Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

"The project 19NRM0 IT4PQ has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme."

EMPIR

EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

IT4PQ
Instrument Transformers for Power Quality

Reference system for the assessment of current transformer's PQ performances

19NRM05 IT^{4}PQ Final Workshop

22 June 2023, INRIM, Torino, Italy

Yeying Chen（陈叶盈）, Enrico Mohns
National Metrology Institute of Germany- PTB
Working group 2.32 „Time-synchronized Measuring Systems and Sensors "
Email: yeying.chen@ptb.de

Agenda

1. Reference system for current sensors
2. Measurement under Power Quality (PQ) phenomena
3. Measurement uncertainties
4. Conclusion and Outlook

Measurement methods and test procedures for assessing accuracy of instrument transformers for power quality measurements

Short Name: IT4PQ, Project Number: 19NRM05

“This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.”

1. Reference system for the current sensors

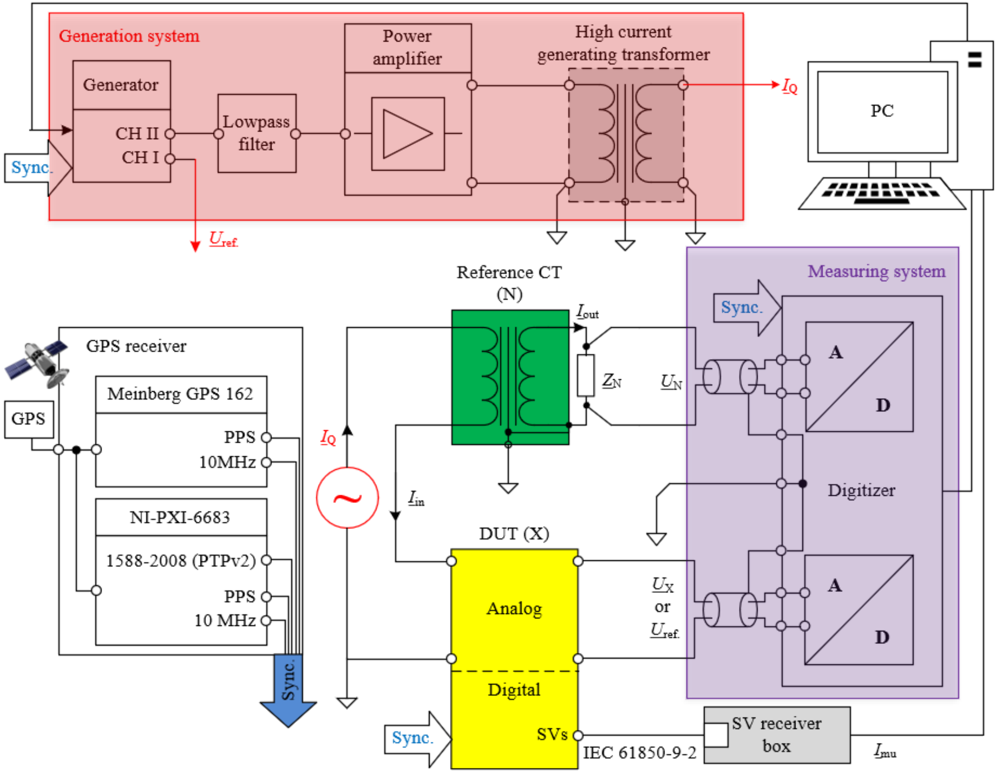


Figure 1: The setup of the reference measurement system for the current sensors

For any kind of analogue current sensors (conventional or non-conventional) or current sensors with digital output, which include the associated Merging unit / Stand-alone merging unit (MU/SAMU)

- **Components**
  - i. a high current generation system
  - ii. a set of analogue reference current transformers (CTs) with precision resistors
  - iii. a precision 2-channel measuring system

  - iv. synchronization signals
  - v. SV receiver box

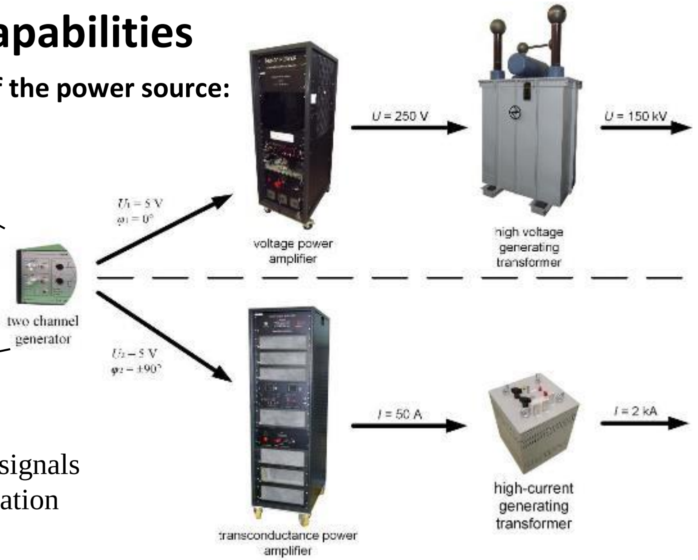
DUT : Device Under Test

1. Reference system for the current sensors

Generation system and capabilities

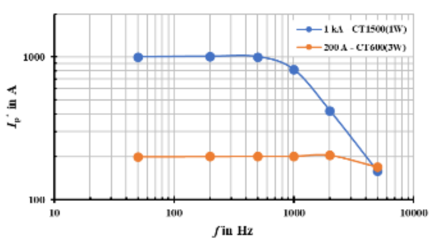
- **Programable generator:**

- **Setup of the power source:**



Generation of sinusoidal signals – blue curve

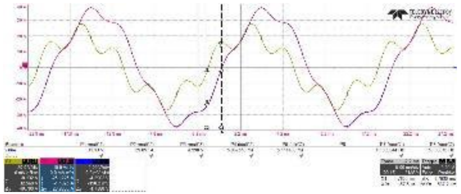
f in Hz	I_p^* in A
50	1000
200	1009
500	1002
1000	815
2000	420
5000	158



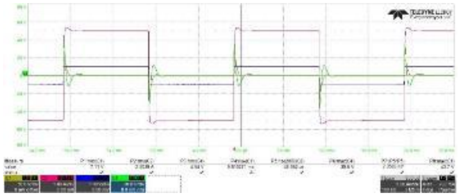
GENERATION CAPABILITIES

- superposition of multiple sinusoidal signals
- amplitude / phase / frequency modulation
- oscillation transient

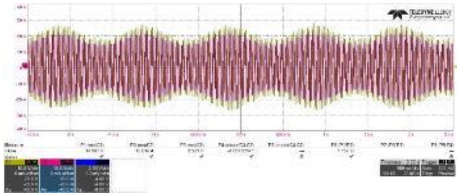
EXAMPLES OF GENERATION CAPABILITIES



Sinusoidal Signal with harmonics (10%, up to 50th) up to 1 kA – rose red curve



Rectangle Signal up to 1 kA – rose red curve



Amplitude Modulated Signal – rose red curve

Reference Current-to-Voltage (C-to-V) transformer set

- A **symmetrical current transformer (CT)** with a precise **measuring resistor**
- Bandwidth: **16 Hz … 12 kHz**

Table 1: Parameters of the C-to-V transformer set

Type	N_p	$I_{P,r}$ in A	$I_{S,r}$	R_m (1V)
CT50	1, …, 6	8.3, …, 50	100 mA	10 Ω
CT200	1, …, 4	50, …, 200	400 mA	2.5 Ω
CT600	1, …, 4	150, …, 600	400 mA	2.5 Ω
CT1500	1, …, 3	500, …, 1500	1 A	1 Ω

Symmetrical CTs

- Symmetrical winding design for providing several ranges with identical errors
- |E| < 10^{-5} at power frequency
- |E|(f < 12 kHz) below 0.1 % and 0.2 crad,
  |U|(f < 12 kHz) below 0.01 % and 0.03 crad (k = 2)

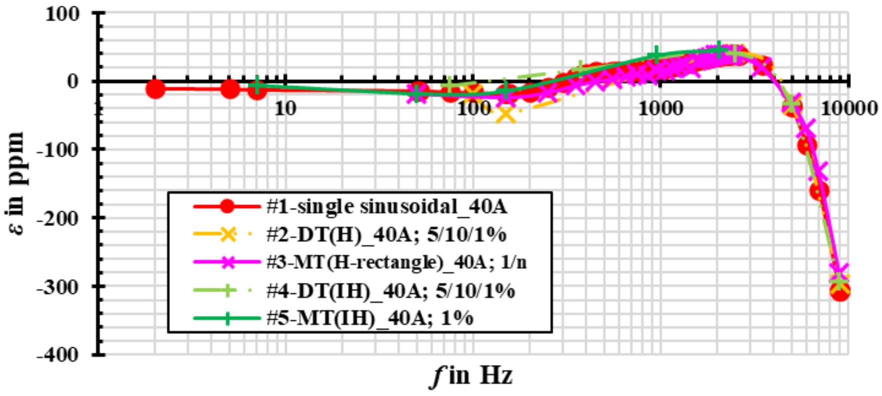
Resistor box (1 Ohm to 20 Ohm)

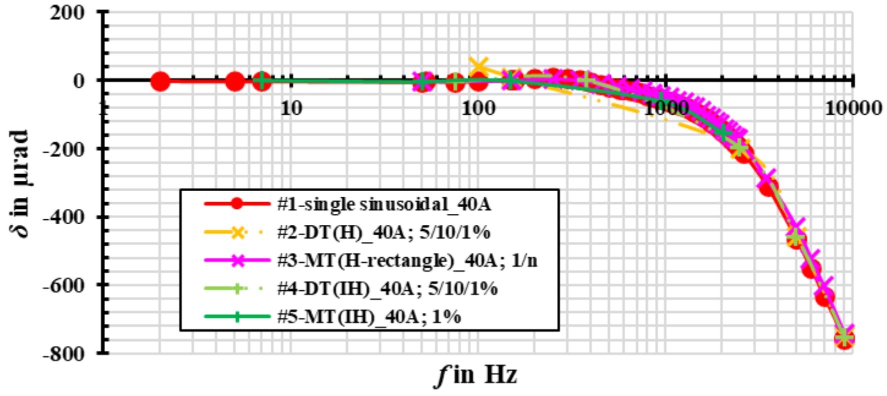
- |E| < 2*10^{-5} at power frequency
- Flat frequency response (< 12 kHz) with time constant below ±1 ns

Figure 2: The accomplished wideband current-to-voltage transformer set for currents up to 2 kA. The symmetrical current transformers (above) and the front panel of the associated precise measuring resistor box (below)

Reference Current-to-Voltage (C-to-V) transformer set – uncertainties under PQ (CT 200)

- Spread of CT200 with harmonics or interharmonics are within ± 30 µV/V and ± 50 µrad.





The frequency response of CT200 and the errors of CT200 under PQ harmonics / interharmonics. (left: ratio errors, right: phase errors. #1 represents the frequency response given by single-tone inputs of 40 A. #2 represents the errors given by dual-tone harmonics: f0 = 50 Hz, A0 = 40 A with n = 2 (5 % · A0) / 3 (10 % · A0) / 50 (1 % · A0) / 100 (1 % · A0) / 180 (1 % · A0). #3 represents the errors given by multi-tone harmonics: 40 A of the fundamental signal and 1 / n of the nth harmonic signals, n is the odd number from 3 up to 179. #4 represents the errors given by dual-tone interharmonics: f0 = 50 Hz, A0 = 40 A with n = 1.5 (5 % · A0) / 7.5 (10 % · A0) / 49.5 (1 % · A0) / 99.5(1 % · A0) / 179.5 (1 % · A0). #5 represents the errors given by multi-tone interharmonics: f0 = 50 Hz, A0 = 40 A with f0 = 7; 149; 951; 2048 Hz, A0 = 1 % · A0.)

1. Reference system for the current sensors

2-channel precision ratio measuring system

- NI 5922 (24 bit A-to-D, 500 kS/s)
- Rated input voltages U_{pk} : ± 2 V and ± 10 V
- Resampling processing for time synchronization
- Measurement results:

  - processed on PC by a LabView-based software

  - based on DFT analysis (“frequency domain”)

Figure 3: Photo of the 2-channel precision ratio measuring system (VRS)

Agenda

1. Reference system for current sensors
2. Measurement under Power Quality (PQ) phenomena
3. Measurement uncertainties
4. Conclusion and Outlook

Measurement methods and test procedures for assessing accuracy of instrument transformers for power quality measurements

Short Name: IT4PQ, Project Number: 19NRM05

"This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme."

2. Measurement under PQ phenomena

Test plans

- 6 PQ phenomena (according to IEC 61000-4-7 and IEC 61000-4-30)

Table 3: Tests under various PQ phenomena and to measuring quantities

Performance Index	Quantity to Measure	Frequency deviation	Amplitude deviation	Harmonics and Interharmonics	Amplitude modulation	Phase modulation	Oscillatory Transient
$\varepsilon(f_0)$ & $\delta(f_0)$	Ratio and Phase	X	X	X	X	X	X
$\varepsilon(f_n)$ & $\delta(f_n)$				X			
Abbreviation (Abb.) of tests		i) FD	ii) AD	iii) (I)H	iv) AM	v) PM	vi) OT

Table 3: Detailed test descriptions for current sensors.

Abb.	Detailed test descriptions
i) FD	TPA: 42.5 Hz; TPB: 50 Hz; TPC: 57.5 Hz (at 100%)
ii) AD	TP1: 1 % (class 0.2S), 5 % (class 0.5); TP2: 100 %; TP3:120% or 200% according to the CT specifications of max. current
iv) AM	TP1: 10 % - 2 Hz; TP2: 10 % - 5 Hz;
v) PM	TP1: 10 % of 1 rad - 2 Hz; TP2: 10 % of 1 rad - 5 Hz;
vi) OT	TP1: 500Hz; TP2: 1 kHz; TP3: 2 kHz TP4: 5 kHz, 22% of rated amplitude, 600 µs time constant

Abb.	Detailed test descriptions
iii) (I)H	Fundamental primary current: sinusoidal, f_0 = 50 Hz, I_0 = 100 A, φ_0 = 0 ° n^{th} harmonic primary current: $f_h = n \cdot f_0$, φ_h = 0 °, n = 3; 11; 20; 50; (115;) 173 Dual-tone signal: I_h = 1 %; 3 %; 10 %; (40 %) of I_0 Multi-tone signal: I_h = 10 % (TP1) or 1 / n of I_0 Interharmonic primary current: Dual-tone signal: TP1: 5 % at 75 Hz; TP2: 10 % at 375 Hz; TP3: 1 % at 2475 Hz Multi-tone signal: 1 % at 7 Hz, 149 Hz, 951 Hz, 2048 Hz (TP2)

TP: Test Point

2. Measurement under PQ phenomena

Three different types of current sensors

I. Inductive current transformers (CTs): CT #1, CT #2
II. Electronic CT [LEM IT 200-S ULTRASTAB]: CT #3
III. Rogowski coil [LEM ART-B22-D70]: RC #4

Table 4: Technical specifications of the current sensors

Type	Inductive CTs		Electronic CT	Rogowski coil
Abb.	CT #1	CT #2	CT #3	RC #4
$I_{Pr,X}$ in A	400	500	100	1000
$K_{n,X}$	1 : 400	1 : 500	1 : 100	22.5 Mv : 1 kA (50 Hz)
$I_{Sr,X}$ ($U_{Sr,X}$)	1 A	1 A	100 mA	
Burden	5 VA	2.5 VA	10 Ω	10 kΩ
Accuracy	Cl. 0.2S	Cl. 0.5	-	Cl. 0.5

CT #1


CT #2


CT #3


RC #4


Tests	i) … vi)	ii); iii) without interharmonics	i) … vi)	ii); iii) without interharmonics

2. Measurement under PQ phenomena (1)

Experimental results - Frequency and amplitude variations

1. errors at 50 Hz by rated primary current

CT #1

$\varepsilon_i(f_0)$ = 0.15 %
$\delta_i(f_0)$ = 0.06 crad

CT #3

$\varepsilon_i(f_0)$ = - 44 µA/A
$\delta_i(f_0)$ = - 28 µrad

2. linear behaviour in terms of and amplitude

3. $\varepsilon_i(f_0)$ and $\delta_i(f_0)$ were "similar" for different f_0

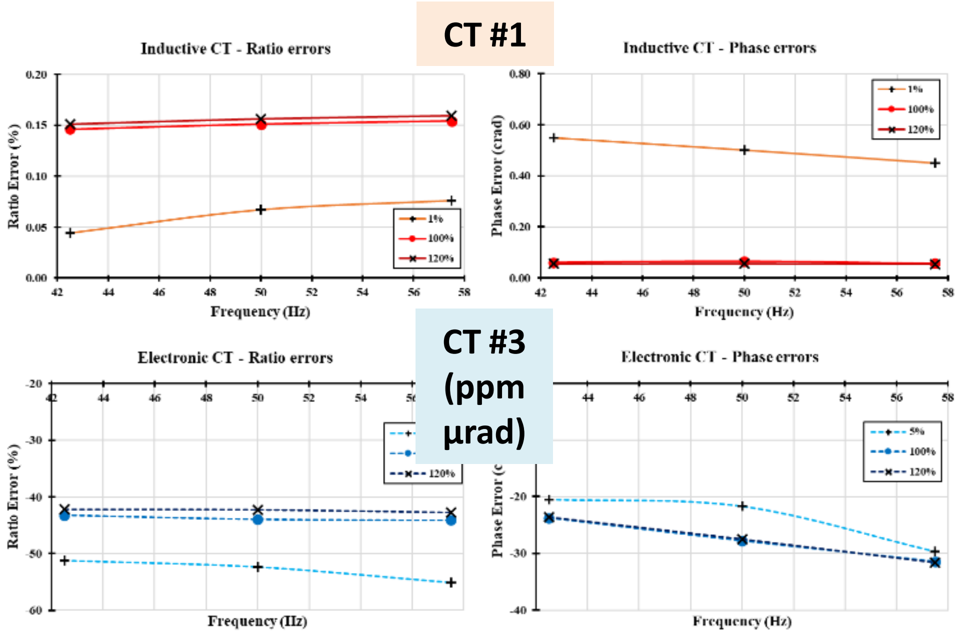


Figure 4: Ratio and phase errors of the inductive CT (above) and the electronic CT (below) with the nominal burden by primary currents ranging from 1 % or 5 % to 120 %.

	Test point 1			Test point 2			Test point 3		
	1.A	1.B	1.C	2.A	2.B	2.C	3.A	3.B	3.C
Frequency (Hz)	42.5	50	57.5	42.5	50	57.5	42.5	50	57.5
Amplitude (% of rated)	1% for class 0.2S (CT) 5% for class 0.5 (CT)			100			120% or 200% according to the CT specifications of max. current (CT)		

Tests	i) FD	ii) AD	iii) (I)H	iv) AM	v) PM	vi) OT

Experimental results - Harmonics and interharmonics

1. $\varepsilon_i(f_0)$ and $\delta_i(f_0)$ were almost identical

Table 5: Ratio and phase errors at 50 Hz of the inductive CT and the electronic CT with the nominal burden by dual-tone ($I_0 = I_{Pr,x}$) signals with interharmonic interactions.

	Inductive CT - Cl. 0.2S (400 A - 1 A -5 VA)		Electronic CT - LEM 100 (100 A - 0.1 A - 10 Ω)	
	$\varepsilon_i(f_0)$ in %	$\delta_i(f_0)$ in crad	$\varepsilon_i(f_0)$ in µA/A	$\delta_i(f_0)$ in µrad
Test Point 1	0.15	0.07	-42	-27
Test Point 2	0.15	0.06	-42	-27
Test Point 3	0.15	0.06	-43	-26

CT #1 CT #3

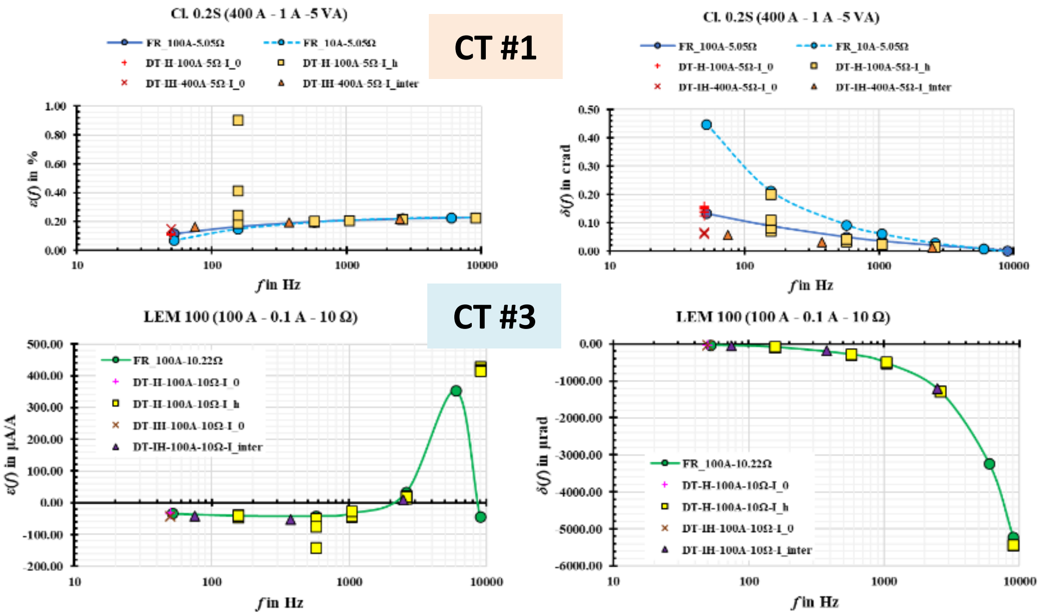
Table 6: Ratio and phase errors at 50 Hz of the inductive CT and the electronic CT with the nominal burden by multi-tone ($I_0 = I_{Pr,x}$) signals.

	Inductive CT - Cl. 0.2S (400 A - 1 A -5 VA)		Electronic CT - LEM 100 (100 A - 0.1 A - 10 Ω)	
	$\varepsilon_i(f_0)$ in %	$\delta_i(f_0)$ in crad	$\varepsilon_i(f_0)$ in µA/A	$\delta_i(f_0)$ in µrad
Test Point 1	0.15	0.06	-42	-27
Test Point 2	0.15	0.06	-43	-28

Interharmonics: dual-tone	Test descriptions		
	Test point 1	Test point 2	Test point 3
Amplitude (% of fundamental)	5	10	1
Frequency (Hz)	75	375	2475

Multi tone	Test descriptions
Harmonics	Test point 1
	Harmonics at 1 % of the fundamental from the 2nd to the 50th order
Interharmonics	Test point 2
	1 % of the fundamental at 7 Hz, 149 Hz, 951 Hz, 2048 Hz

2. **nearly the same error** for a given f_n with adequate current input



Tests	i) FD	ii) AD	iii) (I)H	iv) AM	v) PM	vi) OT

2. Measurement under PQ phenomena (3)

Experimental results - Amplitude and Phase Modulations

$\varepsilon_i(f_0)$ and $\delta_i(f_0)$ were almost identical

Table 7: Ratio and phase errors at 50 Hz of the inductive CT and the electronic CT with the nominal burden by amplitude and phase modulated signals ($I_0 = I_{Pr,X}$)..

	Modulation parameters	Inductive CT - Cl. 0.2S (400 A - 1 A -5 VA)		Electronic CT - LEM 100 (100 A - 0.1 A - 10 Ω)	
		$\varepsilon_i(f_0)$ in %	$\delta_i(f_0)$ in crad	$\varepsilon_i(f_0)$ in µA/A	$\delta_i(f_0)$ in µrad
Amplitude Modulation	10 % / 2 Hz	0.15	0.05	-42	-27
	10 % / 5 Hz	0.15	0.05	-42	-27
Phase Modulation	10 % of 1 rad / 2 Hz	0.15	0.06	-42	-27
	10 % of 1 rad / 5 Hz	0.15	0.06	-42	-28

Experimental results- Oscillatory Transient

CT #1

CT #3

$\varepsilon_i(f_0)$ and $\delta_i(f_0)$ were almost identical

Table 8: Ratio and phase errors at 50 Hz of the inductive CT and the electronic CT with the nominal burden by damped oscillation signals ($I_0 = I_{Pr,X}$)..

Oscillatory Transient	Inductive CT - Cl. 0.2S (400 A - 1 A -5 VA)		Electronic CT - LEM 100 (100 A - 0.1 A - 10 Ω)	
	$\varepsilon_i(f_0)$ in %	$\delta_i(f_0)$ in crad	$\varepsilon_i(f_0)$ in µA/A	$\delta_i(f_0)$ in µrad
500 Hz, 600 µs	0.15	0.06	-41	-27
1 kHz, 600 µs	0.15	0.06	-40	-28
2 kHz, 600 µs	0.15	0.06	-41	-28
5 kHz, 600 µs	0.15	0.06	-42	-27

Tests	i) FD	ii) AD	iii) (I)H	iv) AM	v) PM	vi) OT

Agenda

1. Reference system for current sensors
2. Measurement under Power Quality (PQ) phenomena
3. Measurement uncertainties
4. Conclusion and Outlook

Measurement methods and test procedures for assessing accuracy of instrument transformers for power quality measurements

Short Name: IT4PQ, Project Number: 19NRM05

"This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme."

3. Measurement uncertainties

For $\varepsilon_i(f_n)$ and $\delta_i(f_n)$ – only for single tone up to 9 kHz (BW2: 20kHz, new 61869-1)

$$u_X = \sqrt{u_{MSE}{}^2 + u_{MF}{}^2 + (u_{Zb,X}{}^2 + u_N{}^2 + u_{Zb,N}{}^2 + u_{MS}{}^2)}$$ in ppm and µrad

- Uncertainty (k = 2) of the reference system

at 50 Hz: $\pm 2\cdot10^{-5}$ for the ratio errors, $\pm1\cdot10^{-5}$ for the phase errors

up to 9 kHz: $\pm 1\cdot10^{-4}$ for the ratio errors, $\pm4\cdot10^{-4}$ for the phase errors

- Uncertainty (k = 2) of CT #1 to #3

at 50 Hz: $\pm 2\cdot10^{-5}$ for the ratio and phase errors

up to 9 kHz: $\pm3\cdot10^{-4}$ for the ratio errors, $\pm6\cdot10^{-4}$ for the phase errors

- Uncertainty (k = 2) of RC #4

at 50 Hz: $\pm6\cdot10^{-4}$ for the ratio errors, $\pm1\cdot10^{-4}$ for the phase errors

up to 9 kHz: $\pm6\cdot10^{-4}$ for the ratio and phase errors

u_{MSE} :measured values (type A)
u_{MF} :magnetic field influence between N and X
$u_{Zb,X}$:burden for X
u_N :the reference CT
$u_{Zb,N}$:burden for N
u_{MS} :the measuring system

TBD: uncertainty under PQ test waveforms

Agenda

1. Reference system for current sensors
2. Measurement under Power Quality (PQ) phenomena
3. Measurement uncertainties
4. Conclusion and Outlook

Measurement methods and test procedures for assessing accuracy of instrument transformers for power quality measurements

Short Name: IT4PQ, Project Number: 19NRM05

"This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme."

4. Conclusion and Outlook

Conclusion

- Reference system for CT (type independent) fully completed
- Uncertainty (*k* = 2) of the reference system (well below 10^{-3} up to 9 kHz, single tone):
  - at 50 Hz: $\pm 2 \cdot 10^{-5}$ for the ratio errors, $\pm 1 \cdot 10^{-5}$ for the phase errors
  - up to 9 kHz: $\pm 1 \cdot 10^{-4}$ for the ratio errors, $\pm 4 \cdot 10^{-4}$ for the phase errors
- Uncertainties of the measuring system with PQ test waveforms are underway
- errors at the fundamental of all CT types were almost identical with proposed PQ phenomena

Prospective work

- Validation of program integrated with PQ algorithms (uncertainty)
- Calibrations of the SAMU/MU under PQ phenomena; measurement uncertainties
- Comparison within IT4PQ ongoing

(Abbreviation (Abb.)		i)	ii)	iii)	iv)	v)	vi)	vii)
Performance Index	Quantity to Measure	Frequency deviation	Amplitude deviation	Harmonics and Interharmonics	Amplitude modulation	Phase modulation	Frequency modulation	Oscillatory Transient
$\varepsilon(f_0)$ & $\delta(f_0)$	Ratio and Phase	X	X	X	X	X	X	X
$\varepsilon(f_n)$ & $\delta(f_n)$				X				
Total frequency response error	Amplitude		to be Validated					
Composite error (Total Vector Error)	Combination of amplitude and phase				to be Validated	to be Validated	to be Validated	
Error peak magnitude	Peak magnitude							Validated in f domain
Time shift error	Time shift							
Decay time error	Time shift							

Thanks for your attention !

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

Enrico Mohns and Yeying Chen
working group 2.32 " Time-synchronized Measuring Systems and Sensors “

Telefon: 0531 592-2354
E-Mail: yeying.chen@ptb.de
www.ptb.de

Characterisation by using active LP Filter (12kHz)

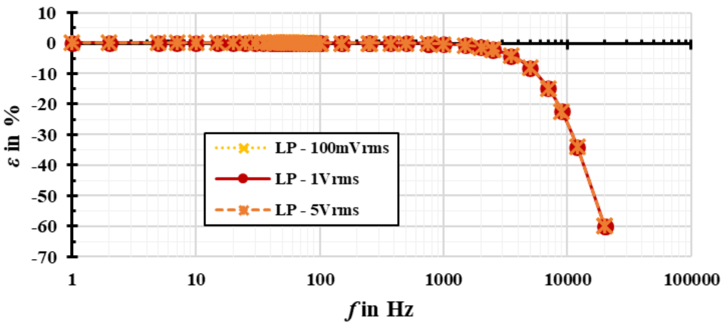
2-channel precision ratio measuring system – uncertainties under PQ

- $|U|(f = 50\text{ Hz})$ under various proposed PQ phenomena: ± 10 x 10^{-6}

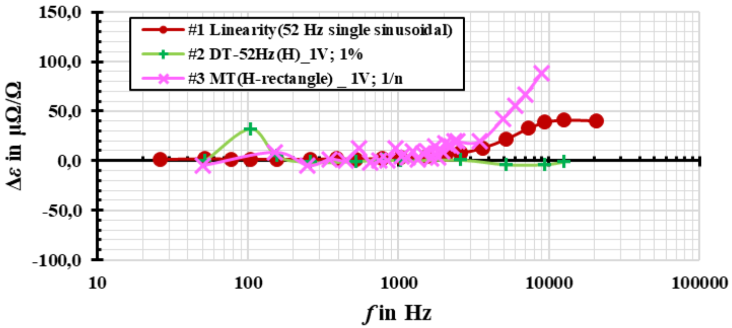
Table 2: The standard uncertainties of the measuring system by 5t0 Hz with input voltage of 1 V under various PQ phenomena

	Frequency deviation	Harmonics / Interharmonics	Amplitude and Phase Modulation	Transient
$\varepsilon(f_0)$ in µV/V	-3	-3	-4	-5
$\delta(f_0)$ in µrad	-3	-5	-4	-4

- $|U|(f < 9\text{ kHz})$ for multi- and dual-tone signals are below ± 200 µV/V and ± 300 µrad (conservative)



a) Frequency response and linearity of the LP filter for the ratio errors.



b) The wideband uncertainties of the measuring system for the ratio errors obtained by using the LP filter.

(#1 represents the result differences of the frequency response given by single-tone inputs of 100 mV, 1 V, and 5 V. #2 represents the results given by dual-tone harmonics: 1 V of the fundamental signal and 1 % of the harmonic signal. #3 represents the results given by multi-tone harmonics: 1 V of the fundamental signal and 1 / n of the nth harmonic signals.)

Acknowledgement

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

"The project 19NRM0 IT4PQ has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme."

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA · CMI CZECH METROLOGY INSTITUTE · LNE · PTB Messen · Forschen · Wissen · TÜBİTAK · VSL · RSE · Università degli Studi della Campania Luigi Vanvitelli · TECHNISCHE UNIVERSITÄT DRESDEN

IT4PQ Instrument Transformers for Power Quality

Dr.-Ing. Enrico Mohns

Mr. Sören de Rose

Mr. Micheal Seckelmann

Mr. Malte Liske

Mr. Räther Peter

Mr. Alexander Dubowik

Technische Universität Braunschweig

B-IGSM Braunschweig International Graduate School of Metrology