correction factors whenever the measured frequency characteristics of the transformers are available. For the 3rd, 5th, and 7th harmonics, even relatively small phase displacement errors may noticeably affect harmonic active and reactive power, especially when the harmonic displacement power factor is low or when the reference reactive power approaches zero. Therefore, accurate measurement at dominant harmonic orders should include calibrated voltage and current transformation channels, controlled secondary burden conditions, synchronized voltage and current sampling, and harmonic-by-harmonic correction of both RMS magnitude and phase displacement errors. The phase character cases C1 and C2 confirm that active and reactive power errors are strongly affected by the phase displacement conditions. In case C1, the reference reactive power is equal to zero; therefore, the relative reactive power error is not physically meaningful and is not reported in Table 8. In such cases, the absolute reactive power error expressed in var should be used instead. In contrast, the capacitive case C2 changes the distribution of active and reactive powers, which modifies the maximum active and reactive power errors. The apparent power error remains practically unchanged in cases R, C1, and C2 because the voltage and current RMS spectra are the same and apparent power is governed mainly by ratio errors.

The assumed distorted voltage and current waveforms used in the simulation are shown in Figure 3. This figure is included to illustrate the time-domain shape of the test signal before the transformer errors are applied.

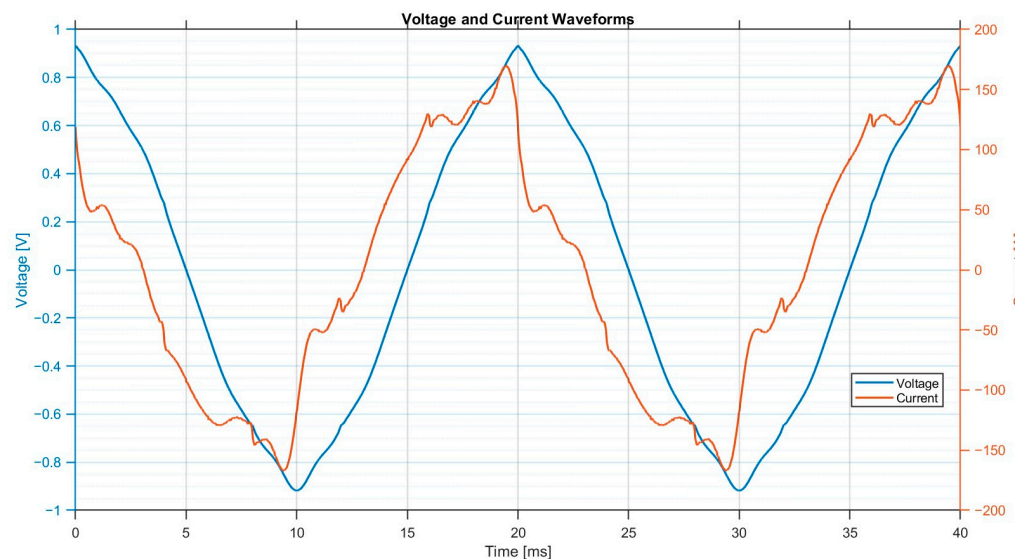


Figure 3. Voltage and current waveforms used in the simulation of power measurement errors introduced by instrument transformers.

Figure 3 shows that the voltage waveform remains relatively close to sinusoidal, whereas the current waveform is more visibly distorted. This is consistent with the assumed test conditions, in which the current contains a larger contribution of harmonic components than the voltage. The waveform distortion is important because, under non-sinusoidal conditions, the total power measurement error is not determined only by the fundamental component, but also by the amplitudes and phase angles of the individual harmonic components.

To quantify the harmonic content of the assumed test signal, the voltage and current spectra are presented in Figure 4. The harmonic amplitudes are expressed as percentages of the corresponding fundamental component. The fundamental component itself is omitted from the plot in order to make the higher harmonic components more visible.

The spectra in Figure 4 confirm that the current waveform is more strongly distorted than the voltage waveform. The dominant harmonic components are located in the lower harmonic range, while the amplitudes of higher-order harmonics gradually decrease. This form of presentation is useful because it allows the voltage and current harmonic contents to be compared directly, despite their different physical units. The adopted spectrum, therefore, provides a suitable basis for analyzing the influence of WB2 accuracy limits on power measurement errors over a wide frequency range.

The influence of the 16 global sign scenarios on individual harmonic power errors is shown in Figure 5. For each harmonic order, the minimum and maximum values of the relative error were selected from all analyzed scenarios. As a result, the plotted regions represent deterministic error envelopes rather than individual error curves.

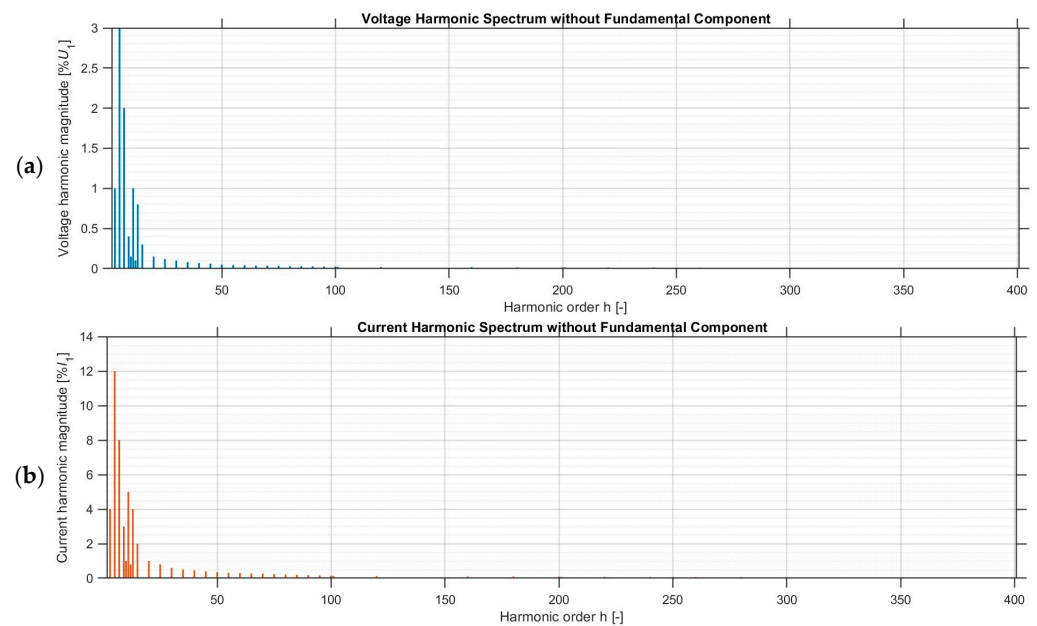


Figure 4. Harmonic spectra of the reference signals expressed as percentages of the fundamental component: (a) voltage harmonics and (b) current harmonics.

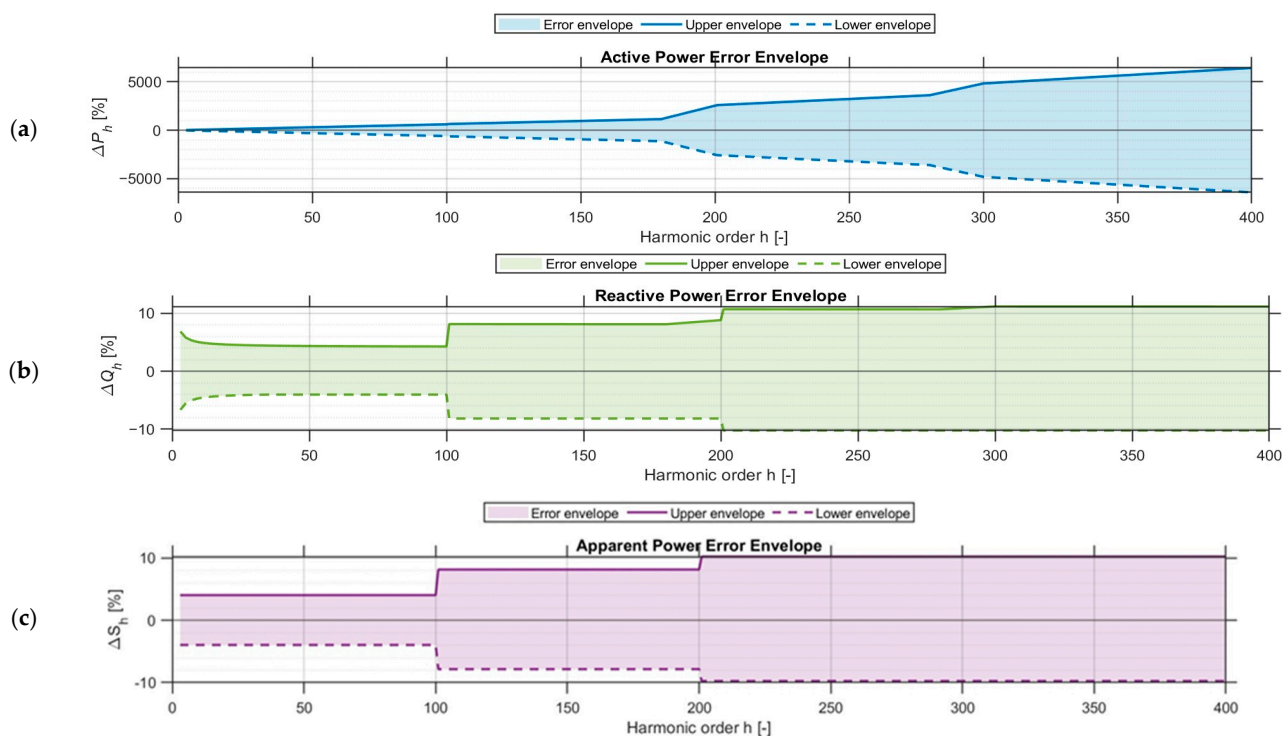


Figure 5. Relative power measurement error envelopes of individual higher harmonics over the 16 global sign scenarios: (a) active power error, (b) reactive power error, and (c) apparent power error.

Figure 5 shows that the error envelopes depend strongly on the type of power component. The apparent power error envelope is mainly governed by the ratio errors of the voltage and current transformers. Therefore, its shape follows the WB2 ratio error limits and exhibits step changes when the harmonic frequency enters a higher WB2 frequency band. The active power error envelope is affected not only by the ratio errors but also by the differential phase displacement error between the voltage and current transformers. This explains why the active power error range may become significantly wider for higher harmonic orders. The largest changes are observed in the frequency ranges where the per-

missible WB2 phase displacement error increases. The reactive power error envelope should be interpreted with particular care. For harmonic components with small reference reactive power, even a limited absolute error may lead to a large relative error. This is a consequence of normalizing the error by Q_{0h} . Therefore, for harmonics with very small reactive power, the relative error should be analyzed together with the corresponding absolute error expressed in var. The very large relative active power errors observed for selected higher harmonics result mainly from the small reference active power values of these components. When $\cos \varphi_h$ approaches zero, P_{0h} also becomes small, and even a limited absolute active power deviation may lead to a high relative error. Therefore, for such harmonics, the relative error should be interpreted together with the corresponding absolute error expressed in watts.

The total power errors obtained for the 16 global sign scenarios are presented in Figure 6. In contrast to Figure 5, which shows the error range for individual harmonics, Figure 6 illustrates the final effect of each global sign scenario on the total active, reactive, and apparent power.

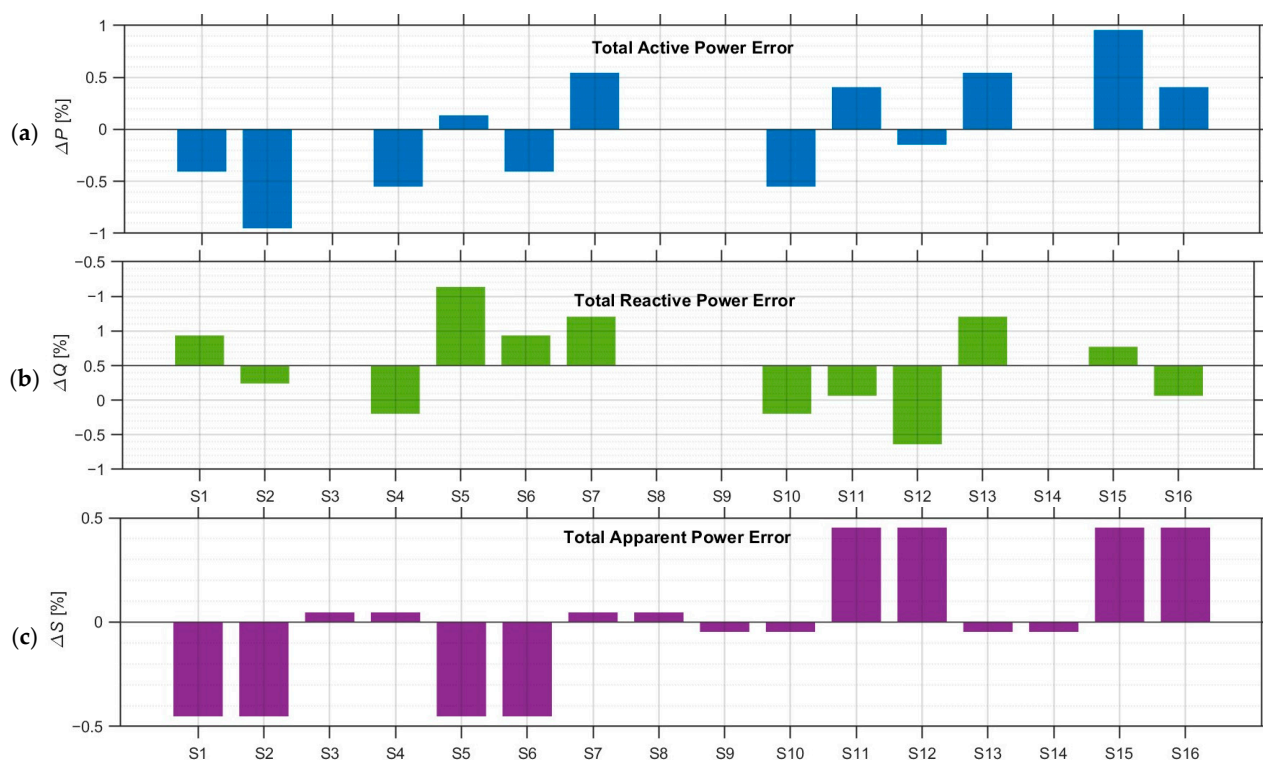


Figure 6. Total power measurement errors for the 16 global sign scenarios: (a) active power error, (b) reactive power error, and (c) apparent power error.

Figure 6 demonstrates that the sign combination of transformer errors has a significant influence on the total power measurement error. Some scenarios lead to partial compensation between the voltage and current transformer errors, whereas other scenarios produce accumulation of errors. This confirms that the worst-case power measurement error cannot be determined only from the magnitudes of individual transformer errors; the relative signs of the ratio and phase displacement errors are also important. For total active power, both amplitude-related and phase-related effects are visible. Depending on the sign scenario, the active power error may be either positive or negative. This behavior results from the combined influence of the ratio errors and the differential phase displacement error. For total reactive power, the variation between scenarios is generally more pronounced. This confirms the high sensitivity of reactive power to phase displacement errors, especially when selected harmonic components have relatively small reference re-

active power. For total apparent power, the influence of phase displacement errors is not direct. The apparent power error is mainly determined by the signs of the voltage and current transformer ratio errors. The largest positive apparent power error occurs when both ratio errors increase the measured RMS values, whereas the largest negative apparent power error occurs when both ratio errors reduce the measured RMS values. Among the analyzed cases, the largest total active power error is obtained for scenario S12, whereas the largest total reactive power error is observed for scenario S15. For apparent power, the largest positive errors occur when both voltage and current ratio errors have positive signs, while the largest negative errors occur when both ratio errors have negative signs.

The results presented in this section show that the deterministic sign scenario approach is useful for identifying the limiting influence of instrument-transformer errors under distorted waveform conditions. The analysis also confirms that the influence of transformer errors depends not only on the WB2 accuracy limits but also on the harmonic spectrum, harmonic phase angles, and the signs of the individual error components.

5. Conclusions

This paper analyzed the influence of voltage and current transformer errors on the measurement of active, reactive, and apparent power under sinusoidal and nonsinusoidal operating conditions. The study considered both the conventional 0.2 accuracy class at the fundamental frequency of 50 Hz and the extended 0.2 WB2 optional accuracy class for individual higher harmonic components. The results obtained for the fundamental component show that the power measurement error depends on both the type of measured power and the operating point of the instrument transformers. The apparent power error is governed mainly by the ratio errors of the voltage and current transformers and is practically independent of the displacement power factor. In contrast, the active and reactive power errors are affected by both ratio errors and the differential phase displacement error. The active power error becomes more sensitive to phase displacement errors at lower power factors, whereas the relative reactive power error increases when the reference reactive power approaches zero. For individual higher harmonic components, the permissible errors defined by the WB2 optional accuracy class may lead to significantly larger power measurement errors than those obtained for the 50 Hz component. This is mainly caused by the larger permissible ratio and phase displacement errors assigned to higher-frequency bands. The error envelopes show step changes at the harmonic orders corresponding to the WB2 frequency band limits. These discontinuities are therefore a direct consequence of the frequency band structure of the WB2 class and should not be interpreted as numerical artifacts. The analysis confirmed that apparent power errors of individual harmonics are determined by amplitude-related effects, whereas active and reactive power errors are additionally influenced by transformer phase displacement errors. The relative active power error may become very large for harmonics whose reference active power is small. Similarly, the relative reactive power error may become large when the corresponding reference reactive power is close to zero. Therefore, in such cases, relative errors should be interpreted together with absolute errors expressed in watts or vars. The deterministic global sign scenario analysis showed that the signs of transformer errors have a significant influence on the final total power measurement error. The 16 analyzed scenarios demonstrate that ratio and phase displacement errors may either compensate for each other or accumulate, depending on their sign combination. Therefore, the worst-case power measurement error cannot be evaluated only from the magnitudes of individual transformer errors; the relative signs of the voltage and current transformer errors are also important. The proposed approach provides a useful method for estimating limiting power measurement errors introduced by instrument transformers under distorted wave-

form conditions. It also enables separate assessment of individual harmonic components and total power errors for selected global sign scenarios. The results indicate that the extended WB2 optional accuracy class should be carefully considered when evaluating power measurement accuracy in systems with significant harmonic content. Future work may include the analysis of measured harmonic spectra obtained from real power system installations, the comparison of deterministic error envelopes with probabilistic error models, and the extension of the proposed method to other optional accuracy classes and a higher-frequency range.

It should be emphasized that the proposed error envelopes are deterministic class-based limiting bounds derived from the maximum permissible ratio and phase displacement errors specified for the 0.2 WB2 optional accuracy class. Therefore, they do not represent the measured frequency response of one specific voltage or current transformer. Instead, they define the maximum power measurement error that may occur when the transformer errors reach the limiting values permitted by the considered accuracy class. For a practical transformer whose measured ratio and phase displacement errors are known as functions of frequency, the same calculation procedure can be applied by replacing the limiting WB2 values with the measured error characteristics. In such a case, the obtained power measurement errors would represent the behavior of a specific transformer rather than the class-based limiting envelope. If the tested transformer complies with the 0.2 WB2 accuracy limits, the power errors calculated from its measured characteristics should remain within the deterministic envelopes presented in this study.

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Abbreviations

The following abbreviations and symbols are used in this manuscript:

<i>DG</i>	distributed generation
<i>RES</i>	renewable energy sources
<i>PV</i>	photovoltaic
<i>PQ</i>	power quality
<i>PLC</i>	power line communication
<i>PCC</i>	point of common coupling
<i>MV</i>	medium voltage
<i>HV</i>	high voltage
<i>IT</i>	instrument transformer
<i>VT</i>	voltage transformer
<i>CT</i>	current transformer
<i>h</i>	harmonic order
f_1	fundamental frequency of the voltage and current waveform
f_h	frequency of the h th harmonic
U_h	RMS value of the h th voltage harmonic component
I_h	RMS value of the h th current harmonic component
U_{mh}	measured RMS value of the h th voltage harmonic component after transformation

I_{mh}	measured RMS value of the hth current harmonic component after transformation
U_{rms}	RMS value of the voltage waveform
I_{rms}	RMS value of the current waveform
U_{mrms}	measured RMS value of the voltage waveform
I_{mrms}	measured RMS value of the current waveform
φ_h	phase displacement angle between the hth voltage and current harmonic components
φ_1	phase displacement angle between the fundamental voltage and current components
φ_{mh}	measured phase displacement angle between the hth voltage and current harmonic components after transformation
$\cos\varphi_h$	power factor of the hth harmonic component
$\cos\varphi_1$	power factor of the fundamental component
ε_{Uh}	relative ratio error of the voltage transformer for the hth harmonic
ε_{Ih}	relative ratio error of the current transformer for the hth harmonic
$\varepsilon_{Uh,max}$	maximum relative ratio error of the voltage transformer for the hth harmonic
$\varepsilon_{Ih,max}$	maximum relative ratio error of the current transformer for the hth harmonic
δ_{Uh}	phase displacement error of the voltage transformer for the hth harmonic
δ_{Ih}	phase displacement error of the current transformer for the hth harmonic
$\delta_{Uh,max}$	maximum phase displacement error of the voltage transformer for the hth harmonic
$\delta_{Ih,max}$	maximum phase displacement error of the current transformer for the hth harmonic
k_h	combined ratio error factor for the hth harmonic
$k_{h,min}$	minimum value of the combined ratio error factor for the hth harmonic
$k_{h,max}$	maximum value of the combined ratio error factor for the hth harmonic
S_{0h}	reference apparent power of the hth harmonic component
P_{0h}	reference active power of the hth harmonic component
Q_{0h}	reference quadrature reactive for the hth harmonic
S_{mh}	measured apparent power of the hth harmonic component
P_{mh}	measured active power of the hth harmonic component
Q_{mh}	measured quadrature reactive for the hth harmonic
S_h	apparent power of the hth harmonic component
P_h	active power of the hth harmonic component
Q_h	quadrature reactive for the hth harmonic
S	total apparent power of the distorted waveform
P	total active power of the distorted waveform
Q_Σ	algebraic sum of the quadrature harmonic reactive power components
S_m	measured total apparent power of the distorted waveform
P_m	measured total active power of the distorted waveform
$Q_{\Sigma,m}$	measured algebraic sum of the quadrature harmonic reactive power components
ΔS_h	apparent-power measurement error of the hth harmonic component
ΔP_h	active-power measurement error of the hth harmonic component
ΔQ_h	quadrature reactive power measurement error of the hth harmonic component
THD_U	voltage total harmonic distortion
THD_I	current total harmonic distortion
S1–S16	global sign scenarios of transformer ratio and phase displacement errors

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