Final Report of comparison

Project EURAMET.EM-S34

Supplementary comparison

"Traceability in high voltage capacitance and dissipation factor measurements"

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This report is made up of 19 pages and two annex of 12 and 14 pages.

1 Introduction

Capacitance and loss dissipation factor (tan δ) are relevant parameters when testing high voltage equipment and also to assess condition of electrical insulation. It is important to ensure the accuracy of measurements especially when applying high voltage.

Measurement of capacitance and tan δ constitutes an important area in high voltage testing and calibration laboratories, as well as manufacturer laboratories. The traceability of such measurements is underpinned by activity of National Metrology Institutes (NMIs) and Designated Institutes (DI). Then, it is key to check metrological capabilities of NMIs and DIs by using specifically developed mechanisms such us international comparison projects which include supplementary comparisons.

This comparison was proposed in order to check the capabilities of the participating institutes in the area of capacitance and loss dissipation factor.

Six national metrology institutes and/or designated institutes took part in this comparison project, all of them from EURAMET. Coordination of the comparison was carried out by the "*Laboratorio Central Oficial de Electrotecnia*" (LCOE) of the "*Fundación para el Fomento de la Innovación Industrial*" (FFII) from Spain as pilot laboratory. The travelling standards were provided by FFII-LCOE and the Swedish National Testing and Research Institute, SP.

A set of Reference Travelling Capacitors (TRCs) circulated among the participants that measured the capacitance and tan δ parameters of the travelling standards by using their own measuring systems. All the participants were asked to follow their usual measurement procedures corresponding to their best measurement capabilities.

The measurement period of this comparison started in March 2 010 and ended in May 2 013. Analysis of results called for additional measurements on the features of TRMS up to April 2016. Some draft reports were discussed before issuing this final report B. Previous draft reports were presented in May 2015 and January 2016.

2 Participants

The participants and their affiliation, the six institutes involved, are listed in Table 1 in order of the TRMS circulation:

R. Martín / T. García	FFII - LCOE, *Fundación para el Fomento de la Innovación Industrial – Laboratorio Central Oficial de Electrotecnia*, Madrid, Spain
I.Blanc / M. Agazar	LNE, *Laboratoire National de métrologie et d'Essais*, Trappes, France
J. Hällström / E. Suomalainen	MIKES, Centre for Metrology and Accreditation, Helsinki, Finland
Anders Bergman/ Allan Bergman/Gunnar Eklund	SP, Technical Research Institute of Sweden, Borås, Sweden
A. Merev	TÜBITAK UME, *TÜBITAK Ulusal Metroloji Enstitüsü*, Gebze/Kocaeli, Turkey
H. Seifert	PTB, *Physikalisch-Technische Bundesanstalt*, Braunschweig, Germany

Table 1. List of comparison participants.

3 Equipment

3.1 Travelling standards

General requirements

The travelling standard consisted of a set of four reference capacitors (TRC) with fixed input and grounding leads and the corresponding connection cables.

Description of the TRMS:

Note: Annex I, "*TRMS's Photos*", of the comparison's technical protocol included pictures of the TRC as well as some setup details.

System 1:

Capacitor: Manufacturer: TETTEX
Type: 3370/100/200
LCOE reference: III-2-DT09-001
Nominal capacitance: 100 pF
Nominal voltage: 200 kV

System 2:

Capacitor: Manufacturer: GenRad
Type: ---
Nominal capacitance: 100 pF
Nominal voltage: 700 V

System 3:

Capacitor: Manufacturer: SP
Type: ---
LCOE reference: III-2-DT09-009
Nominal capacitance: 500 nF
Nominal voltage: 10 V

System 4:

Capacitor: Manufacturer: SP
Type: ---
LCOE reference: III-2-DT09-010
Nominal capacitance: 5 000 nF
Nominal voltage: 10 V

3.2 Reference measuring systems of participants

According to the reports provided each participating institute carried out the comparison measurements using the following devices:

FFII-LCOE – Spain.

- High voltage measurements:
  - High precision C, L and tan δ measuring bridge, TETTEX, type CT 2840, nº 176167.

- Low voltage measurements:
  - Capacitance bridge GENERAL RADIO, type 1615 A, S/N: 055 001.
  - LCR meter QUADTECH, type 1693, S/N: 7 496 590.

LNE – France

- Low voltage measurements:
  - Capacitance bridge: Andeen Hangerling, type 2700 A, S/N 00061.
  - Low voltage capacitor reference: Andeen Hangerling, type 11A, 100 pF, S/N 01268.
  - Low voltage capacitor reference 1-1111 µF, LCIE, id 1019266

- High voltage measurements:
  - Current comparator bridge: Tettex, type 2809, S/N 138050
  - High voltage capacitor reference: High Volt, type MCP300, 100 pF, S/N 881757.

MIKES – Finland

- Measurements with 53 Hz and 50 Hz frequency:
  - Current comparator bridge: Tettex, type 2809.
  - Standard capacitor: Tettex, 100 pF, 2 kV, type 3320.
  - Standard capacitor: Tettex, 1 nF, 2 kV, type 3320.
  - Standard capacitor: Tettex, 10 nF, 2 kV, type 3320.
  - Standard capacitor: Micafil, 100 pF, 200 kV, type PG1.

- Measurements with 1 kHz frequency, bridge method:
  - Capacitance bridge: Andeen Haagerling, type 2500 A.
  - Capacitance reference: Andeen Haagerling, AH11A 1192, 100 pF, code MIKES000129.
  - Capacitance reference: Genrad, 1404-A, 1 nF, code MIKES000138.
  - Capacitance reference: Genrad, 1409-L, 10 nF, code MIKES000136.
  - Capacitance reference: Genrad, 1409-T, 100 nF, code MIKES000137.
  - Capacitance reference: Quadtech, 1409-Y, 1 µF, code MIKES000139.

- Measurements with 1 kHz frequency, two DVM-method:
  - Sampling voltmeters: Agilent Technologies, type 3458 A.
  - Reference current shunt: 2 Ω, code MIKES000026.

SP – Sweden

- Measurements with power frequency (SP method 2903):
  - Manual current comparator bridge: Guildline, type 9910, SP ref. 602538.
  - Phase-sensitive null detector to detect bridge balance: Stanford Research SR850, SP ref. 503041

  - Low voltage capacitance reference: set of Genrad, GR 1404, 100 pF – 10 nF, SP ref. 900107.
  - High voltage capacitance reference: Haefely, NK300, 50 pF, SP ref. 501990.

- Measurements at 1 kHz, low voltage
  - 100 pF standard Andeen-Hagerling 11A, s/n 1114
  - 100 pF standard General Radio 1404-B, s/n 1382
  - 100 nF standard Sullivan mica, s/n 52217
  - 1000 nF standard Sullivan mica, s/n 51802
  - Capacitance bridge SP, SP ref. 602666
  - Capacitance bridge, Andeen-Hagerling AH2700A, s/n 00700326
  - LCR-meter Agilent E4980A, s/n E4980A-ATO-53425
  - Decade capacitor General Radio 1413, s/n 940

TÜBITAK UME – Turkey

- Low voltage measurements:
  - Capacitance measurement bridge: Andeen-Hangerling, type 2700A, TÜBİTAK ref : G1KA0027 sn: 000700166
  - Capacitance comparison bridge: UME, this is a homemade system and there is no serial number
  - Low voltage capacitance reference: Genrad, 1404A, 1000 pF, TÜBİTAK ref : G1KA0027 , sn: 3041335177
  - Low voltage capacitance reference: Agilent Technologies, 16380, 10 nF and 100 nF, G1KA0029, G1KA0030, sn :2519J00657.

- High voltage measurements:
  - Capacitance measurement bridge: LDIC, type LDV-5, TÜBITAK ref. UME-G1YG-0154, serial number 11743222.
  - Capacitance reference: High Volt, type MCP200, 100 Pf – 200 kV, TÜBITAK ref. UME-G1KA-0009, serial number 884675.

PTB – Germany

- Measurements with 1 kHz frequency, bridge method:
  - Capacitance bridge: Andeen Haagerling, type 2500 A, nr. 00761.
  - Low voltage capacitance reference: Genrad, 1404-B, nr. 2878.

- Measurements with 50 Hz frequency, bridge method:
  - Current comparator bridge (H.V.): PTB - 1985, nr. 1.
  - Standard capacitor (L.V.): Genrad, 1404-B, nr. 2878.
  - Standard capacitor (H.V.): H&B CLP 250, nr. 40570.

3.3 Traceability

Each national metrology institute carried out the comparison measurements using their own standards.

Information provided about traceability for high voltage measurements is the following:

- LCOE: internal and CEM.
- LNE: internal.
- MIKES: internal.
- SP: internal.
- TÜBITAK UME: internal.
- PTB: internal.

4 Organization of the comparison

The travelling equipment was transported during the comparison inside robust containers made of metal, wood and styrofoam. As a result no damage of the TRCs occurred during the comparison measurements and it was not necessary to transport the standards personally.

The final time schedule of the comparison is shown in Table 2.

Laboratory / Place of measurement	**Measurement month**
FFII-LCOE I / Madrid, Spain	March, 2 010
LNE / Trappes, France	July - August, 2 010
MIKES / Helsinki, Finland	August - September, 2 010
SP / Boras, Sweden	July - August, 2 011
TÜBITAK UME / Gebze/Kocaeli, Turkey	November, 2 011 - May, 2 012
PTB / Braunschweig, Germany	October 2 012 - April, 2 013
LCOE / Madrid, Spain (TRC Check)	May, 2 012 and September 2013
LCOE / Madrid, Spain (TRC temperature dependence)	July, 2 014
LCOE / Madrid, Spain (long term drift behaviour of system 1)	April, 2016

Table 2. Final comparison schedule.

The initial comparison schedule suffered several delays on account of different issues over the measurement stage. Additionally the schedule of this comparison was affected by the comparison project reference EURAMET.EM-S33 which ran in parallel sharing part of the travelling standards. As a result of that, several delays related to measurements of EURAMET.EM-S33 project ended up affecting this comparison.

Additionally, during the EURAMET's high voltage experts meeting held in September 2 011, the German institute PTB requested to take part in this comparison project so that this institute was included among the participants. PTB was due for comparison measurements in November 2 011 however they failed to carry out the measurements on account of internal planning issues and characterization of the standards they had to use on this project. Then the TRCs ended up in Turkey in order TÜBITAK UME could do the comparison measurements. PTB managed the ATA carnet required to get the system into Turkey.

The comparison measurements at TÜBITAK UME took also much longer than expected because of lack of qualified personnel due to unexpected on-site works plus the fact that the head of the high voltage service was in Finland to participate in work related to the development of the ultra-high voltage DC divider in the frame of the EMRP ENG07. That delay was related to EURAMET.EM-S33 comparison project measurements. Several attempts were made in order to bring forward some remaining measurements but it was not possible in the end.

The TRMS was shipped from Turkey to Spain where FFII-LCOE checked it. When PTB was ready to do the comparison measurements the travelling standards were shipped again to Germany, where measurements were finally carried out.

At the end of April 2 013 the TRMS arrived to LCOE in Madrid where a new set of checking measurements was performed in September.

In order to correct the influence of the different temperature conditions of participants, additional measurements of capacitance coefficient of TRMS were performed at LCOE during 2014.

After referring the capacitance measurements to 23 ºC some important differences between participant measurements for system 1 still persist, this could be explained due to some long term drift of 200 kV capacitor, due perhaps to some small gas leak. Previous measurements at LCOE could not detect this drift due to large uncertainty, but taking into account that intercomparison lasted for more than three years and that measurement uncertainty of some of participants is very small, this effect should not be neglected. For this reason, long term drift was evaluated and confirmed, repeating low voltage measurements with lower uncertainty at LCOE in April 2016. Finally a new reference value of system 1 was evaluated taking into account this long term drift and the measurement date of each participant.

5 Comparison measurements

5.1 General

Capacitance and loss dissipation factor of each travelling reference capacitor described in clause 3.1 above was proposed on this comparison project. The participating laboratories were asked to follow their usual measurement procedures to reach their best measurement capabilities with respect to the allowed time frame for the comparison.

Ambient temperature of 23°C ± 2°C during the comparison measurements was recommended in order to avoid the uncertainty source related to temperature dependence of the travelling standards.

All participants were asked to provide their results with the associated uncertainty of measurement, a comprehensive uncertainty budget at the level of one standard uncertainty and information about the number of effective degrees of freedom. The uncertainty of measurement had to be estimated according to the ISO Guide to the Expression of Uncertainty in Measurement (GUM).

A different set of measurements was suggested depending on the travelling system considered.

5.2 System 1: voltage dependence from 1 kV to 200 kV

Determination of the relative change of capacitance and tangent δ of the System 1 at the following voltage levels:

lowest practical	50 kV	100 kV	150 kV	200 kV

Table 3. Comparison measurements: voltage dependence of System 1.

Measurement frequency: 50 Hz.

5.3 System 1: measurement of absolute value of capacitance and tan δ

Determination of the capacitance and tangent δ of the System 1 was proposed at the voltage levels of 0.7 V and /or 2 kV. These measurements had to be done at the frequencies of 53 Hz and 1 kHz according to the following table.

Frequency (Hz)	Voltage levels
53	0.7 kV or/and 2 kV
1 000	1 V to 10 V, determined by the low voltage bridge

Table 4. Comparison measurements: capacitance and tan δ of System 1.

5.4 System 2: measurement of absolute value of capacitance and tan δ

Determination of the capacitance and tangent δ of the System 2 was proposed at the frequencies and voltages shown in the following table:

Frequency (Hz)	Voltage levels
53	0.7 kV
1 000	1 V to 10 V, determined by the low voltage bridge

Table 5. Comparison measurements: capacitance and tan δ of System 2.

5.5 Systems 3 and 4: measurement of absolute value of capacitance and tan δ

Determination of the capacitance and tangent δ of the Systems 3 and 4 was proposed at the frequencies and voltages shown in the following table:

Frequency (Hz)	Voltage levels (V)		
50	1	3	10
1 000	1 V to 10 V, determined by the low voltage bridge		

Table 6. Comparison measurements: capacitance and tan δ of Systems 3 and 4.

6 Comparison results

6.1 General

The comparison results provided by the participants are shown in the following clauses. Every institute did not perform every set of measurements scheduled so that the number of participants changes depending on the part of the comparison considered.

Capacitance and loss dissipation factor are shown as reported by the participants, together with their measurement uncertainties (k = 1). Moreover, ambient temperatures during measurements are included so that it is possible to estimate their influence on compatibility and consistency of results.

Annex II of this report includes the graphical image of this comparison results so that it is possible to check consistency among the participants on the base of their measurements and standard uncertainties.

6.2 TRMS stability and temperature coefficient.

LCOE measured the TRMS twice, in May 2012 and in September 2013. Taking into account the measuring uncertainty of LCOE, the TRMS systems 2, 3 and 4 are considered very stable because the relative change between measurements is very small in comparison with the measuring uncertainty.

Capacitor	Nominal	Measuring conditions		Relative change (ppm)	u(ppm)
System 2	100 pF	(23±1)ºC	10 V, 1 kHz	-20	50
System 3	500 nF	(23±1)ºC	10 V, 1 kHz	-14	57
System 4	5000 nF	(23±1)ºC	10 V, 1 kHz	-2	100

Table 7. Relative change between initial and final measurements and associated standard uncertainty.

LCOE measured capacitance of system 1 in May 2012 and in September 2013, but measurement uncertainty was too big to clearly detect a possible drift in a relatively short period. Taking into account that participant measurements suggest a possible linear drift of system 1 capacitance, due perhaps a small gas leak, additional low voltage capacitance measurements were repeated at LCOE in April 2016 with the minimum possible uncertainty. Results are summarized in table 8 and show important drift for system 1 capacitance.

Due to the fact that the comparison lasted for more than three years with quite small measurement uncertainty for some of participants, it is clear that the long term drift should be considered when determining CRV for system 1

Capacitor	Date	Measured value (pF)	Measuring conditions		Relative change (ppm)	u(ppm)
System 1	September 2013	100,044	(23±1)ºC	10 V, 1 kHz		60
	April 2016	100,0385	(23±1)ºC	10 V, 1 kHz	-55	16

Table 8. Relative change between initial and final measurements and associated standard uncertainty for system 1.

According to LCOE characterization in low voltage (10 V or 1 V, 1kHz) temperature coefficients, TC, of capacitor systems 1, 3 and 4 are summarized in table 9.

Temperature coefficient of system 2 is very small (2 ± 2) ppm /ºC according to manufacturer specifications. The actual temperature coefficient was measured by SP in June 2015, resulting a value of (1,8 ± 0,8) ppm/ºC.

Capacitor	Nominal	Temperature range	TC (ppm/ºC)	u(ppm/ºC)
System 1	100 pF	20,5ºC ... 23ºC	14,2	3
		23ºC ... 25,5ºC	17,3	3
System 2	100 pF	-20ºC … 65ºC	1,8	0,8
System 3	500 nF	20,5ºC …. 23ºC	2,7	1
		23ºC …. 25ºC	3,3	1
System 4	5000 nF	20,5ºC …. 23ºC	6,9	2
		23ºC …. 25ºC	4,9	2

Table 9. Temperature coefficients of capacitor systems.

6.3 Results of voltage dependence of System 1 from 1 kV to 200 kV

Results of voltage dependence study performed by the participating institutes are summarized in tables 10 and 11. Voltage dependence is referred to the value measured at the lowest voltage level.

Table 10 includes voltage dependence of the travelling System 1 regarding capacitance measurements whilst table 11 shows the voltage dependence to tan δ values.

Voltage level (kV)	Change of **capacitance** from lowest practical voltage									
	Participating Institute									
	LNE		MIKES		SP		PTB		TÜBITAK	
	ΔC (pF)	u (ppm)	ΔC (pF)	u (ppm)	ΔC (pF)	u (ppm)	ΔC (pF)	u (ppm)	ΔC (pF)	u (ppm)
0,005	0	-	-	-	-	-	-	-	-	-
1	-	-	-	-	-	-	0	-	0	-
10	-	-	0	-	0	-	-	-	-	-
50	-0.0000	25	0.0004	2	0.0005	5	0.0005	3	0.0186	203
100	0.0016	25	0.0020	3	0.0019	5	0.0021	3	0.0129	202
150	0.0040	25	0.0046	4	0.0045	5	0.0047	3	0.0234	203
200	0.0076	35	0.0083	5	0.0082	5	0.0083	3	0.0244	203

Note: Missing participants did not perform the measurements.

Table 10. Comparison results: Voltage dependence System 1. Capacitance measurements with standard uncertainty reported by participants.

Voltage level (kV)	Change of **tan δ** from lowest practical voltage							
	Participating Institute							
	LNE		MIKES		SP		TÜBITAK	
	Δtan δ (. 10^{-6})	u (. 10^{-6})	Δtan δ (. 10^{-6})	u (. 10^{-6})	Δtan δ (. 10^{-6})	u (. 10^{-6})	Δtan δ (. 10^{-6})	u (. 10^{-6})
0,005	0	-	-	-	-	-	-	-
1	-	-	-	-	-	-	0	-
10	-	-	0	-	0	-	-	-
50	-6	20	-1	2	2	4	4	20
100	-6	20	-0	2	2	4	-0	20
150	-6	20	0	2	2	4	5	20
200	-6	20	12	10	4	4	4	20

Note: Missing participants did not perform the measurements.

Table 11. Comparison results: Voltage dependence System 1. Tan δ measurements with standard uncertainty reported by participants.

Next ambient temperature measurement conditions of the room reported by the participants are collected in table 12.

Ambient temperature conditions during measurements				
Participating Institute				
LNE	MIKES	SP	PTB	TÜBITAK
23 °C ± 1 °C	21.0 °C ± 0.2 °C	23 °C ± 1 °C	21.9 °C ± 0.05 °C	23 °C ± 1 °C

Table 12. Comparison results: Voltage dependence System 1. Ambient temperature conditions

Concerning the measurement temperatures, the participating institutes had apparently not the same understanding of the information to be reported. The objective of the intercomparison was to maintain ambient temperature as close as possible to 23 °C in such a way those measurements could be easily compared. Nevertheless this objective was not clearly identified in the technical protocol because the condition was only to keep ambient temperature on the value 23°C ± 2°C. In consequence some participants reported ambient temperature conditions of the HV laboratory (typically 23 ºC ± 1ºC) and others reported the exact temperature of the laboratory and its change (for instance 21,9 ºC ± 0,05ºC).

6.4 Results of measurement of absolute value of capacitance and tan δ, System 1

Tables 13 and 14 show results of capacitance and tan δ values reported by the participants for the travelling System 1, respectively, as well as the corresponding uncertainties. Voltage and frequency measurement parameters used by each institute are also indicated.

Frequency / Voltage	**Capacitance** of **System 1**									
	Participating Institute									
	LCOE		MIKES		SP		PTB		TÜBITAK	
	C (pF)	u (ppm)	C (pF)	u (ppm)	C (pF)	u (ppm)	C (pF)	u (ppm)	C (pF)	u (ppm)
50 Hz / 0.7 kV	-	-	-	-	100.0441	4	100.03992	2.5	100.0360	200
53 Hz / 2 kV	-	-	100.0430	11	-	-	100.03992	2.5	100.0410	200
1 kHz / ≤ 10 V	100.044	60	-	-	100.04344	17	-	-	-	-
1 kHz / 0.7 kV	-	-	-	-	-	-	100.03992	1.4	-	-

Note: Missing participants did not perform the measurements.

Table 13. Comparison results: Capacitance measurement of System 1 with standard uncertainty reported by participants.

Frequency / Voltage	**Loss dissipation factor** of **System 1**									
	Participating Institute									
	LCOE		MIKES		SP		PTB		TÜBITAK	
	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})
50 Hz / 0.7 kV	-	-	-	-	5	3	-	-	3	20
53 Hz / 2 kV	-	-	9	3	-	-	-	-	2	20
1 kHz / ≤ 10 V	7	49	-	-	2	1	-	-	-	-
1 kHz / 0.7 kV	-	-	-	-	-	-	-	-	-	-

Note: Missing participants did not perform the measurements.

Table 14. Comparison results: tan δ measurement of System 1 with standard uncertainty reported by participants.

Ambient temperature measurement conditions reported by the participants are shown in table 15.

Ambient temperature conditions during measurements				
Participating Institute				
LCOE	MIKES	SP	PTB	TÜBITAK
23 °C ± 1 °C	21.0 °C ± 0.2 °C	23 °C ± 1 °C	21.9 °C ± 0.3 °C	23 °C ± 1 °C

Table 15. Comparison results: Capacitance and tan δ of System 1. Ambient temperature conditions.

In order to better compare measurements, all results should be referred to 23 ºC, using for instance the temperature coefficient of the capacitor.

6.5 Results of measurement of absolute value of capacitance and tan δ, System 2

Tables 16 and 17 show results of capacitance and tan δ values reported by the participants for the travelling System 2, respectively, as well as the corresponding uncertainties. Voltage and frequency measurement parameters used by each institute are also indicated.

Frequency / Voltage	**Capacitance** of **System 2**									
	Participating Institute									
	LCOE		LNE		MIKES		SP		TÜBITAK	
	C (pF)	u (ppm)	C (pF)	u (ppm)	C (pF)	u (ppm)	C (pF)	u (ppm)	C (pF)	u (ppm)
50-53 Hz / ≤ 10 V	-	-	100.09895	2.6	-	-	-	-	100.09877	9
53 Hz / 700 V	-	-	-	-	100.0986	2.3	100.0987	4	-	-
1 kHz / ≤ 10 V	100.098	50	100.09881	1.4	100.09885	1.1	100.09886	1.5	100.09871	3.8

Note: Missing participants did not perform the measurements.

Table 16. Comparison results: Capacitance measurement of System 2 with standard uncertainty reported by participants.

Frequency / Voltage	**Loss dissipation factor** of **System 2**									
	Participating Institute									
	LCOE		LNE		MIKES		SP		TÜBITAK	
	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})
50-53 Hz / ≤ 10 V	-	-	1	27	-	-	-	-	0	7
53 Hz / 700 V	-	-	-	-	7	3	2	3	-	-
1 kHz / ≤ 10 V	9	24	1	27	-	-	1.8	0.6	1	1.7

Note: Missing participants did not perform the measurements.

Table 17. Comparison results: tan δ measurement of System 2 with standard uncertainty reported by participants.

Ambient temperature measurement conditions reported by the participants are shown in table 18.

Ambient temperature conditions during measurements				
Participating Institute				
LCOE	LNE	MIKES	SP	TÜBITAK
23 °C ± 1 °C	23 °C ± 0,5°C	21.6 °C ± 0.7 °C	23 °C ± 1 °C	23 °C ± 1 °C

Table 18. Comparison results: Capacitance and tan δ of System 2. Ambient temperature conditions.

In order to compare measurements, all results should be reported to 23°C, even if temperature coefficient for capacitance system 2 is very small (according to manufacturer lower than 2 ppm/°C).

6.6 Results of measurement of absolute value of capacitance and tan δ, System 3

Tables 19 and 20 show results of capacitance and tan δ values reported by the participants for the travelling System 3, respectively, as well as the corresponding uncertainties. Voltage and frequency measurement parameters used by each institute are also indicated.

Frequency / Voltage	**Capacitance** of **System 3**											
	Participating Institute											
	LCOE		LNE		MIKES		SP		PTB		TÜBITAK	
	C (nF)	u (ppm)	C (nF)	u (ppm)	C (nF)	u (ppm)	C (nF)	u (ppm)	C (nF)	u (ppm)	C (nF)	u (ppm)
50-53 Hz / 1 V	496.93	330	-	-	496.976	26	496.9604	9	-	-	496.953	67
50-53 Hz / 3 V	-	-	-	-	496.967	22	496.9614	9	-	-	496.953	67
50-53 Hz / 8 V	-	-	496.957	10.5	496.966	16	496.9622	9	-	-	495.953	67
1 kHz / ≤ 10 V	496.863	57	496.866	8	496.861	37	496.870	12	496.872	42	496.870	44

Table 19. Comparison results: Capacitance measurement of System 3 with standard uncertainty reported by participants.

Frequency / Voltage	**Loss dissipation factor** of **System 3**											
	Participating Institute											
	LCOE		LNE		MIKES		SP		PTB		TÜBITAK	
	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})
50-53 Hz / 1 V	100	36	-	-	90	5	97	3	-	-	87	103
50-53 Hz / 3 V	-	-	-	-	93	5	97	3	-	-	87	103
50-53 Hz / 8 V	-	-	110	27	94	4	97	3	-	-	87	103
1 kHz / ≤ 10 V	170	60	130	27	167	80	118	33	-	-	227	105

Table 20. Comparison results: tan δ measurement of System 3 with standard uncertainty reported by participants.

Ambient temperature measurement conditions reported by the participants are shown in table 21.

Ambient temperature conditions during measurements					
Participating Institute					
LCOE	LNE	MIKES	SP	PTB	TÜBITAK
23 °C ± 1 °C	23 °C ± 0,5 °C	21.0 °C ± 0.2 °C	23 °C ± 1 °C	21.9 °C ± 0.3 °C	23 °C ± 1 °C

Table 21. Comparison results: Capacitance and tan δ of System 3. Ambient temperature conditions.

In order to better compare measurements, all results should be referred to 23 ºC, using for instance the temperature coefficient of the capacitor.

6.7 Results of measurement of absolute value of capacitance and tan δ, System 4

Tables 22 and 23 show results of capacitance and tan δ values reported by the participants for the travelling System 4, respectively, as well as the corresponding uncertainties. Voltage and frequency measurement parameters used by each institute are also indicated.

Frequency / Voltage	**Capacitance** of **System 4**									
	Participating Institute									
	LCOE		LNE		MIKES		SP		TÜBITAK	
	C (nF)	u (ppm)	C (nF)	u (ppm)	C (nF)	u (ppm)	C (nF)	u (ppm)	C (nF)	u (ppm)
100 Hz / ≤ 10 V	-	-	4998.9	20	-	-	-	-	-	-
50-53 Hz / 1 V	4999.8	330	-	-	4999.930	29	4999.759	9	4999.80	77
50-53 Hz / 3 V	-	-	-	-	4999.870	25	4999.767	9	4999.80	77
50-53 Hz / 8-10 V	-	-	-	-	4999.860	20	4999.777	9	4999.80	77
1 kHz / 0.7-1 V	4999.7	180	-	-	4999.050	36	4999.11	36	4999.95	52
1 kHz / ≤ 10 V	4998.91	100	4998.4	15	-	-	-	-	4999.95	52

Note: Missing participants did not perform the measurements.

Table 22. Comparison results: Capacitance measurement of System 4 with standard uncertainty reported by participants.

Frequency / Voltage	**Loss dissipation factor** of **System 4**									
	Participating Institute									
	LCOE		LNE		MIKES		SP		TÜBITAK	
	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})	tan δ (. 10^{-6})	u (. 10^{-6})
100 Hz / ≤ 10 V	-	-	130	27	-	-	-	-	-	-
50-53 Hz / 1 V	90	360	-	-	95	9	87	3	92	122
50-53 Hz / 3 V	-	-	-	-	100	6	87	3	92	122
50-53 Hz / 8-10 V	-	-	-	-	100	5	87	3	92	122
1 kHz / 0.7-1 V	340	160	-	-	394	140	119	255	459	129
1 kHz / ≤ 10 V	-	-	320	27	-	-	-	-	459	129

Note: Missing participants did not perform the measurements.

Table 23. Comparison results: tan δ measurement of System 4 with standard uncertainty reported by participants.

Ambient temperature measurement conditions reported by the participants are shown in table 24.

Ambient temperature conditions during measurements				
Participating Institute				
LCOE	LNE	MIKES	SP	TÜBITAK
23 °C ± 1 °C	23 °C ± 0,5 °C	21.0 °C ± 0.2 °C	23 °C ± 1 °C	23 °C ± 1 °C

Table 24. Comparison results: Capacitance and tan δ of System 4. Ambient temperature conditions.

In order to better compare measurements, all results should be referred to 23 ºC, using the temperature coefficient of the capacitors according to 6.2.

7 Analysis of comparison results

7.1 General

Analysis of comparison results has been performed using the weighted mean together with a consistency test based on classical statistics.

The followed procedure has been applied considering that the next three conditions are satisfied:

1. Each participant gives one result of capacitance, or tan δ which has good short term stability and a good stability during transportation too.
2. Measurements of different institutes are independent from each other. According to the information provided by the participating institutes, they all get their traceability by applying internal procedures and their own national standards so it is considered that there is no mutual dependence among the measurements of the comparison participants.
3. A Gaussian distribution can be assigned to the measurements by each laboratory (mean value equals the laboratory measurement and standard deviation equals the corresponding standard uncertainty).

On each type of measurement (capacitance, or tan δ), the comparison reference value, CRV, is considered as an estimation, y, of the measured according to the measurements provided by the participating laboratories.

This estimation, y, is determined as a weighted mean of the results provided where the weights are the inverse values of the squares of the associated standard uncertainties. However, this procedure cannot be applied in case of some of the measurements are not consistent with the others.

The number of participating laboratories, N, depends on the case considered (capacitance, or tan δ, voltage and frequency). It ranges from 3 to 6.

The input magnitudes to evaluate are:

- Change of capacitance (system 1) with voltage
- Change of tanδ (system 1) with voltage
- Capacitance of systems 1, 2, 3 and 4 (at 50-53 Hz and 1kHz)
- Tanδ of systems 1, 2, 3 and 4 (at 50-53 Hz and 1kHz)

Note 1: for measurements of change of capacitance and tanδ with voltage, standard uncertainty of each participant has been assumed equal to the reported uncertainty for 50kV, 100 kV, 150 kV or 200 kV measurements, because no information is provided about possible correlation with the initial measured value at the lowest practical level.

Note 2: measurements of capacitance systems at ambient temperature lower than 23ºC have been corrected to 23ºC. Consequently uncertainty has been enlarged taking into account the uncertainty of the correction due to the temperature coefficient. This correction is negligible for systems 3 and 4, and has little effect for capacitance systems 1 and 2.

The procedure is developed in the following steps:

a) Estimation of the CRV, y, as weighted means according to the following expression:

$$y = \frac{\sum_{i=1}^{N} \varepsilon_i u^{-2}(\varepsilon_i)}{\sum_{i=1}^{N} u^{-2}(\varepsilon_i)} \qquad (1)$$

b) Calculation of standard uncertainty of CRV, $u(y)$, according to the following expression:

$$u(y) = \frac{1}{\sqrt{\sum_{i=1}^{N} u^{-2}(\varepsilon_i)}} \qquad (2)$$

Compatibility with CRV

A chi-squared test has been applied to carry out an overall consistency check of the results obtained (i.e. if all results can be regarded as belonging to the same statistical ensemble). For each measurement point the observed chi-squared value χ^2_{obs} has been determined as:

$$\chi^2_{\mathrm{obs}} = \sum_{i=1}^{N} \frac{(\delta_{id} - \delta_R)^2}{u^2_{\mathrm{id}}} \qquad (3)$$

The degrees of freedom are $\nu = N - 1$, for N results.

The consistency check is considered failed if Pr{ $\chi^2(\nu) > \chi^2_{obs}$ }< 5%

where Pr denotes “probability of”.

If the chi-squared does not fail the determined CRV is deemed valid. When the chi-squared test fails, then the compatibility indexes $|d_i|$ are considered:

Degrees of equivalence of laboratory i, $i = 1, 2, ..., N$, with the corresponding estimated CRV is determined as the pair of values for the deviation from the estimation y and the uncertainty of this deviation [$\Delta\varepsilon_i$, $U(\Delta\varepsilon_i)$] according to the expressions:

$$\Delta\varepsilon_{\mathrm{i}} = \varepsilon_i - y \qquad (4)$$

$$U(\Delta\varepsilon_i) = 2 \cdot u(\Delta\varepsilon_i) \qquad (5)$$

Where $u(\Delta\varepsilon_i)$ is obtained applying the following expression:

$$u^2(\Delta\varepsilon_i) = u^2(\varepsilon_i) - u^2(y) \qquad (6)$$

Note 3: The factor 2 in expression (5) above indicates a coverage factor of 95 % corresponding to a Gaussian distribution function.

Note 4: Expression (6) establishes a difference of two variances as consequence of the mutual dependence (or correlation) between ε_i and CRV.

Compatibility index, d_i, is defined as the ratio between the difference from the reference value and the standard uncertainty:

$$d_i = \frac{\Delta\varepsilon_i}{u(\Delta\varepsilon_i)} = \frac{\varepsilon_i - y}{\sqrt{u^2(\varepsilon_i) - u^2(y)}} \qquad (7)$$

The compatibility index $|d_i|$ describes the deviation from the estimated CRV in relation to the calculated standard uncertainty of the deviation.

Assuming results ε_i follow a normal distribution and their standard uncertainty $u(\varepsilon_i)$ are properly estimated, indexes d_i would follow a normal distribution with zero mean value and variance one. Then the probability that $|d_i|$ (absolute value) is higher than 2 is approximately 5 % and so comparison results with $|d_i|$ higher than 2 (confidence level of 95 %) could be deemed non-compatible with the CRV.

Then, in each measurement point, where the corresponding chi-squared test fails the laboratory with larger compatibility index $|d_i|$ is excluded from the determination of the CRV and the whole process is repeated again (estimation of CRV and their uncertainties, chi-squared test and calculation of compatibility indexes). This procedure is followed as many times as needed until the chi-square test is successful.

The standard uncertainties of the differences corresponding to those laboratories whose results are not considered in the reference value calculation are obtained applying the following expression:

$$u^2(\Delta\varepsilon_i) = u^2(\varepsilon_i) + u^2(y) \qquad (8)$$

since now the values are not correlated.

7.2 Analysis of results for system 1 capacitance.

The general procedure defined in 7.1 for the determination of CRV should be slightly modified for the capacitance value of system 1, because its long term drift cannot be ignored.

For this purpose an objective function to be minimized is defined:

$$E_{min} = \sum_{i=1}^{N} \frac{(\varepsilon_i - y^*)^2}{u^2(\varepsilon_i)} \qquad (9)$$

where, y^*, is the weighted reference straight line to be used as CRV. This line is defined as a function of the measurement date of the participants.

$$y^* = a + b \cdot t_i \qquad (10)$$

Through an iterative process values a, b, minimizing the objective function (9) are calculated. According to the measurement date of each laboratory the comparison reference value, CRV, and compatibility index, d_i, are calculated using (10) and (7) respectively. If any of the laboratories is excluded (when $|d_i|$ value is higher than 2) it will be necessary to repeat the process again, minimizing the function (9) and calculating a new CRV.

7.3 Determination of CRV.

The comparison reference values, *CRV*, and compatibility index, d_i, are summarized in Annex I of this report.

8 Final remarks

Six EURAMET institutes participated in this international supplementary comparison of capacitance and loss dissipation factor up to 200 kV. The participants used their best measurement methods in order to achieve their best calibration capabilities.

The comparison reference values, *CRV*, and their uncertainties were calculated as weighted means according to the above mentioned formulae. For system 1 the long drift of the high voltage capacitor was taking into account in order to calculate the CRV.

In each measurement the consistency of the *CRV* was checked studying the difference of each provided result and the estimation of the comparison reference value, together with the standard uncertainties of those differences. Those results non consistent were not included in the calculation of the comparison *CRV*.

The differences from the *CRV* and their uncertainties together with the compatibility index, d_i, of each laboratory result are presented. There are significant differences among the uncertainties given by the participants and as a result of that the *CRV* are biased towards the institutes with lowest uncertainties.

The number of participants was quite small and some of the institutes did not perform all the measurements, therefore comparison reference values are based sometimes in the results of only 3 or 4 institutes. Very good agreement between institutes is obtained for high voltage capacitance measurements and for low or high voltage dissipation factor measurements. Only a few low voltage measurements of capacitance are not compatible.

Results of the comparison offer the chance to check the calibration and measurement capabilities of the participants in the field of capacitance and dissipation factor measurements, not only for low voltage, but especially for high voltage up to 200 kV.

ANNEX I

Determination of comparison reference values, *CRV*, and compatibility index, d_i.

Change of capacitance from lowest practical voltage to 50 kV

Laboratory	X_i (fF)	$u(x_i)$ (fF)	$1/u^2(x_i)$ (fF^{-2})	Weight (%)	x_0 (fF)	Δx_i(fF)	$u(\Delta x_i)$ (fF)	di	chi^2 test	Exclude
LCOE					0,44					
LNE	-0,01	2,5	0,160	0,40%	$u(x_0)$ (fF)	-0,45	2,5	-0,18	0,03	
MIKES	0,4	0,20	25,000	62,1%	0,16	-0,04	0,12	-0,30	0,09	
SP	0,5	0,50	4,000	9,9%		0,06	0,47	0,13	0,02	
PTB	0,5	0,30	11,111	27,6%		0,06	0,26	0,25	0,06	
TÜBITAK	18,6	20,3	0,002	0,01%		18,16	20,3	0,89	0,80	
				100,0%				χ^2_{obs}	1,00	
								N-1	4	
								Probability	91,0%	

Accepted

Change of capacitance from lowest practical voltage to 100 kV

Laboratory	X_i (fF)	$u(x_i)$ (fF)	$1/u^2(x_i)$ (fF^{-2})	Weight (%)	x_0 (fF)	Δx_i(fF)	$u(\Delta x_i)$ (fF)	di	chi^2 test	Exclude
LCOE					2,03					
LNE	1,6	2,5	0,160	0,61%	$u(x_0)$ (fF)	-0,43	2,5	-0,17	0,03	
MIKES	2,0	0,30	11,111	42,1%	0,19	-0,03	0,23	-0,11	0,01	
SP	1,9	0,50	4,000	15,2%		-0,13	0,46	-0,27	0,07	
PTB	2,1	0,30	11,111	42,1%		0,07	0,23	0,33	0,11	
TÜBITAK	12,9	20,2	0,002	0,01%		10,87	20,2	0,54	0,29	
				100,0%				χ^2_{obs}	0,51	
								N-1	4	
								Probability	97,2%	

Accepted

Change of capacitance from lowest practical voltage to 150 kV

Laboratory	X_i (fF)	$u(x_i)$ (fF)	$1/u^2(x_i)$ (fF^{-2})	Weight (%)	x_0 (fF)	Δx_i(fF)	$u(\Delta x_i)$ (fF)	di	chi^2 test	Exclude
LCOE					4,63					
LNE	4	2,5	0,160	0,74%	$u(x_0)$ (fF)	-0,63	2,5	-0,25	0,06	
MIKES	4,6	0,40	6,250	29,0%	0,22	-0,03	0,34	-0,09	0,01	
SP	4,5	0,50	4,000	18,6%		-0,13	0,45	-0,29	0,08	
PTB	4,7	0,30	11,111	51,6%		0,07	0,21	0,33	0,11	
TÜBITAK	23,4	20,3	0,002	0,01%		18,77	20,3	0,92	0,85	
				100,0%				χ^2_{obs}	1,12	
								N-1	4	
Accepted								Probability	89,1%	

Change of capacitance from lowest practical voltage to 200 kV

Laboratory	X_i (fF)	$u(x_i)$ (fF)	$1/u^2(x_i)$ (fF^{-2})	Weight (%)	x_0 (fF)	Δx_i(fF)	$u(\Delta x_i)$ (fF)	di	chi^2 test	Exclude
LCOE					8,28					
LNE	7,6	2,5	0,160	0,83%	$u(x_0)$ (fF)	-0,68	2,5	-0,27	0,07	
MIKES	8,3	0,50	4,000	20,8%	0,23	0,02	0,45	0,06	0,00	
SP	8,2	0,50	4,000	20,8%		-0,08	0,45	-0,17	0,03	
PTB	8,3	0,30	11,111	57,6%		0,02	0,20	0,13	0,02	
TÜBITAK	24,4	20,3	0,002	0,01%		16,12	20,3	0,79	0,63	
				100,0%				χ^2_{obs}	0,75	
								N-1	4	
Accepted								Probability	94,5%	

Change of tan δ from lowest practical voltage to 50 kV

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE					-0,41					
LNE	-6	20	0,003	0,79%	$u(x_0)$ (10^{-6})	-5,59	19,9	-0,28	0,08	
MIKES	-1	2,0	0,250	78,7%	1,77	-0,59	0,92	-0,64	0,41	
SP	2	4,0	0,063	19,7%		2,41	3,58	0,67	0,45	
PTB										
TÜBITAK	4	20	0,003	0,79%		4,41	19,9	0,22	0,05	
				100,0%				χ^2_{obs}	0,99	
								N-1	3	
Accepted								Probability	80,4%	

Change of tan δ from lowest practical voltage to 100 kV

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE					0,35					
LNE	-6	20	0,003	0,79%	$u(x_0)$ (10^{-6})	-6,35	19,9	-0,32	0,10	
MIKES	0	2,0	0,250	78,7%	1,77	-0,35	0,92	-0,38	0,14	
SP	2	4,0	0,063	19,7%		1,65	3,58	0,46	0,21	
PTB										
TÜBITAK	0	20	0,003	0,79%		-0,35	19,9	-0,02	0,00	
				100,0%				χ^2_{obs}	0,46	
								N-1	3	
Accepted								Probability	92,9%	

Change of tan δ from lowest practical voltage to 150 kV

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE					0,39					
LNE	-6	20	0,003	0,79%	$u(x_0)$ (10^{-6})	-6,39	19,9	-0,32	0,10	
MIKES	0	2,0	0,250	78,7%	1,77	-0,39	0,92	-0,42	0,18	
SP	2	4,0	0,063	19,7%		1,61	3,58	0,45	0,20	
PTB										
TÜBITAK	5	20	0,003	0,79%		4,61	19,9	0,23	0,05	
				100,0%				χ^2_{obs}	0,53	
								N-1	3	
								Probability	91,1%	

Accepted

Change of tan δ from lowest practical voltage to 200 kV

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE					4,71					
LNE	-6	20	0,003	3,23%	$u(x_0)$ (10^{-6})	-10,71	19,7	-0,54	0,30	
MIKES	12	10	0,010	12,9%	3,59	7,29	9,33	0,78	0,61	
SP	4	4,0	0,063	80,6%		-0,71	1,76	-0,40	0,16	
PTB										
TÜBITAK	4	20	0,003	3,23%		-0,71	19,7	-0,04	0,00	
				100,0%				χ^2_{obs}	1,07	
								N-1	3	
								Probability	78,4%	

Accepted

Capacitance system 1, f = 50 - 53 Hz, U ≤ 2 kV

TC (ppm/ºC)= 14,2 u(TC) = 3 ppm/ºC

Date	Lab	X_i (pF)	Temp ºC	X_i (pF)$_{corrected\ 23ºC}$	$u(x_i)$ (pF)	$u(x_{i\ corr\ 23ºC})$ (pF)	$1/u^2(x_i)$ (pF^{-2})	Weight (%)	x_0 (pF)	$u(x_0)$ (10^{-6})	Δx_i(pF)	$u(\Delta x_i)$ (pF)	di	chi^2 test	Exclude
	LCOE														
	LNE														
01/09/2010	MIKES	100,043	21	100,0458	0,0011	0,0013	636359	5,01%	100,04641	0,00028	-0,00056	0,0012	-0,46	0,21	
01/08/2011	SP	100,0441	23	100,0441	0,0004	0,0004	6244491	49,12%	100,04441	0,00028	-0,00031	0,0003	-1,07	1,14	
01/02/2013	PTB	100,03992	21,9	100,0415	0,0003	0,0004	5829468	45,86%	100,04111	0,00028	0,00037	0,0003	1,22	1,48	
15/02/2012	TÜBITAK	100,0385	23	100,0385	0,020	0,0200	2498	0,02%	100,04322	0,00028	-0,00472	0,0200	-0,24	0,06	
								100,0%					χ^2_{obs}	2,89	
													N-1	3	
													Probability	40,8%	

Accepted

Capacitance system 1, f = 1kHz, U ≤ 0.7 kV

TC (ppm/ºC)= 14,2 u(TC) = 3 ppm/ºC

Date	Lab	X_i (pF)	Temp ºC	X_i (pF)$_{corrected\ 23ºC}$	$u(x_i)$ (pF)	$u(x_{i\ corr\ 23ºC})$ (pF)	$1/u^2(x_i)$ (pF^{-2})	Weight (%)	x_0 (pF)	$u(x_0)$ (10^{-6})	Δx_i(pF)	$u(\Delta x_i)$ (pF)	di	chi^2 test	Exclude
01/09/2013	LCOE	100,044	23	100,0440	0,0060	0,0060	27753	0,33%	100,04095	0,00034	0,00305	0,0060	0,51	0,26	
22/04/2016	LCOE	100,0385	23	100,0385	0,0016	0,0016	390324	4,59%	100,03824	0,00034	0,00026	0,0016	0,17	0,03	
	LNE														
	MIKES														
01/08/2011	SP	100,04344	23	100,0434	0,0017	0,0017	345720	4,05%	100,04309	0,00034	0,00035	0,0017	0,21	0,05	
01/02/2013	PTB	100,03992	21,9	100,0415	0,00014	0,00036	7775649	91,06%	100,04154	0,00034	-0,00006	0,0001	-0,56	0,31	
	TÜBITAK														
								100,0%					χ^2_{obs}	0,64	
													N-1	3	
													Probability	88,7%	

Accepted

Capacitance system 2, f = 50 - 53 Hz, U ≤ 0.7 kV

TC (ppm/ºC)= 1,8 u(TC) = 0,8 ppm/ºC

Laboratory	X_i (pF)	Temp ºC	X_i (pF)$_{corrected\ 23ºC}$	$u(x_i)$ (pF)	$u(x_{i\ corr\ 23ºC})$ (pF)	$1/u^2(x_i)$ (pF^{-2})	Weight (%)	x_0 (pF)	Δx_i(pF)	$u(\Delta x_i)$ (pF)	di	chi^2 test	Exclude
LCOE								100,09886					
LNE	100,09895	23	100,09895	0,00026	0,00026	14763668	39,39%	$u(x_0)$ (10^{-6})	0,00009	0,00020	0,43	0,19	
MIKES	100,0986	21,6	100,09885	0,00023	0,00026	15250075	40,68%	0,00016	-0,00001	0,00020	-0,05	0,00	
SP	100,0987	23	100,09870	0,00040	0,00040	6237681	16,64%		-0,00016	0,00037	-0,45	0,20	
PTB													
TÜBITAK	100,09877	23	100,09877	0,00090	0,0009	1232133	3,29%		-0,00009	0,00089	-0,10	0,01	
							100,0%				χ^2_{obs}	0,40	
											N-1	3	
											Probability	94,1%	

Accepted

Capacitance system 2, f =1kHz, U ≤ 10 V

TC (ppm/ºC)= 1,8 u(TC) = 0,8 ppm/ºC

Laboratory	X_i (pF)	Temp ºC	X_i (pF)$_{corrected\ 23ºC}$	$u(x_i)$ (pF)	$u(x_{i\ corr\ 23ºC})$ (pF)	$1/u^2(x_i)$ (pF^{-2})	Weight (%)	x_0 (pF)	Δx_i(pF)	$u(\Delta x_i)$ (pF)	di	chi^2 test	Exclude
LCOE	100,098	23	100,09800	0,0050	0,00500	39922	0,03%	100,09890	-0,00090	0,00500	-0,18	0,03	
LNE	100,09881	23	100,09881	0,00014	0,00014	50919731	35,68%	$u(x_0)$ (10^{-6})	-0,00009	0,00011	-0,83	0,69	
MIKES	100,09885	21,6	100,09910	0,00011	0,00016	40497521	28,37%	0,00008	0,00020	0,00013	1,50	2,24	
SP	100,09886	23	100,09886	0,00015	0,00015	44356699	31,08%		-0,00004	0,00012	-0,35	0,12	
PTB													
TÜBITAK	100,09871	23	100,09871	0,00038	0,0004	6911556	4,84%		-0,00019	0,00037	-0,52	0,27	
							100,0%				χ^2_{obs}	3,35	
											N-1	4	
											Probability	50,1%	

Accepted

Capacitance system 3, f = 50-53 Hz, U = 1 V

TC (ppm/ºC)= 2,7 u(TC) = 1 ppm/ºC

Laboratory	X_i (nF)	Temp ºC	X_i (nF)$_{corrected\ 23ºC}$	$u(x_i)$ (nF)	$u(x_{i\ corr\ 23ºC})$ (nF)	$1/u^2(x_i)$ (nF^{-2})	Weight (%)	x_0 (nF)	Δx_i(nF)	$u(\Delta x_i)$ (nF)	di	chi^2 test	Exclude
LCOE	496,93	23	496,930	0,164	0,164	37	0,07%	496,9621	-0,03208	0,16393	-0,20	0,04	
LNE								$u(x_0)$ (10^{-6})					
MIKES	496,976	21	496,978	0,013	0,013	5954	10,47%	0,0042	0,01571	0,01226	1,28	1,64	
SP	496,9604	23	496,960	0,004	0,004	49989	87,88%		-0,00168	0,00156	-1,08	1,17	
PTB													
TÜBITAK	496,953	23	496,953	0,033	0,033	902	1,59%		-0,00908	0,03303	-0,27	0,08	
							100,0%				χ^2_{obs}	2,92	
											N-1	3	
											Probability	40,4%	

Accepted

Capacitance system 3, f = 50-53 Hz, U = 8 V

TC (ppm/ºC)= 2,7 u(TC) = 1 ppm/ºC

Laboratory	X_i (nF)	Temp ºC	X_i (nF)$_{corrected\ 23ºC}$	$u(x_i)$ (nF)	$u(x_{i\ corr\ 23ºC})$ (nF)	$1/u^2(x_i)$ (nF^{-2})	Weight (%)	x_0 (nF)	Δx_i(nF)	$u(\Delta x_i)$ (nF)	di	chi^2 test	Exclude
LCOE								496,9611					
LNE	496,957	23	496,957	0,0052	0,0052	36727	35,59%	$u(x_0)$ (10^{-6})	-0,00411	0,00419	-0,98	0,96	
MIKES	496,966	21	496,968	0,0080	0,0080	15573	15,09%	0,0031	0,00668	0,00738	0,90	0,82	
SP	496,9622	23	496,962	0,0045	0,0045	49988	48,44%		0,00109	0,00321	0,34	0,11	
PTB													
TÜBITAK	496,953	23	496,953	0,033	0,033	902	0,87%		-0,00811	0,03315	-0,24	0,06	
							100,0%				χ^2_{obs}	1,96	
											N-1	3	
											Probability	58,1%	

Accepted

Capacitance system 3, f = 1kHz, U ≤ 10 V

TC (ppm/ºC)= 2,7 u(TC) = 1 ppm/ºC

Laboratory	X_i (nF)	Temp ºC	X_i (nF)$_{\text{corrected 23ºC}}$	$u(x_i)$ (nF)	$u(x_{i\text{ corr 23ºC}})$ (nF)	$1/u^2(x_i)$ (nF^{-2})	Weight (%)	x_0 (nF)	Δx_i(nF)	$u(\Delta x_i)$ (nF)	di	chi^2 test	Exclude
LCOE	496,863	23	496,863	0,028	0,028	1247	1,25%	496,8672	-0,00424	0,02814	-0,15	0,02	
LNE	496,866	23	496,866	0,0040	0,0040	63291	63,29%	$u(x_0)$ (10^{-6})	-0,00124	0,00241	-0,51	0,26	
MIKES	496,861	21	496,863	0,018	0,018	2950	2,95%	0,0032	-0,00445	0,01814	-0,25	0,06	
SP	496,870	23	496,870	0,0060	0,0060	28129	28,13%		0,00276	0,00505	0,55	0,30	
PTB	496,872	21,9	496,873	0,021	0,021	2295	2,29%		0,00575	0,02063	0,28	0,08	
TÜBITAK	496,870	23	496,870	0,022	0,022	2092	2,09%		0,00276	0,02163	0,13	0,02	
							100,0%				χ^2_{obs}	0,74	
											N-1	5	
Accepted											Probability	98,1%	

Capacitance system 4, f = 50 - 53 Hz, U = 1 V

TC (ppm/ºC)= 6,9 u(TC) = 2 ppm/ºC

Laboratory	X_i (nF)	Temp ºC	X_i (nF)$_{\text{corrected 23ºC}}$	$u(x_i)$ (nF)	$u(x_{i\text{ corr 23ºC}})$ (nF)	$1/u^2(x_i)$ (nF^{-2})	Weight (%)	x_0 (nF)	Δx_i(nF)	$u(\Delta x_i)$ (nF)	di	chi^2 test	Exclude
LCOE	4999,8	23	4999,80	1,6	1,6	0	0,07%	4999,7758	0,02415	1,64938	0,01	0,00	
LNE								$u(x_0)$ (10^{-6})					
MIKES	4999,93	21	4999,95	0,14	0,15	47	8,63%	0,0427	0,17215	0,13893	1,24	1,54	
SP	4999,759	23	4999,759	0,045	0,0450	494	90,07%		-0,01685	0,01418	-1,19	1,41	
PTB													
TÜBITAK	4999,80	23	4999,80	0,38	0,385	7	1,23%		0,02415	0,38261	0,06	0,00	
							100,0%				χ^2_{obs}	2,95	
											N-1	3	
Accepted											Probability	39,9%	

Capacitance system 4, f = 1kHz, U ≤ 10 V

TC (ppm/ºC)= 6,9 u(TC) = 2 ppm/ºC

Laboratory	X_i (nF)	Temp ºC	X_i (nF)$_{\text{corrected 23ºC}}$	$u(x_i)$ (nF)	$u(x_{i\text{ corr 23ºC}})$ (nF)	$1/u^2(x_i)$ (nF^{-2})	Weight (%)	x_0 (nF)	Δx_i(nF)	$u(\Delta x_i)$ (nF)	di	chi^2 test	Exclude
LCOE	4998,91	23	4998,91	0,50	0,50	4	6,09%	4999,0781	-0,16812	0,48442	-0,35	0,12	
LNE	4998,4	23	4998,40	0,075	0,075			$u(x_0)$ (10^{-6})	-0,67812	0,14440	-4,70		X
MIKES	4999,05	21	4999,07	0,18	0,18	31	46,88%	0,1234	-0,01012	0,13137	-0,08	0,01	
SP	4999,11	23	4999,11	0,18	0,18	31	47,02%		0,03188	0,13099	0,24	0,06	
PTB													
TÜBITAK	4999,95	23	4999,95	0,26	0,26				0,87188	0,28780	3,03		X
							100,0%				χ^2_{obs}	0,19	
											N-1	2	
Accepted											Probability	91,1%	

Tan δ system 1, f = 50 - 53 Hz, U ≤ 2 kV

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{-12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE					7,0					
LNE					$u(x_0)$ (10^{-6})					
MIKES	9	3	0,1111	49,44%	2,1	2,0	2,1	0,96	0,92	
SP	5	3	0,1111	49,44%		-2,0	2,1	-0,92	0,84	
PTB										
TÜBITAK	3	20	0,0025	1,11%		-4,0	20	-0,20	0,04	
				100,0%				χ^2_{obs}	1,80	
								N-1	2	
								Probability	40,7%	

Accepted

Tan δ system 2, f = 50 - 53 Hz, U ≤ 700 V

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{-12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE					4,1					
LNE	1	27	0,00137	0,56%	$u(x_0)$ (10^{-6})	-3,1	27	-0,12	0,01	
MIKES	7	3	0,11111	45,54%	2,0	2,9	2,2	1,31	1,71	
SP	2	3	0,11111	45,54%		-2,1	2,2	-0,95	0,90	
PTB										
TÜBITAK	0	7	0,02041	8,36%		-4,1	6,7	-0,61	0,38	
				100,0%				χ^2_{obs}	3,00	
								N-1	3	
								Probability	39,1%	

Accepted

Tan δ system 2, f = 1 kHz, U ≤ 10 V

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{-12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE	9	24	0,002	0,06%	1,7	7,3	24	0,30	0,09	
LNE	1	27	0,001	0,04%	$u(x_0)$ (10^{-6})	-0,7	27	-0,03	0,00	
MIKES					0,6					
SP	1,8	0,6	2,778	88,83%		0,1	0,2	0,42	0,18	
PTB										
TÜBITAK	1	1,7	0,346	11,07%		-0,7	1,6	-0,45	0,20	
				100,0%				χ^2_{obs}	0,47	
								N-1	3	
Accepted								Probability	92,5%	

Tan δ system 3, f = 50 -53 Hz, U ≤ 8 V

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{-12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE	100	36	0,00077	0,44%	95,9	4,1	36	0,11	0,01	
LNE	110	27			$u(x_0)$ (10^{-6})	14,1	27	0,52	0,27	
MIKES	94	4	0,06250	35,82%	2,4	-1,9	3,2	-0,60	0,36	
SP	97	3	0,11111	63,68%		1,1	1,8	0,59	0,35	
PTB										
TÜBITAK	87	103	0,00009	0,05%		-8,9	103	-0,09	0,01	
				100,0%				χ^2_{obs}	1,01	
								N-1	4	
Accepted								Probability	90,9%	

Tan δ system 3, f = 1 kHz, U ≤ 10 V

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{-12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE	170	60	0,00028	9,87%	135	35	57	0,61	0,37	
LNE	130	27	0,00137	48,73%	$u(x_0)$ (10^{-6})	-5	19	-0,27	0,07	
MIKES	167	80	0,00016	5,55%	19	32	78	0,41	0,17	
SP	118	33	0,00092	32,62%		-17	27	-0,64	0,40	
PTB										
TÜBITAK	227	105	0,00009	3,22%		92	103	0,89	0,79	
				100,0%				χ^2_{obs}	1,81	
								N-1	4	
Accepted								Probability	77,1%	

Tan δ system 4, f = 50 - 53Hz, U =1 V

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{-12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE	90	360	0,00001	0,01%	87,8	2,2	360	0,01	0,00	
LNE					$u(x_0)$ (10^{-6})					
MIKES	95	9	0,0123	9,99%	2,8	7,2	8,5	0,84	0,71	
SP	87	3	0,1111	89,95%		-0,8	1,0	-0,84	0,71	
PTB				0,00%						
TÜBITAK	92	122	0,0001	0,05%		4,2	122	0,03	0,00	
				100,0%				χ^2_{obs}	1,42	
								N-1	3	
Accepted								Probability	70,0%	

Tan δ system 4, f = 1 kHz, U ≤ 10 V

Laboratory	X_i (10^{-6})	$u(x_i)$ (10^{-6})	$1/u^2(x_i)$ (10^{-12})	Weight (%)	x_0 (10^{-6})	Δx_i(10^{-6})	$u(\Delta x_i)$ (10^{-6})	di	chi^2 test	Exclude
LCOE	340	160	0,00004	2,54%	326	14	158	0,09	0,01	
LNE	320	27	0,00137	89,23%	$u(x_0)$ (10^{-6})	-6	9	-0,72	0,52	
MIKES	394	140	0,00005	3,32%	26	68	138	0,49	0,24	
SP	119	255	0,00002	1,00%		-207	254	-0,82	0,67	
PTB										
TÜBITAK	459	129	0,00006	3,91%		133	126	1,05	1,10	
				100,0%				χ^2_{obs}	2,54	
								$N-1$	4	
Accepted								Probability	63,8%	

ANNEX II
Graphs of comparison results

Graphs included in this annex intend to summarize the results of this comparison project so that it is possible to check compatibility and consistency of the results provided by every participant.

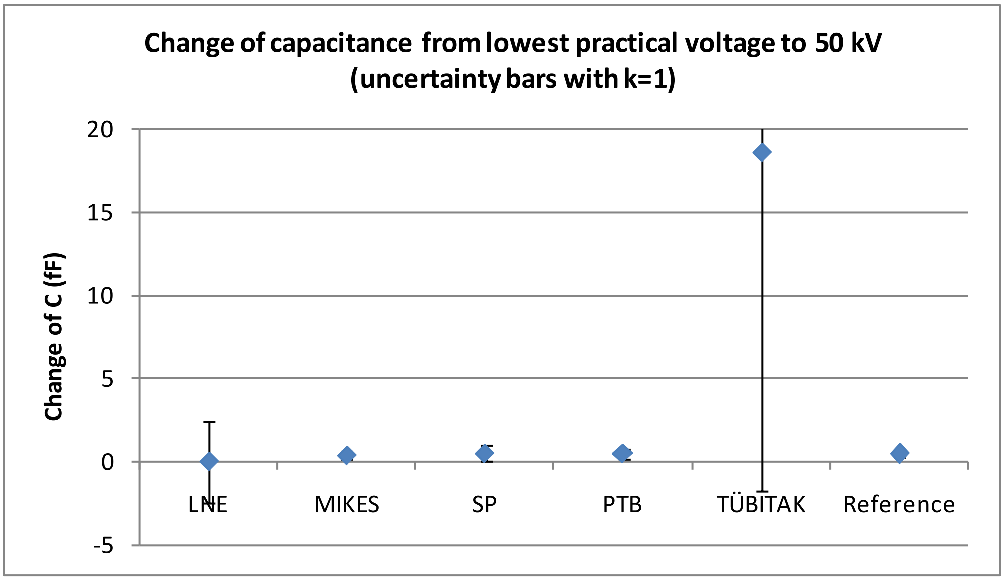
When several measurements were reported by a participant related to the same measurement point or parameter, only the most accurate is considered on the relevant graph.

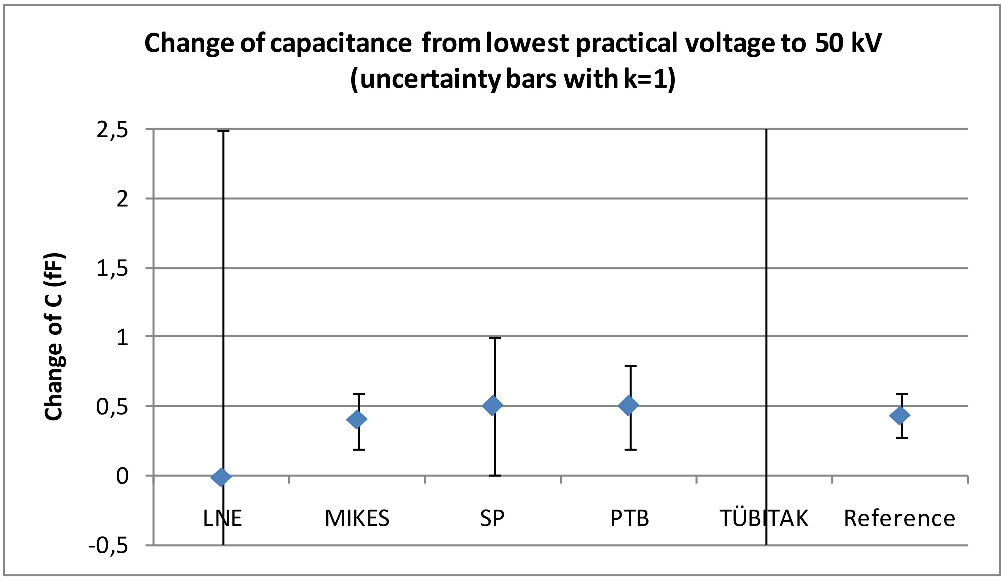
Uncertainties are reported as standard uncertainties (k=1).

Voltage dependence of System 1 from 1 kV to 200 kV

The following graphs show the change of capacitance value of System 1 with respect to the initial capacitance measured at the lowest practical voltage level.

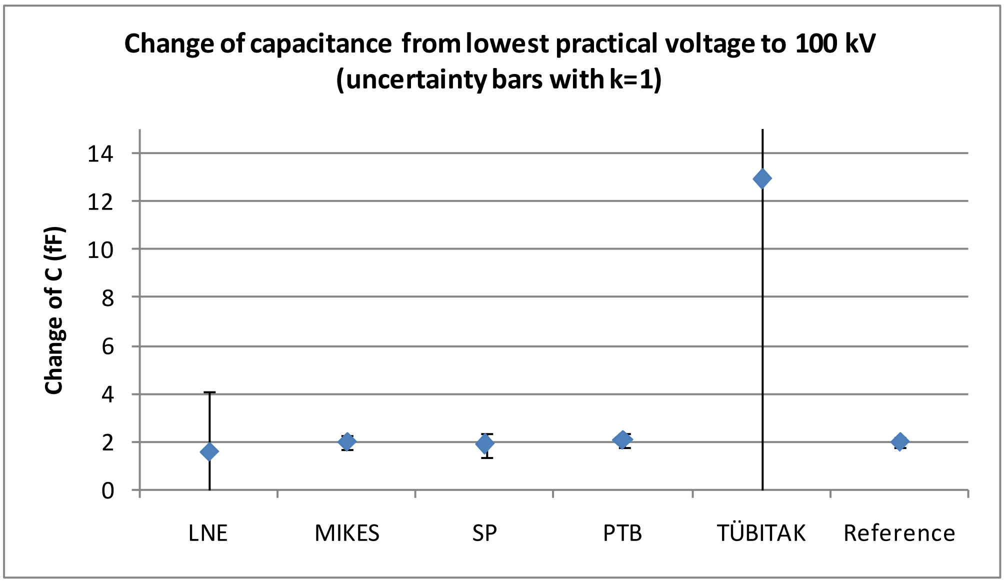
Capacitance measurement

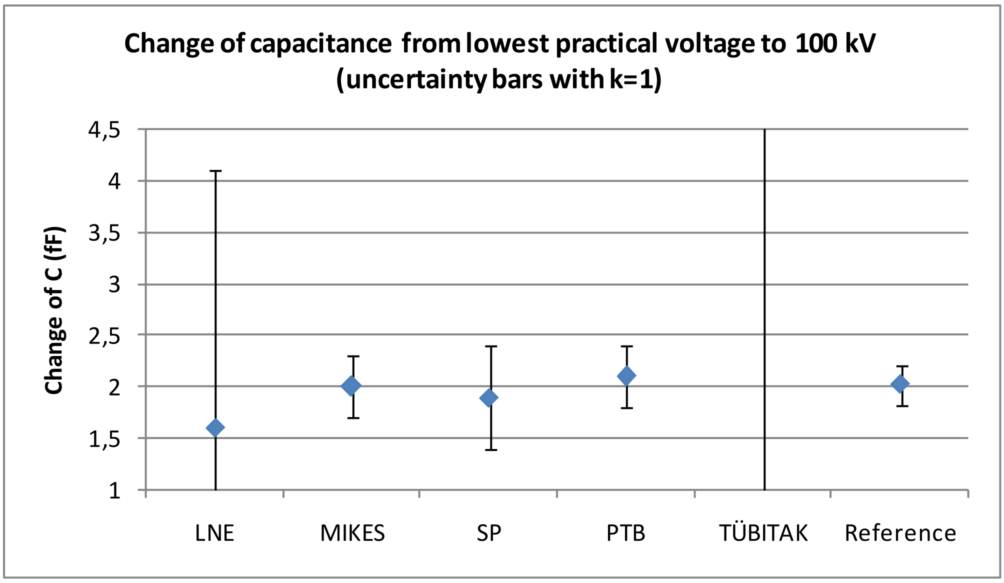




Nominal capacitance of system 1 is 100 pF, so a change of 1 fF represents a change of 10 ppm.

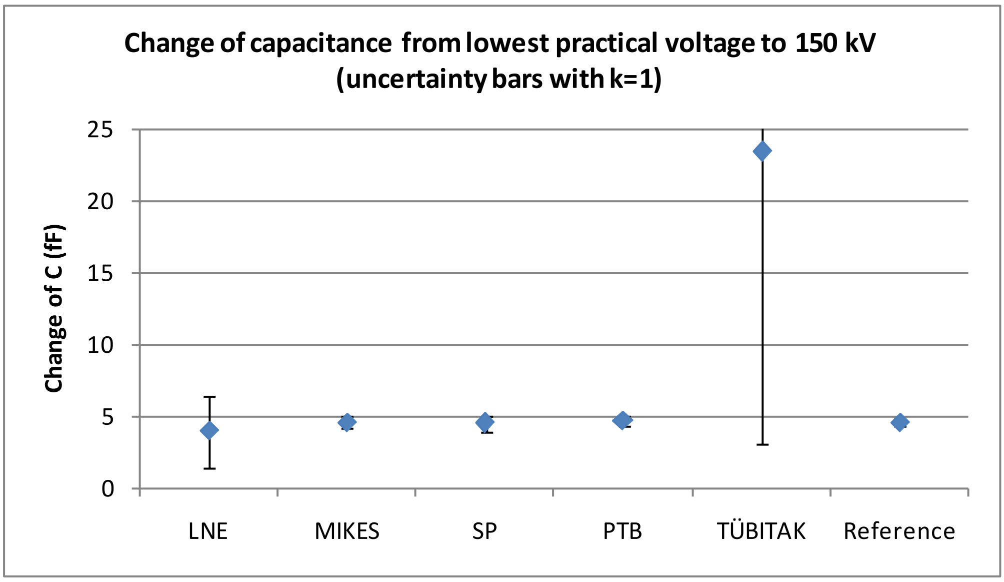
Capacitance measurement

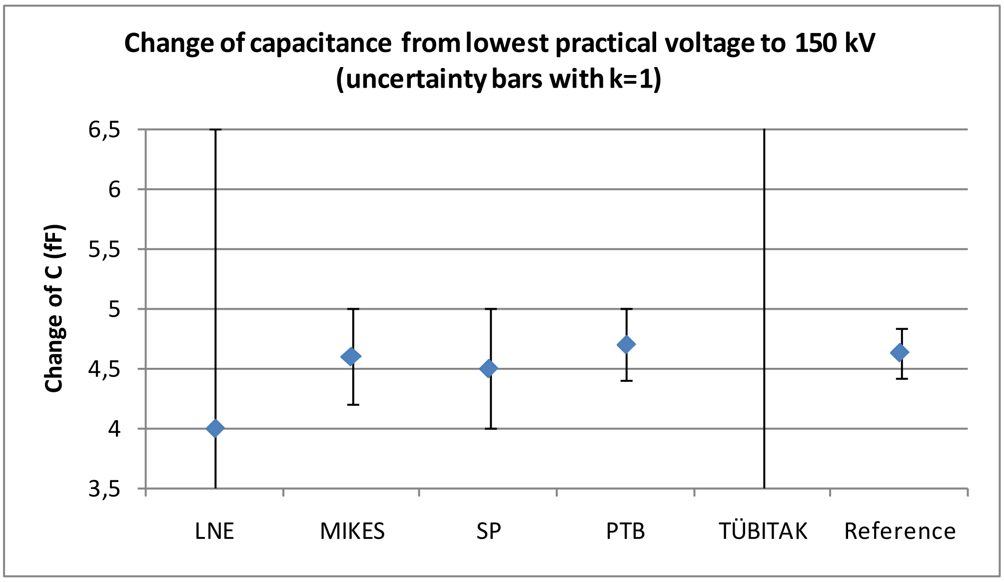




Nominal capacitance of system 1 is 100 pF, so a change of 1 fF represents a change of 10 ppm.

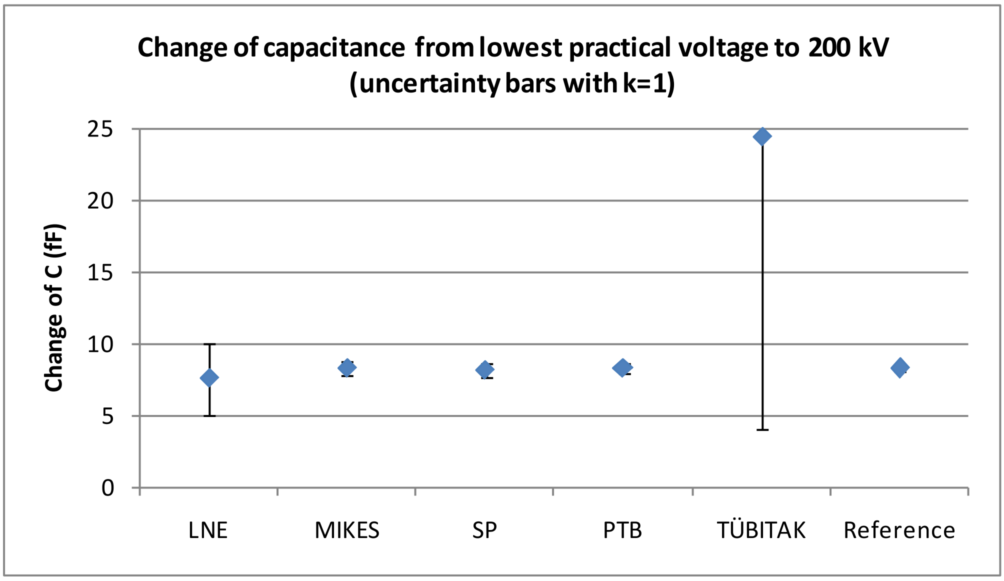
Capacitance measurement

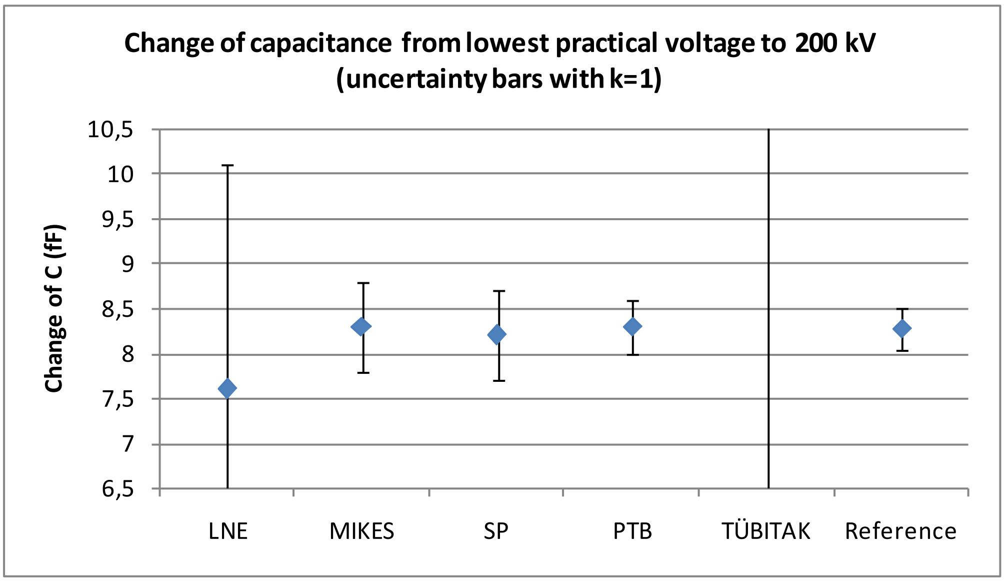




Nominal capacitance of system 1 is 100 pF, so a change of 1 fF represents a change of 10 ppm.

Capacitance measurement



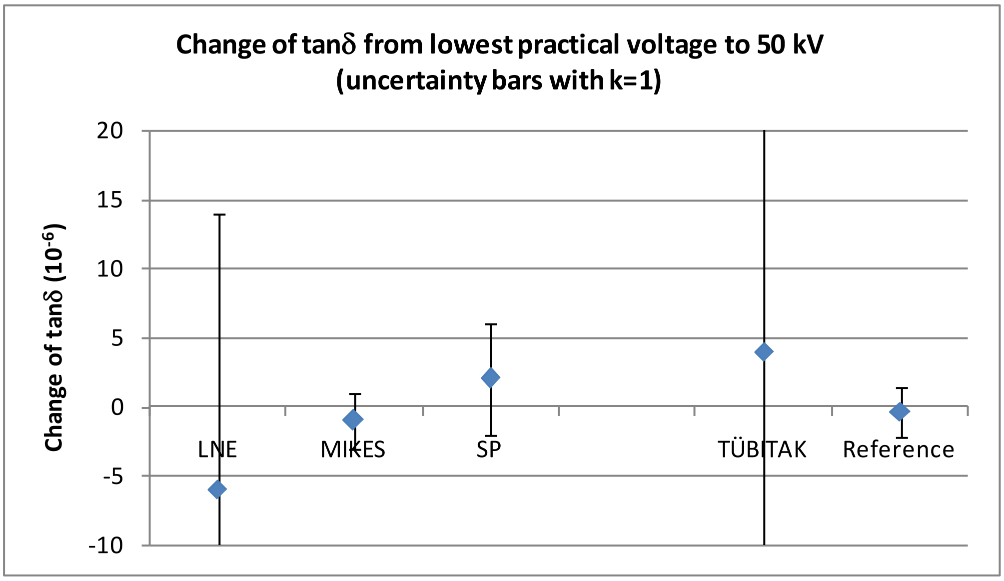


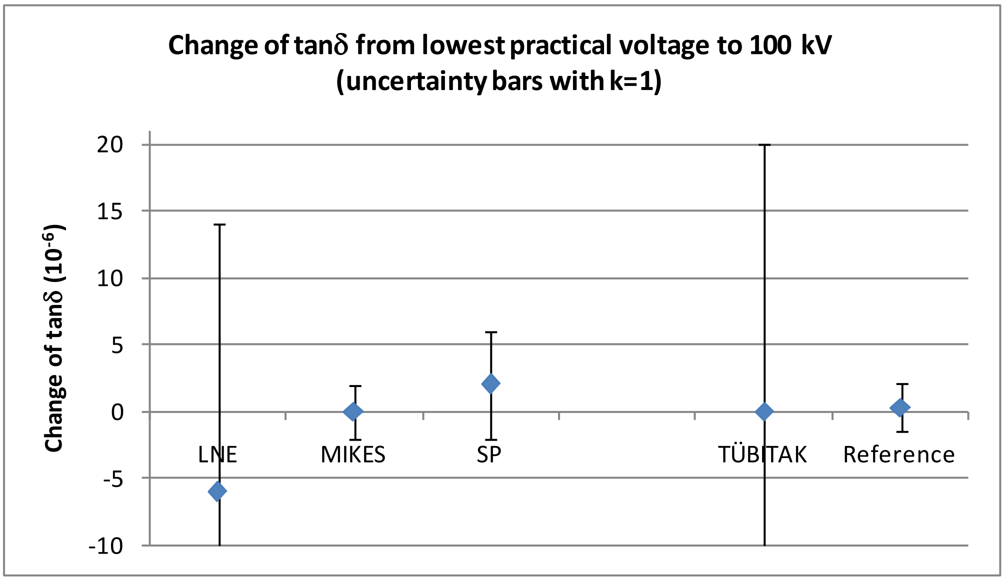
Nominal capacitance of system 1 is 100 pF, so a change of 1 fF represents a change of 10 ppm.

Voltage dependence of System 1 from 1 kV to 200 kV

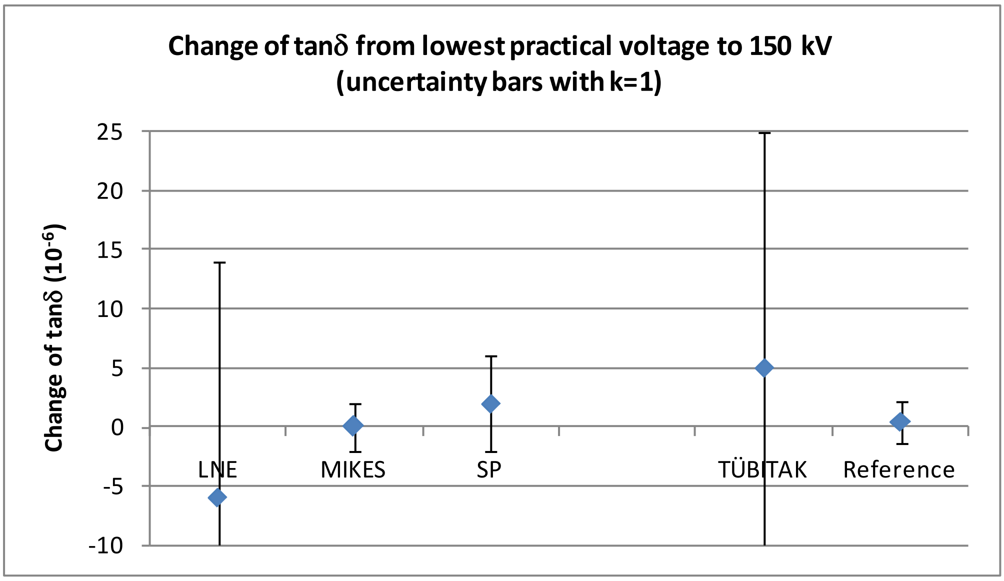
The following graphs show the change of tan δ value of System 1 with respect to the corresponding initial value measured at the lowest practical voltage level.

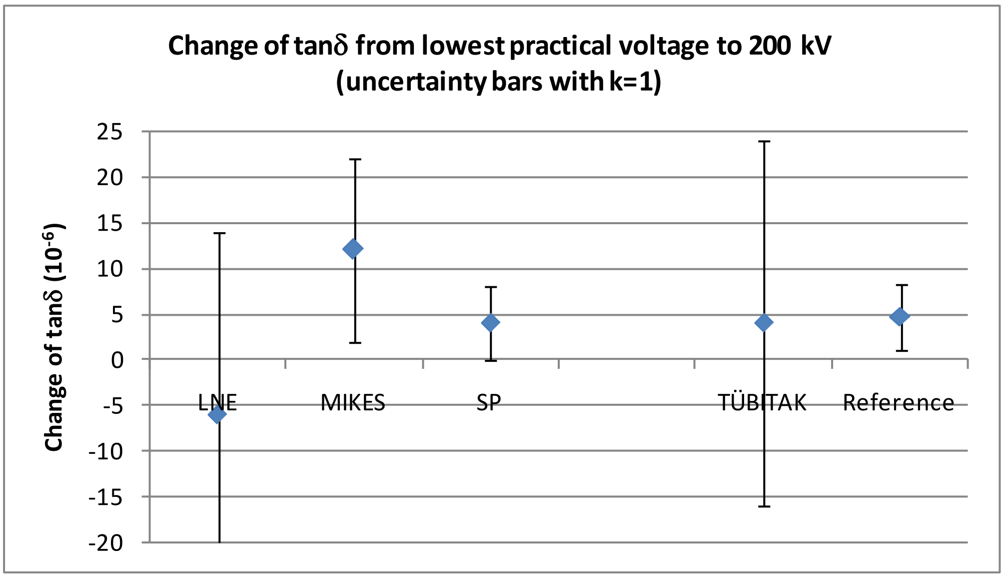
Loss dissipation factor (tan δ) measurement



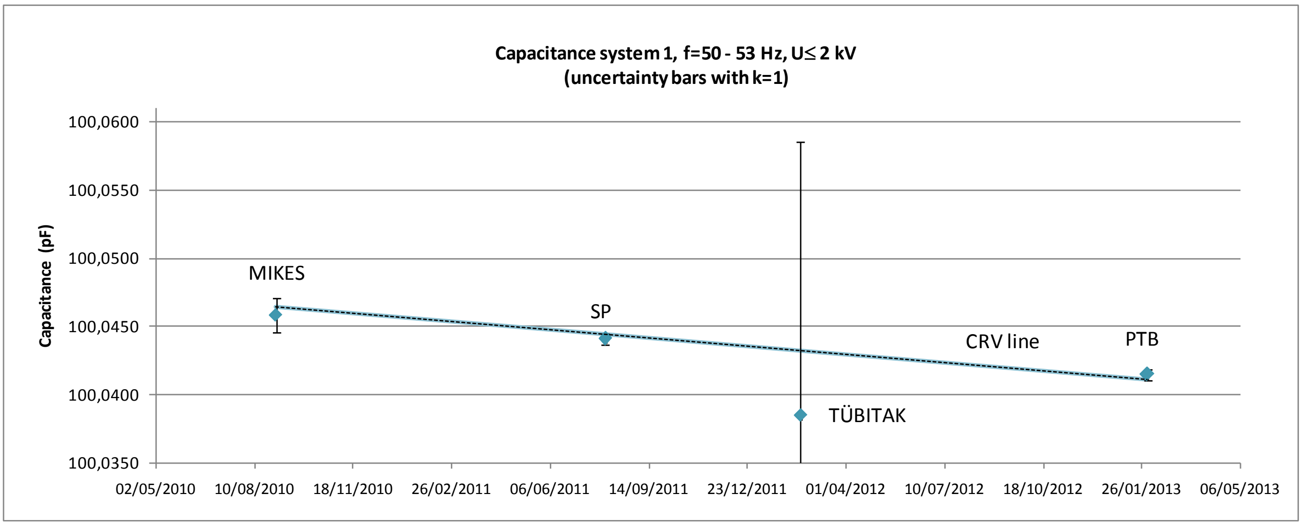


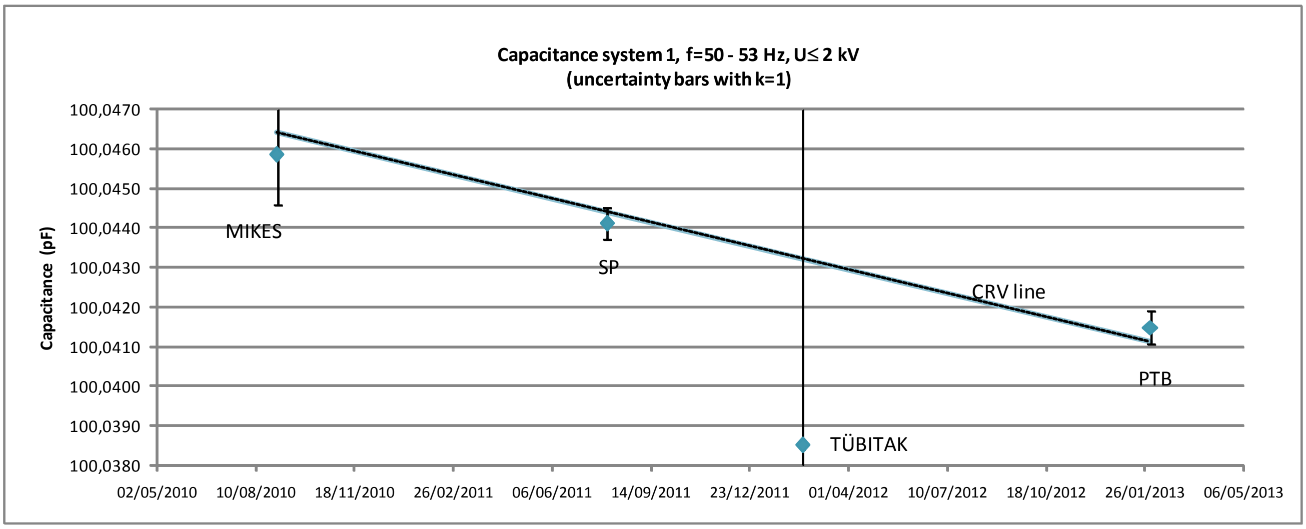
Loss dissipation factor (tan δ) measurement

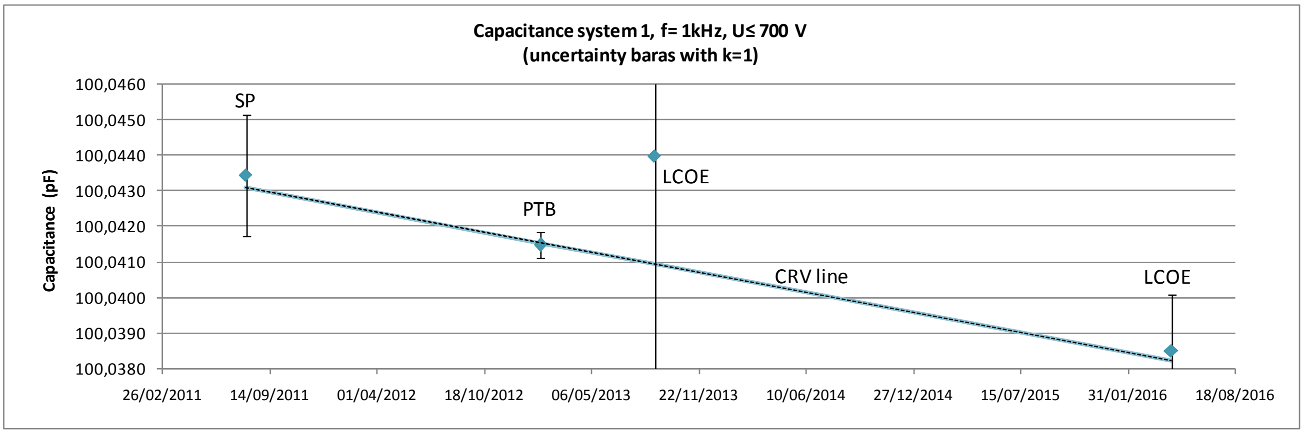




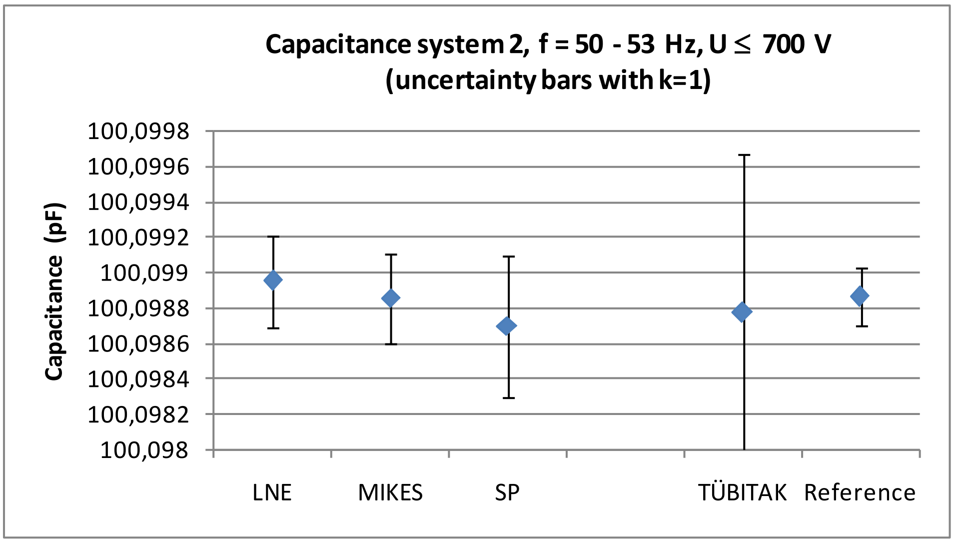
Measurement of absolute value of capacitance, System 1

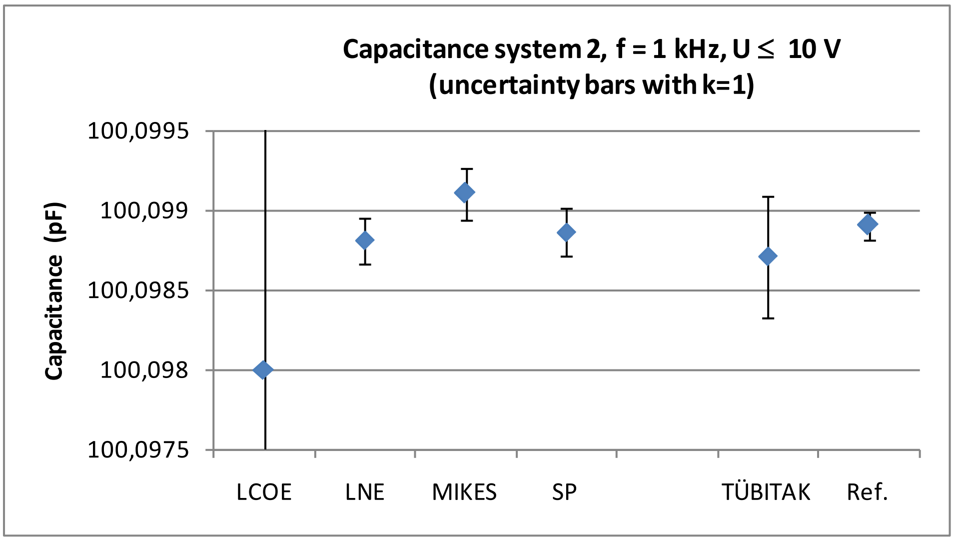




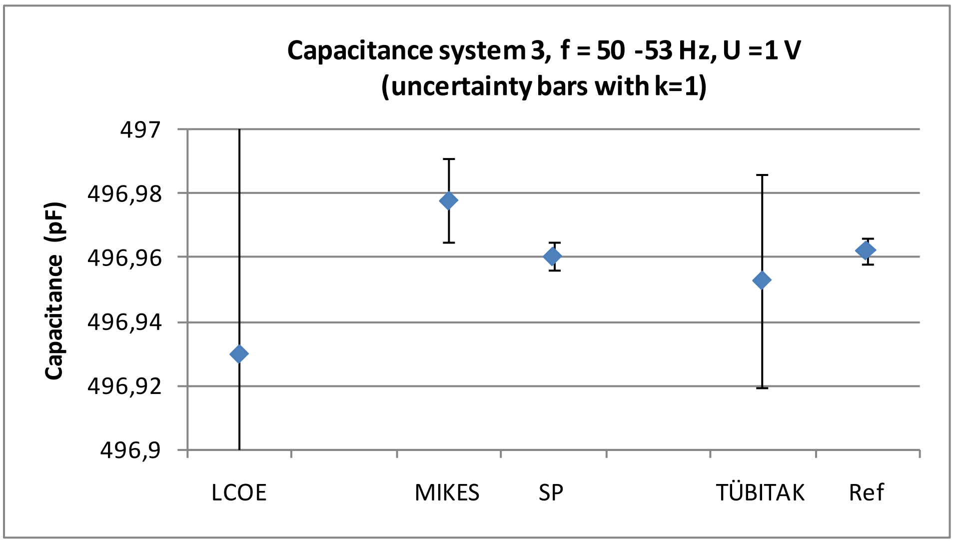


Measurement of absolute value of capacitance, System 2

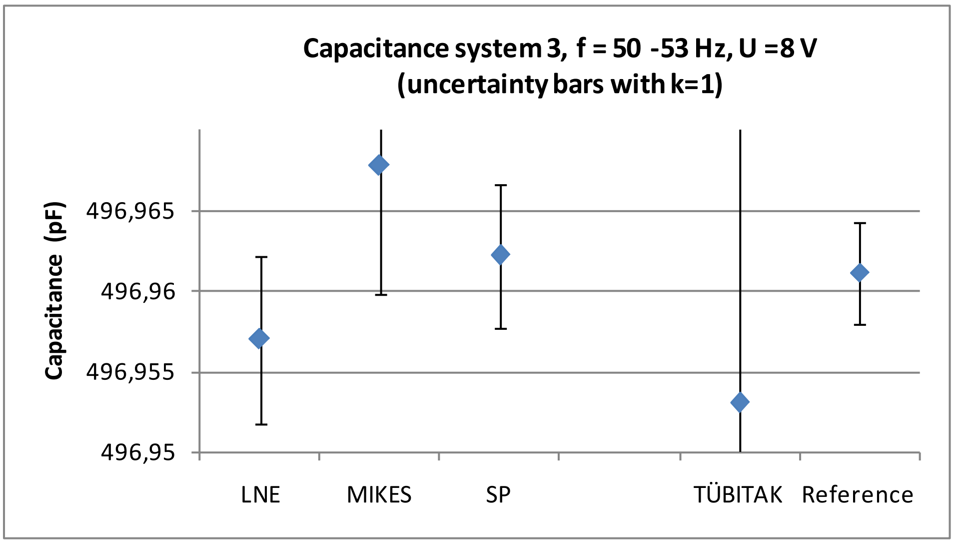


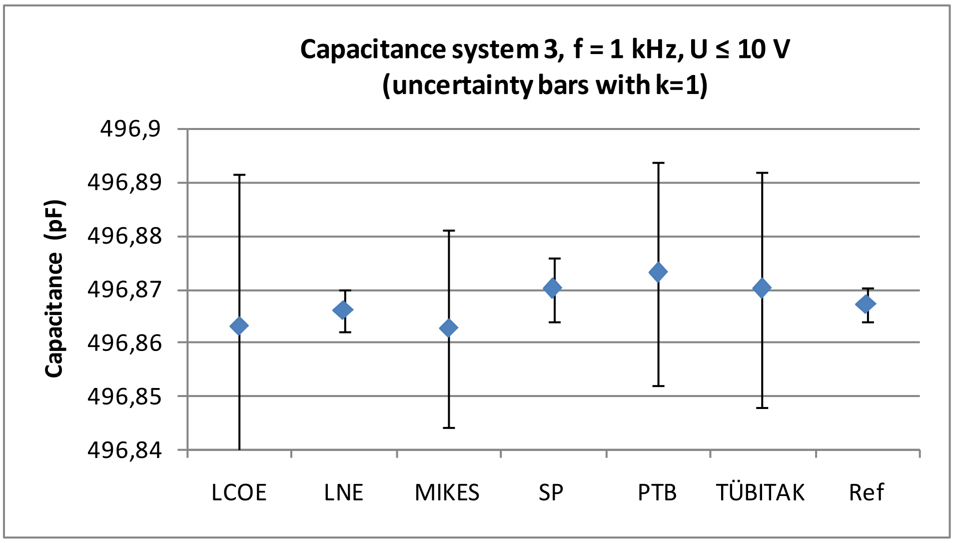


Measurement of absolute value of capacitance, System 3

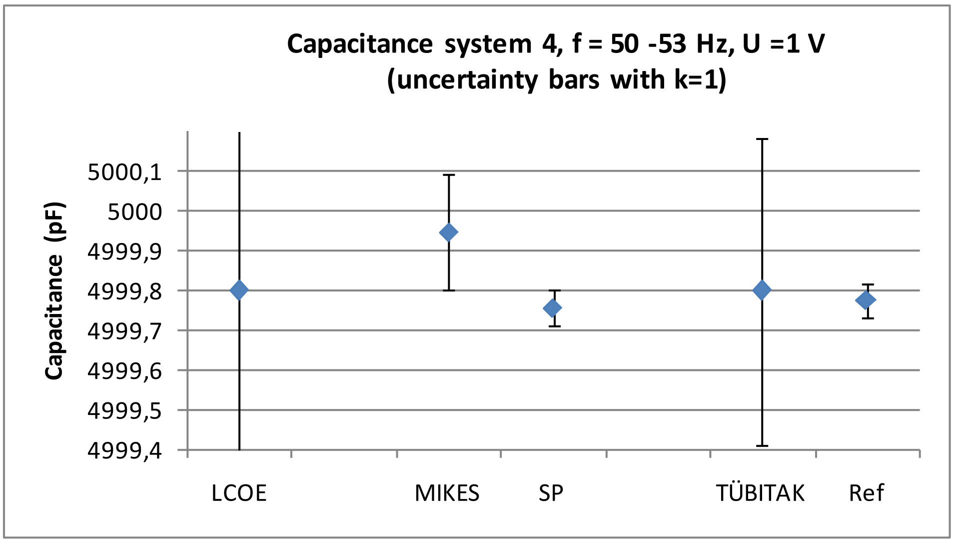


Measurement of absolute value of capacitance, System 3

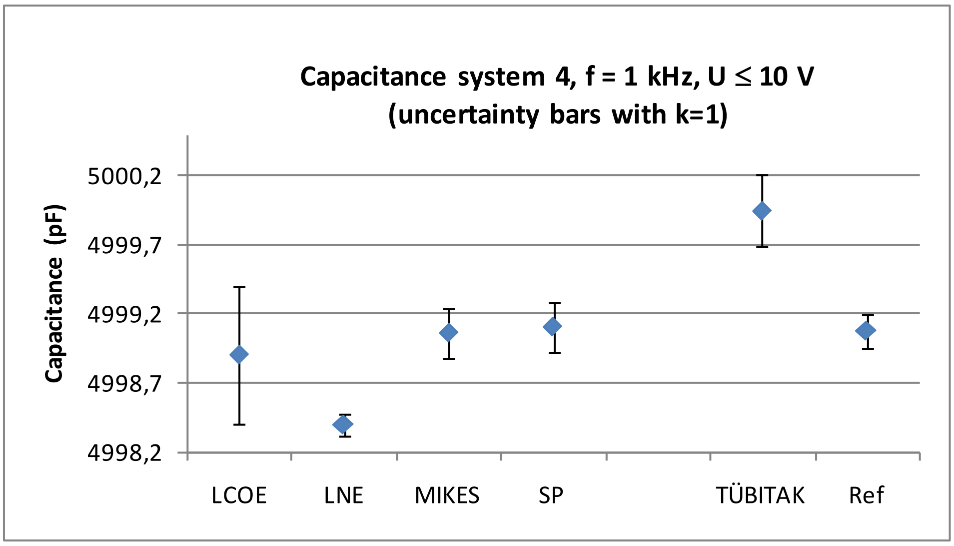




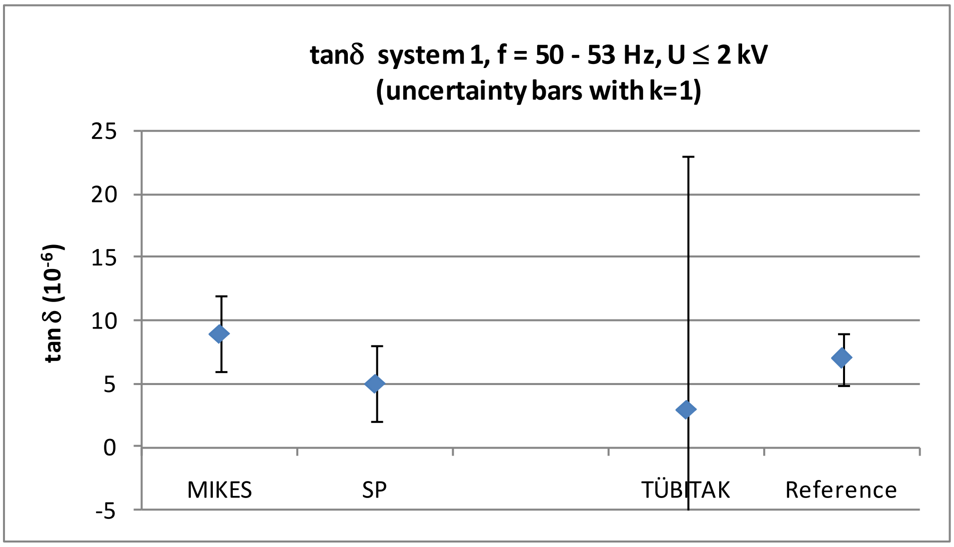
Measurement of absolute value of capacitance, System 4



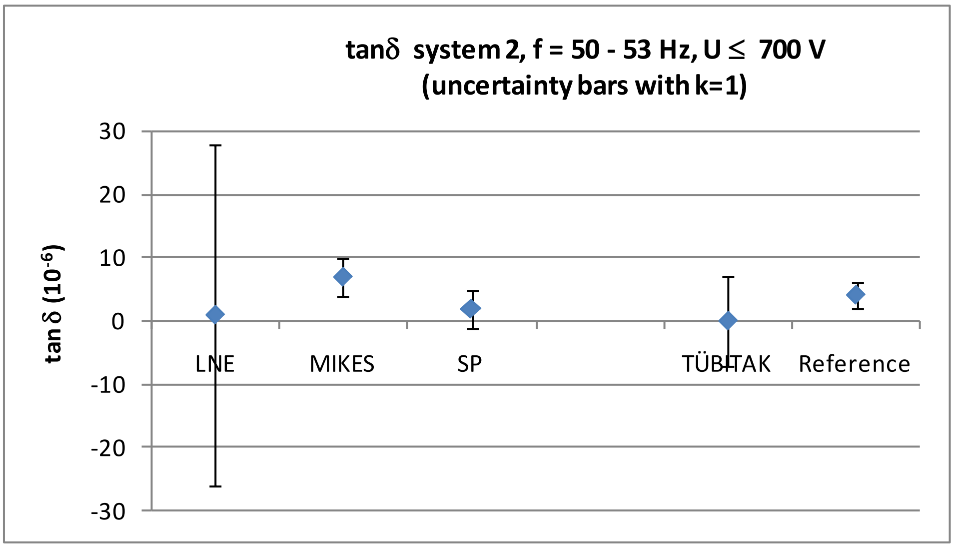
Measurement of absolute value of capacitance, System 4

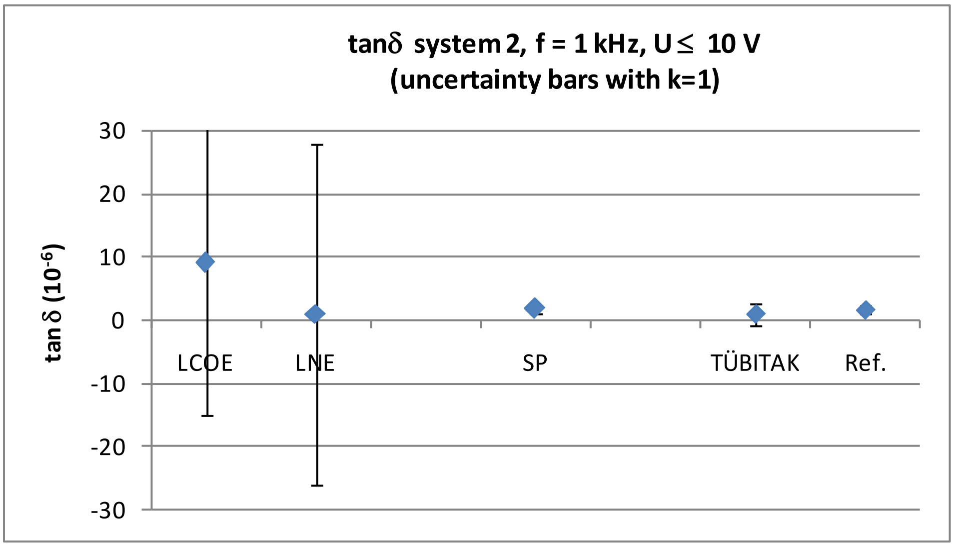


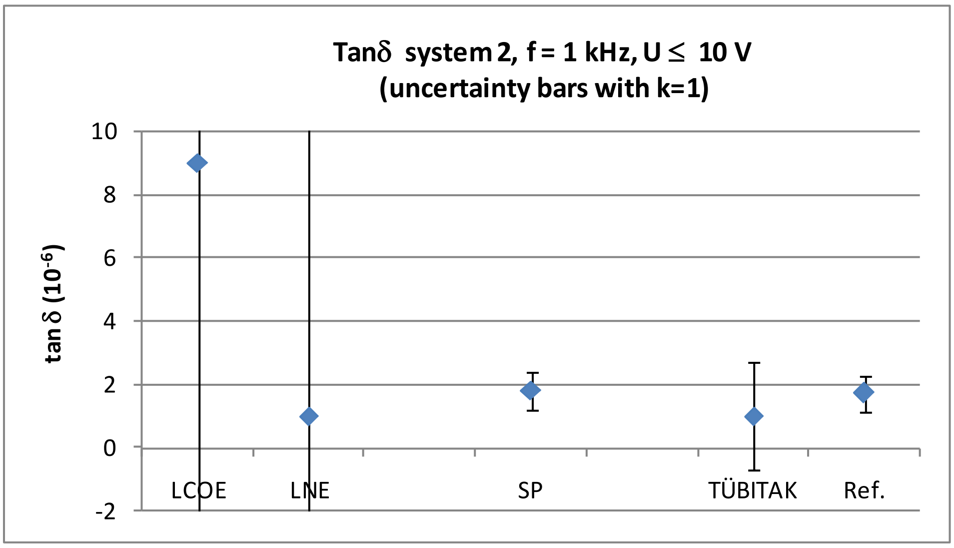
Measurement of absolute value of tan δ, System 1



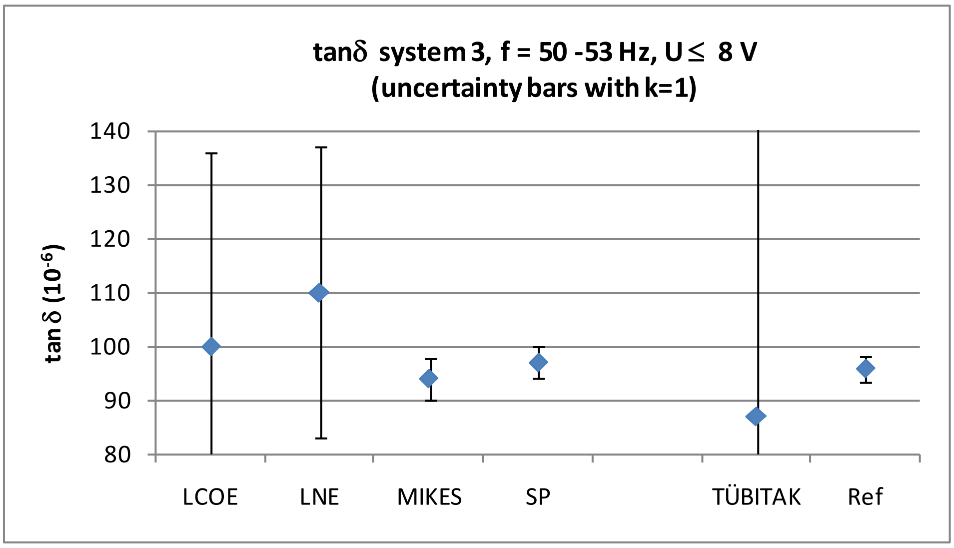
Measurement of absolute value of tan δ, System 2

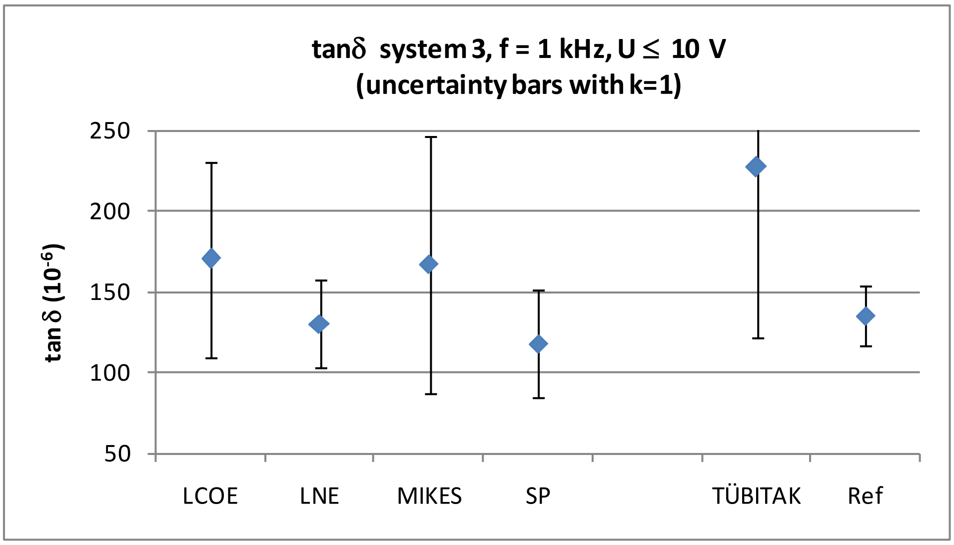




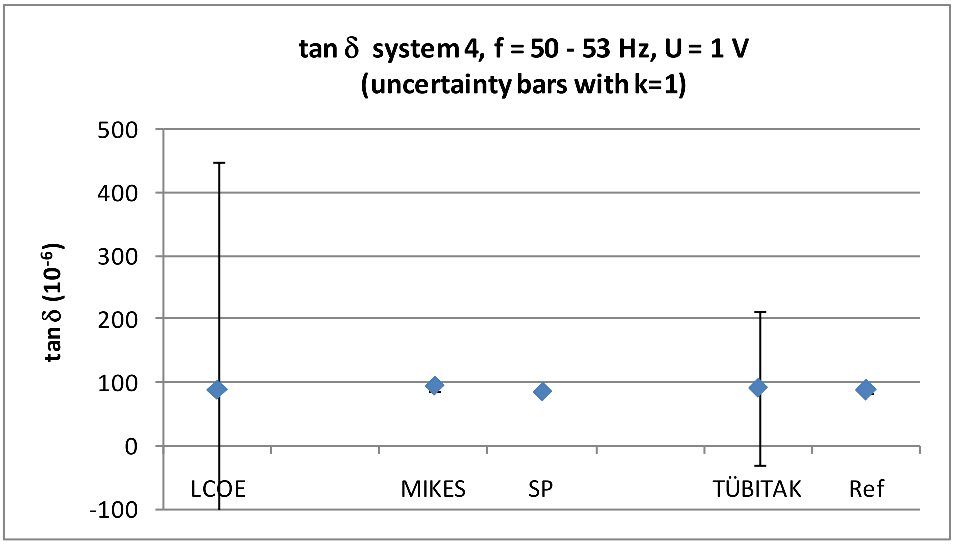


Measurement of absolute value of tan δ, System 3





Measurement of absolute value of tan δ, System 4



Measurement of absolute value of tan δ, System 4