# 1st Part, 10 minutes

- Presentation in 2021
- For more detail, please refer to this paper

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## Resonance at the Front of Lightning Impulse Voltage Waveforms Caused by the Load Capacitor

Wei Zhao, *Senior Member, IEEE*, Haiming Shao, *Member, IEEE*, Jiandong Ding, Chuansheng Li, and Jiafu Wang, *Member, IEEE*

# Resonance at the front of lightning impulse voltage waveforms caused by the load capacitor

Wei Zhao, Haiming Shao, Chuansheng Li and Jiafu Wang

National Institute of Metrology, China

zhaowei@nim.ac.cn

# Content

1. Motivation of this research
2. Circuit analysis and simulation
3. Experimental verification
4. Conclusion

# 1. Motivation

Contact person RISE
Alf-Peter Elg
Measurement Science and Technology
+46 10 516 57 34
alf.elg@ri.se

Date
2017-10-10

Reference

Page
1 (2)

**Letter of agreement - RMO Key Comparison Euramet.EM-S42, Comparison of lightning impulse (LI) Reference Measuring Systems**

The intercomparison of lightning impulse (LI) Reference Measuring Systems started in Nov 2016 and runs throughout 2018.

The following national labs/countries have agreed to participate in the intercomparison EM-S42:

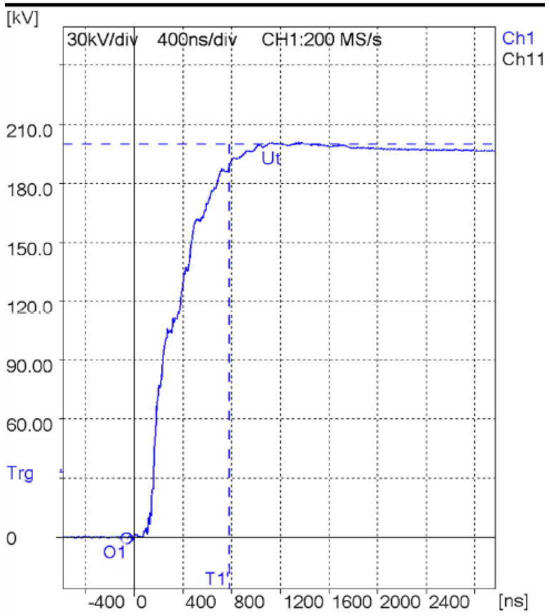
*Table 2-1. Comparison participants*

| No | Country | Institute | Acronym | Status | Region | Contact person |
|---|---|---|---|---|---|---|
| 1 | Sweden | RISE Research Institutes of Sweden | RISE | NMI | EURAMET | Dr. Alf-Peter Elg alf.elg@ri.se |
| 2 | Finland | VTT Technical Research Centre of Finland, National Metrology Institute VTT MIKES | VTT | NMI | EURAMET | Dr. Jari Hällström jari.hallstrom@vtt.fi |
| 3 | Spain | LCOE-FFII, High Voltage Technological Centre | LCOE | DI | EURAMET | Prof. Fernando Garnacho fernando.garnacho@ffii.es |
| 4 | France | Laboratoire national de métrologie et d'essais | LNE | NMI | EURAMET | Mohamed Agazar Mohamed.Agazar@lne.fr |
| 5 | Germany | Physikalisch-Technische Bundesanstalt | PTB | NMI | EURAMET | Dr. Johann Meisner johann.meisner@ptb.de |
| 6 | Italy | Istituto Nazionale di Ricerca Metrologica | INRIM | NMI | EURAMET | Dr. Paolo Roccato p.roccato@inrim.it |
| 7 | Turkey | TÜBİTAK National Metrology Institute | TUBITAK | NMI | EURAMET | Dr. Ahmet Merev ahmet.merev@tubitak.gov.tr |
| 8 | Japan | Japan High-voltage Testing Laboratory Liaison | JHILL | Other [1] | APMP | Takayuki Wakimoto wakimoto@calibration.jp |
| 9 | China | National Institute of Metrology | NIM | NMI | APMP | Dr. Wei Zhao zhaowei@nim.ac.cn |
| 10 | Australia | National Measurement Institute | NMIA | NMI | APMP | Dr. Yi Li yi.li@measurement.gov.au |
| 11 | Argentina | Instituto de alta tensión y transmisión de energía | IATTE | Other [2] | SIM | Prof. Ricardo Diaz rdiaz@herrera.unt.edu.ar |
| 12 | Canada | National Research Council | NRC | NMI | SIM | Dr. Harold Parks harold.parks@nrc-cnrc.gc.ca |
| 13 | Russia | Russian Research Institute for Metrological Service | VNIIMS | DI | COOMET | Tatiana Dubrovskaya dubrovskaya_ta@vniims.ru |

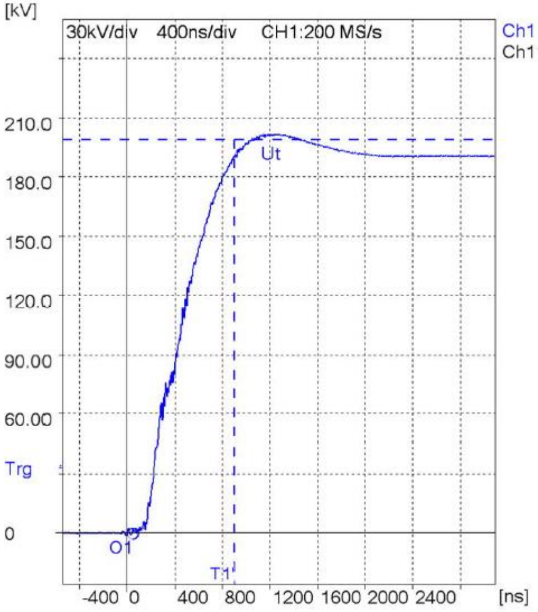
[1] Participation authorized by NMIJ AIST (Japanese NMI)
[2] Participation authorized by INTI (Argentinian NMI)

# 1. Motivation

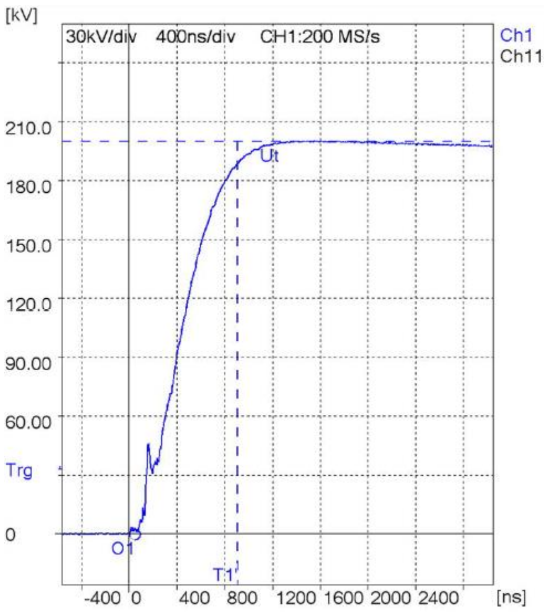
**TRMS recorded waveforms in different laboratories**



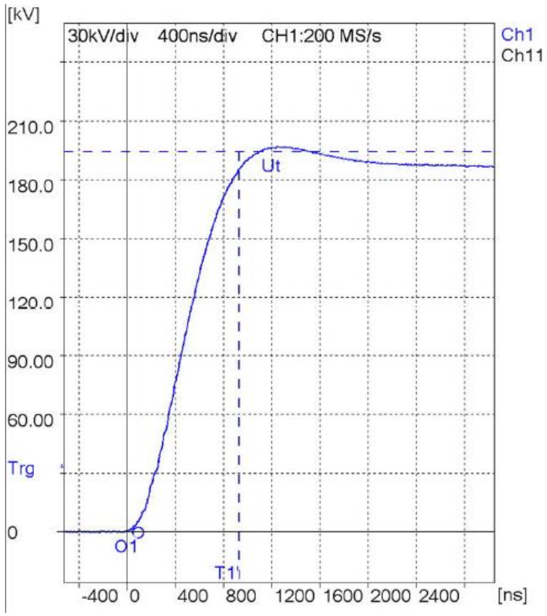

Lab A




Lab B




Lab C




Lab D


- J. Hällström, A-P. Elg, J. Havunen and F. Garnacho,
Final REPORT of Comparison of lightning impulse (LI) reference measuring systems.

# Content

1. Motivation of this research
2. Circuit analysis and simulation
3. Experimental verification
4. Conclusion

# 2. Circuit analysis and simulation

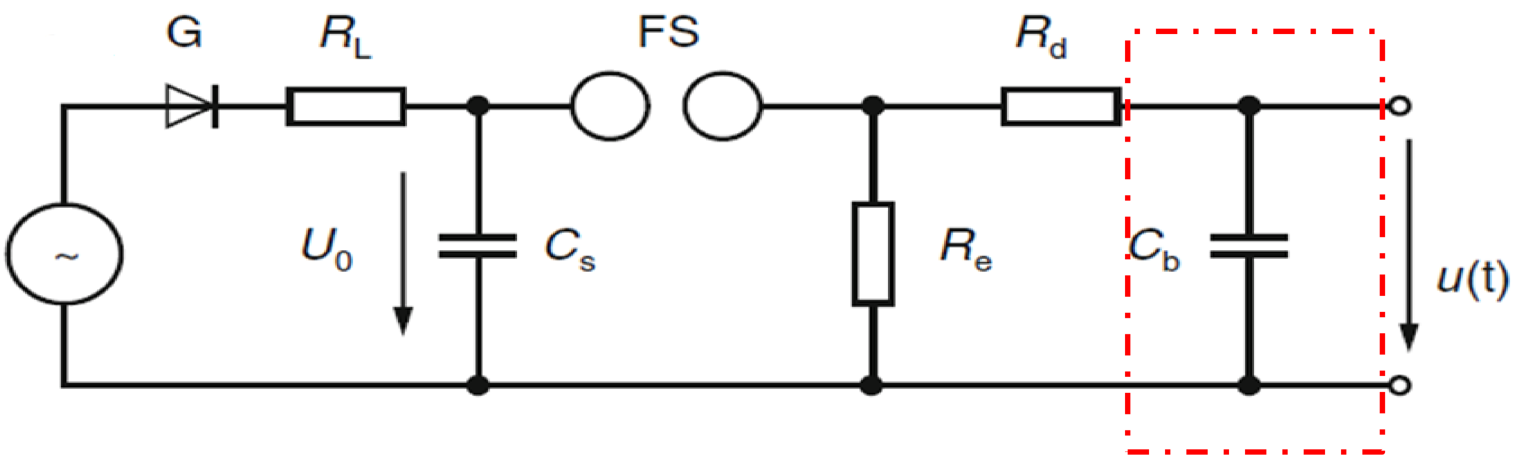



Fig. 1 Single-stage basic circuits for the generation of LI voltage waveform

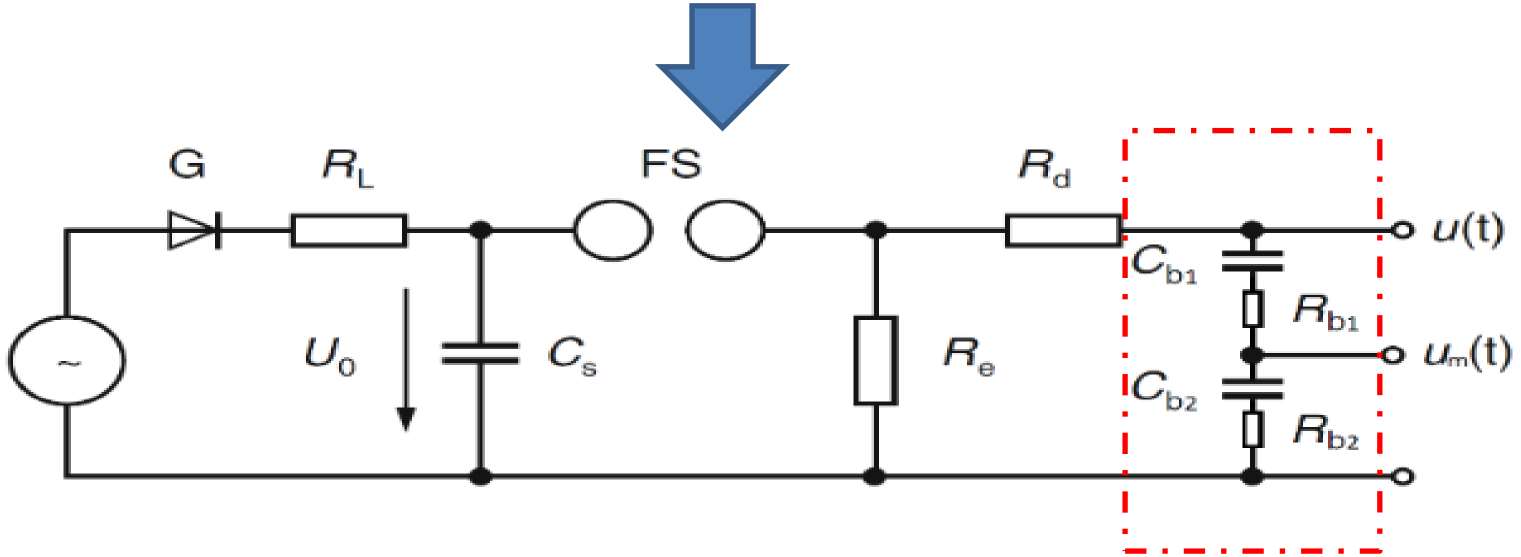



Fig. 2 circuits for the generation of LI voltage with damped capacitive divider as the load capacitor

# 2. Circuit analysis and simulation

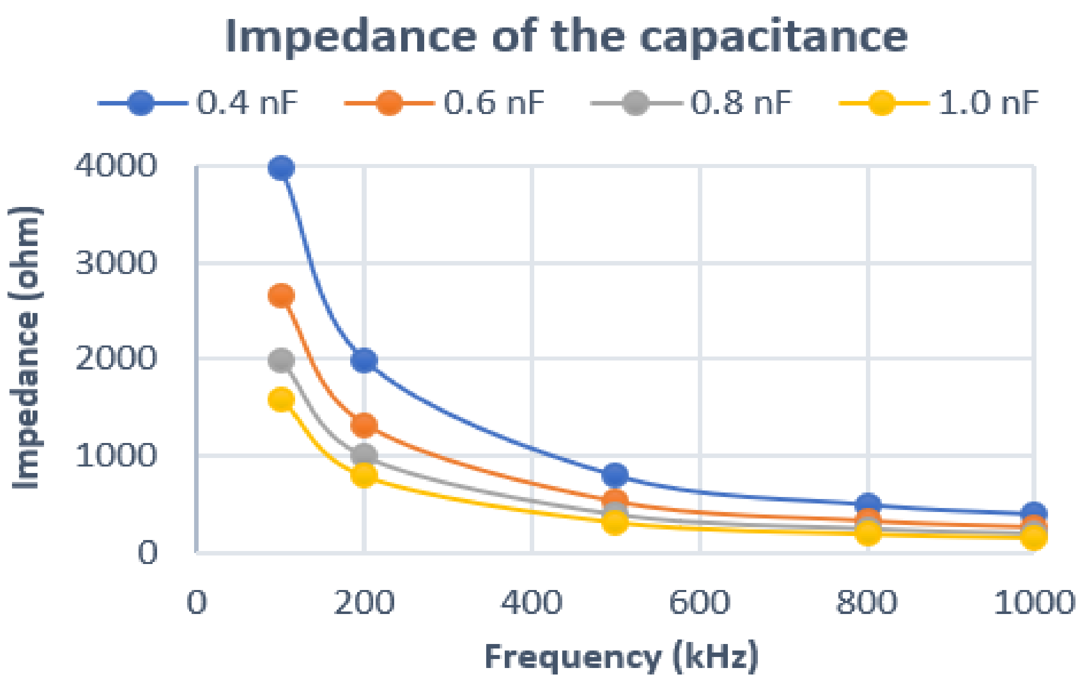
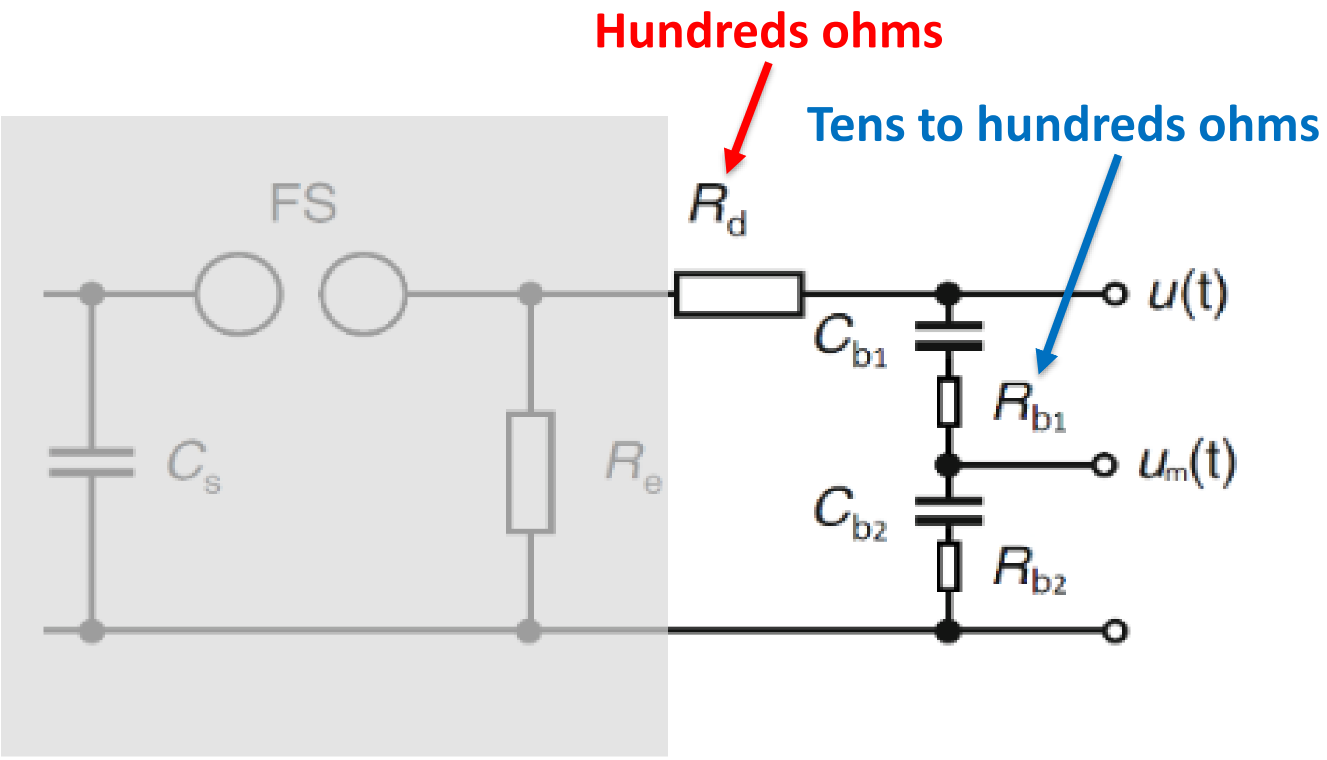



Fig. 3 Impedance of the capacitors at different frequency




Damped capacitive divider is usually designed as,

$$R_{b1} \times C_{b1} \approx (100 \sim 200)\ \Omega \cdot \text{nF} \qquad (1)$$

# 2. Circuit analysis and simulation

**Theoretical calculation:**

$$\frac{U_s}{U_0} = \frac{R_b}{R_b+R_d} \qquad (2)$$

**Simulated result:** $R_b$ =150 Ω, $R_d$ =350 Ω

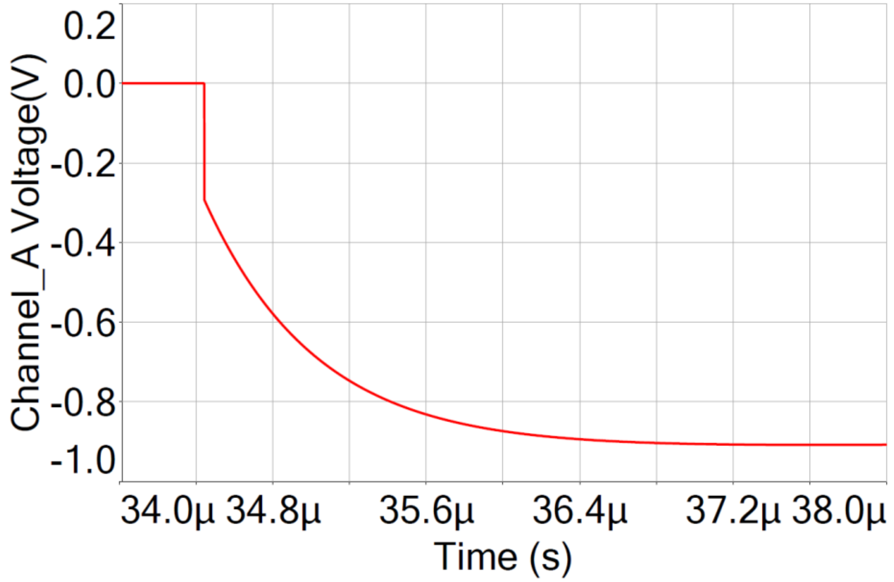



Fig 5(a) no inductances were considered in the circuit

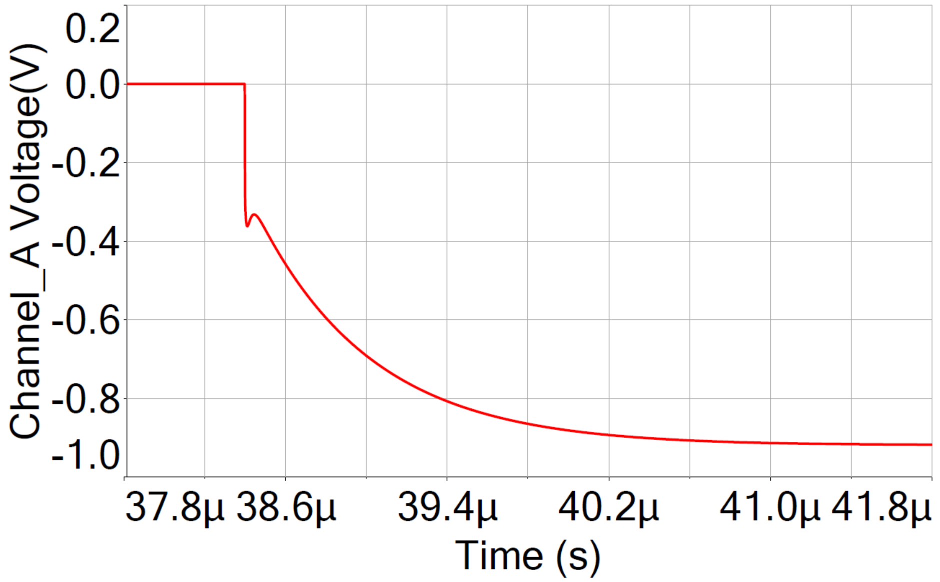



Fig5(b) inductances were added to the circuit

# Content

1. Motivation of this research
2. Circuit analysis and simulation
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# 3. Voltage step experiments

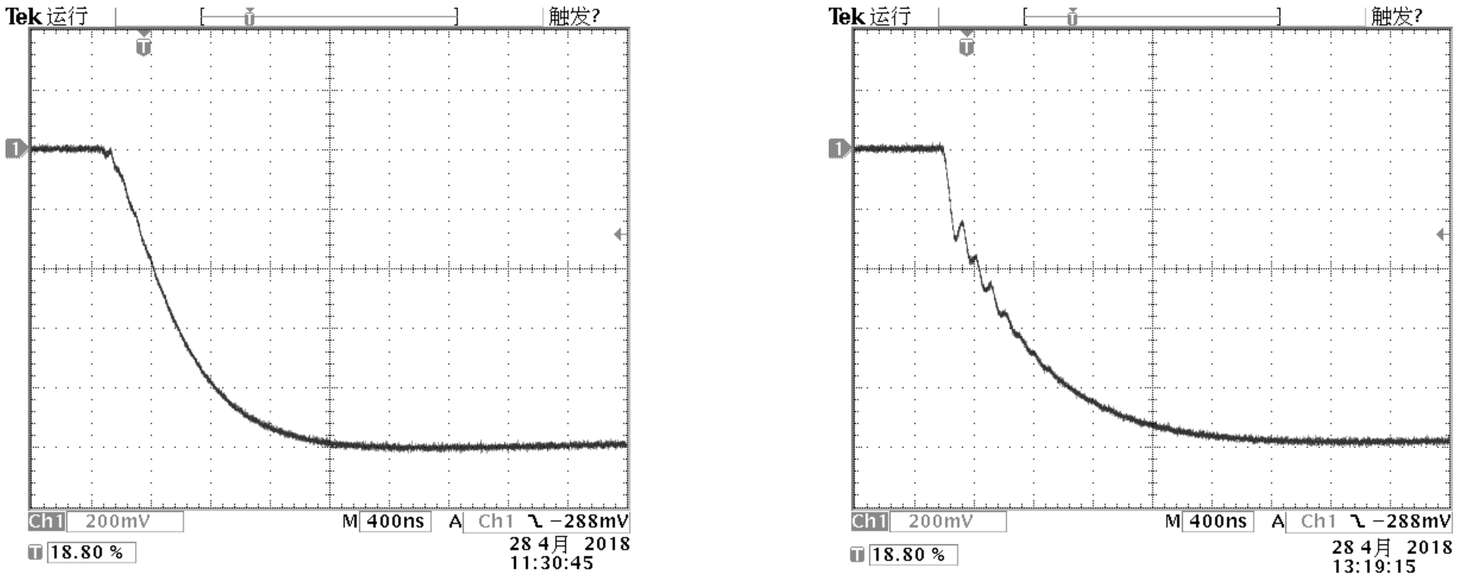



Fig. 6. recorded LI waveform, when the resistor in series with the capacitor is (a) 0, (b) 150 Ω.

| $R_b$ (Ω) | 70 | 150 | 400 |
|---|---|---|---|
| Calculated Ratio | 16% | 29% | 51% |
| Simulated Ratio with inductance | 22% | 35% | 55% |
| Simulated Ratio with no inductance | 18% | 30% | 52% |
| Measured Ratio | 18% | 27% | 47% |

# 3. Difference on two measuring systems

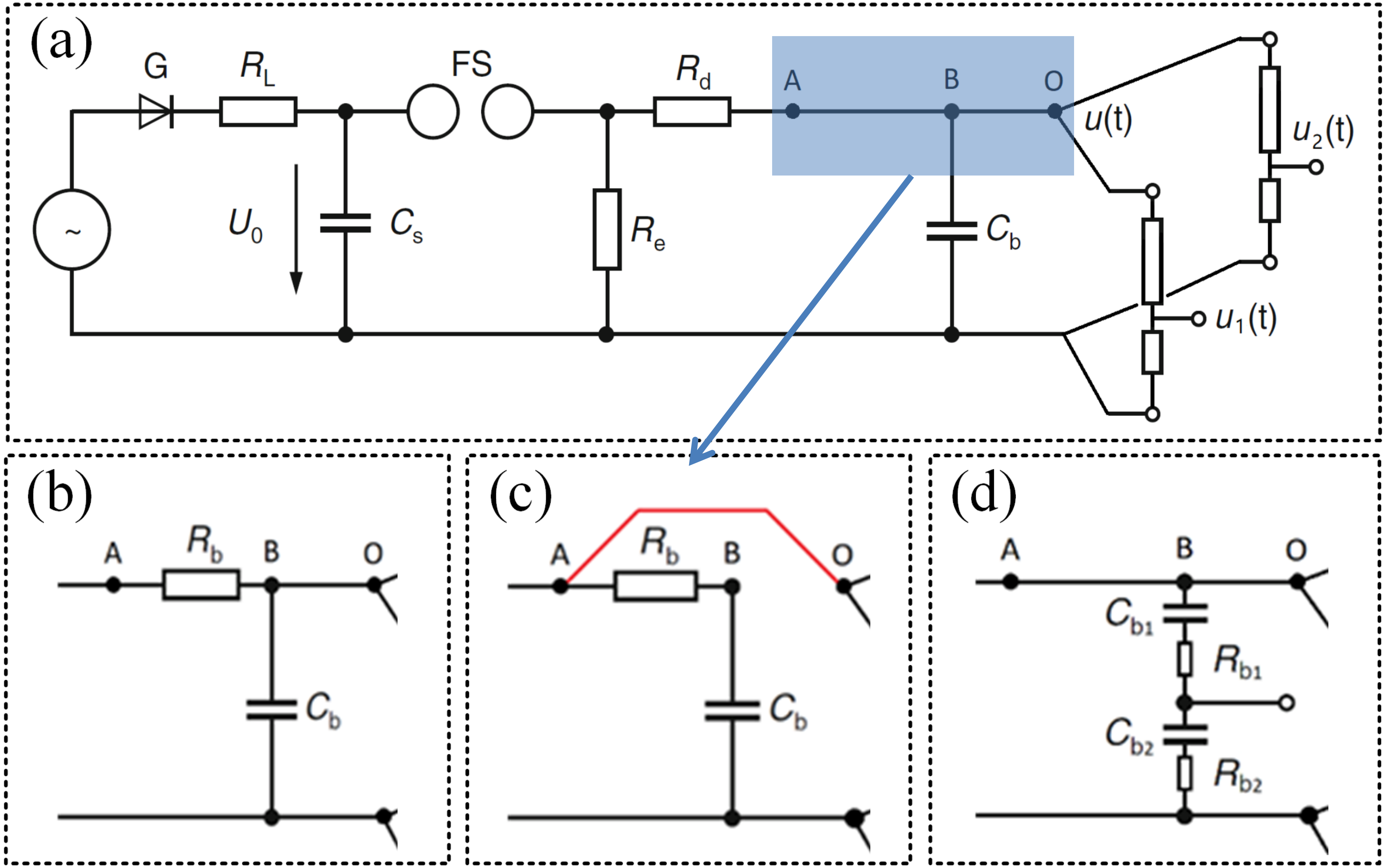



Fig. 7. experiment setup for verifying the difference between two reference measuring systems at difference LI waveform.

# 3. Difference on two measuring systems

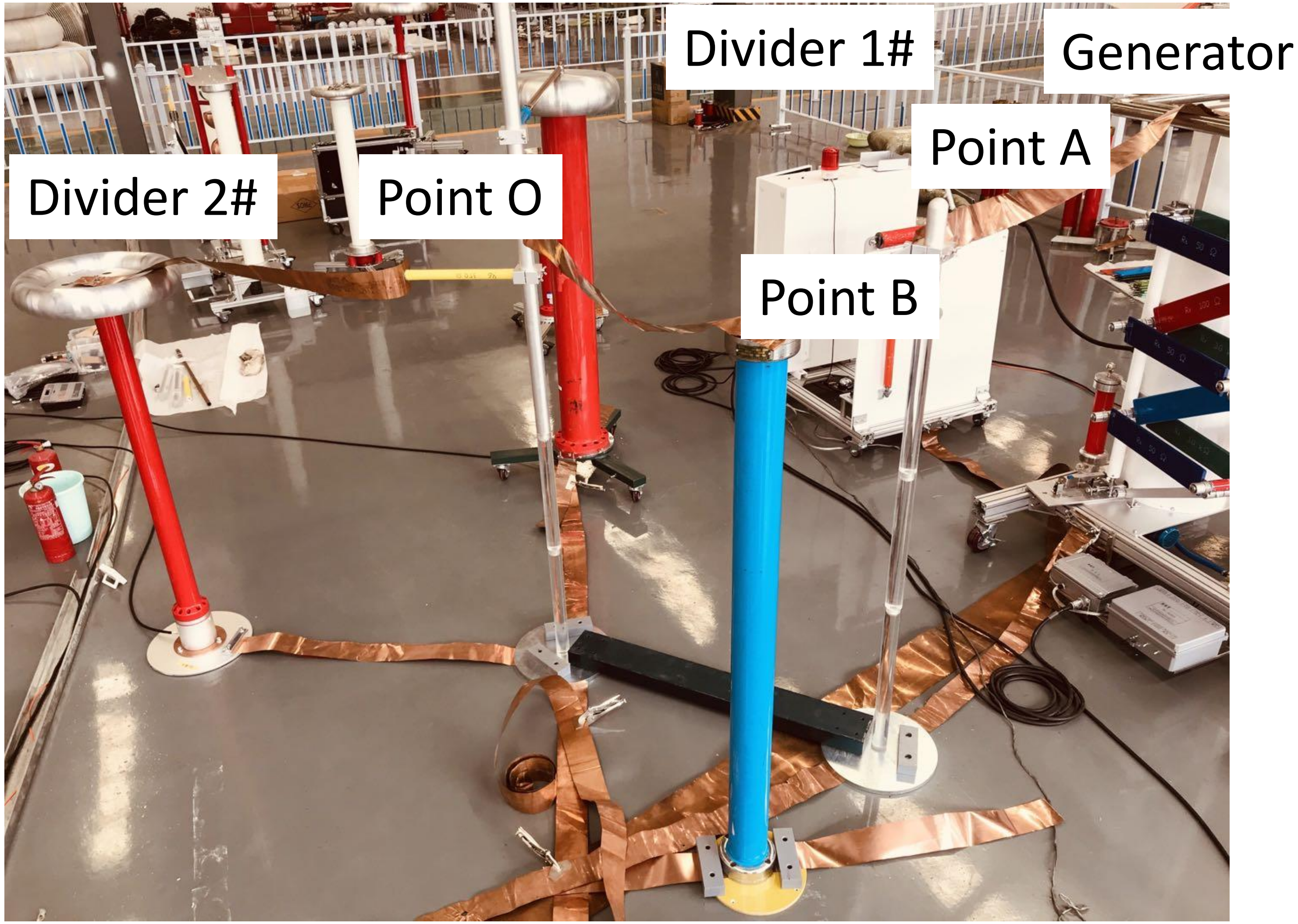



Fig. 8. Photo of the experiment setup in the laboratory

# 3. Step Response experiments

Table III. Step response parameters of dividers with different length cables

| Divider | Cable | $T_\alpha$ (ns) | $T_N$ (ns) | $t_s$ (ns) | $\beta_{rs}$ (%) |
|---|---|---|---|---|---|
| D700v2 | 30 m RG214 | 8 | 10 | 120 | 15.0 |
| D700v2 | 10 m RG214 | 5 | 6 | 80 | 18.3 |
| D600v1 | 10 m RG214 | 22 | 26 | 60 | 40.4 |

Table IV. Errors of parameters by convolving the ideal lightning impulse waveform with step response of the dividers

| Divider | Cable | Nominal $T_1$ (μs) | $U_t$ error (%) | $T_1$ error (%) | $T_2$ error (%) |
|---|---|---|---|---|---|
| D700v2 | 30 m RG214 | 0.84 | -0.0 | 2.7 | 0.4 |
| | | 1.20 | 0.1 | 2.2 | 0.3 |
| | | 1.56 | 0.1 | 1.9 | 0.2 |
| D700v2 | 10 m RG214 | 0.84 | -0.0 | 1.4 | 0.1 |
| | | 1.20 | 0.0 | 1.2 | 0.1 |
| | | 1.56 | 0.1 | 1.1 | 0.0 |
| D600v1 | 10 m RG214 | 0.84 | -0.0 | 0.4 | -0.0 |
| | | 1.20 | 0.0 | 0.5 | -0.1 |
| | | 1.56 | 0.1 | 0.5 | -0.1 |

# 3. Lightning impulse voltage experiments

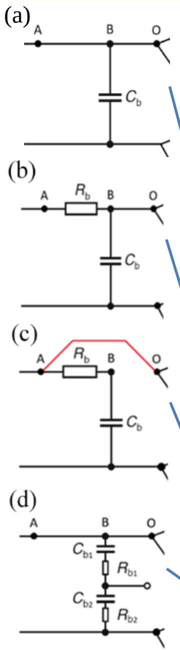



Table V. Divider D700v2 connected with 10 m RG214

| Connection | Test NO. | $R_d$ (Ω) | $R_b$ (Ω) | waveform (μs) | $\Delta U_t$(%) | $\Delta T_1$ (%) | $\Delta T_2$ (%) |
|---|---|---|---|---|---|---|---|
| Fig. 7(a) | 1 | 116 | 0 | 0.91/51 | 0.1 | 1.5 | -0.2 |
| | 2 | 164 | 0 | 1.26/52 | 0.3 | 0.7 | -0.3 |
| | 3 | 208 | 0 | 1.60/53 | 0.2 | 0.3 | -0.3 |
| Fig. 7(b) | 4 | 116+206 | 0 | 2.34/55 | 0.2 | 0.2 | -0.3 |
| Fig. 7(c) | 5 | 59 | 105 | 0.87/52 | 0.1 | 2.3 | -0.2 |
| | 6 | 116 | 206 | 1.51/54 | 0.2 | 0.8 | -0.2 |
| Fig. 7(d) | 7 | 208 | 0 | 0.83/51 | -0.2 | 1.2 | 0.0 |

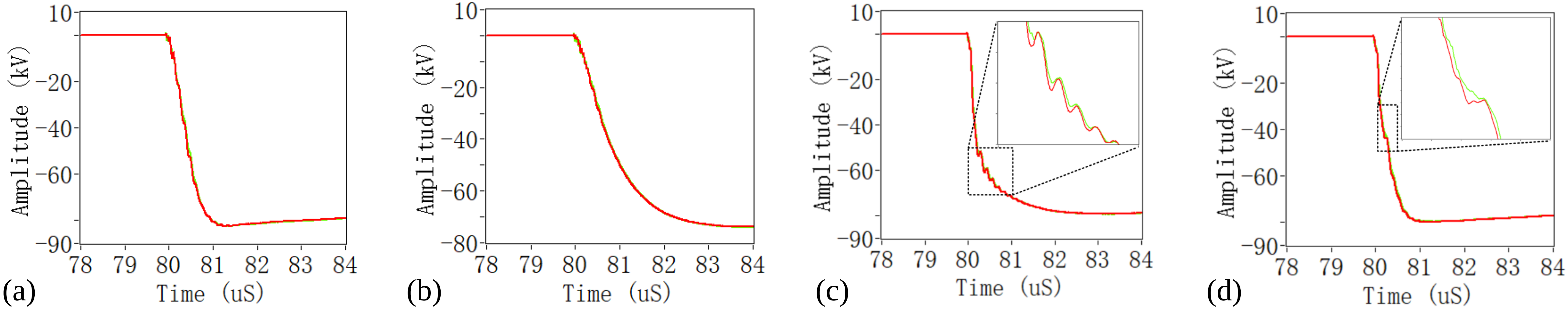



Fig. 9. recorded waveforms of the two system in (a) test 1, (b) test 4, (c) test 6, and (d) test 7

# 3. Lightning impulse voltage experiments

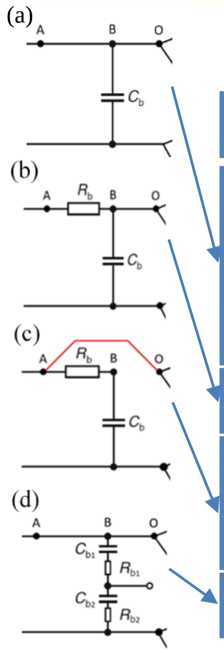



Table V. Divider D700v2 connected with 10 m RG214

| Connection | Test NO. | $R_d$ (Ω) | $R_b$ (Ω) | waveform (μs) | $\Delta U_t$(%) | $\Delta T_1$ (%) | $\Delta T_2$ (%) |
|---|---|---|---|---|---|---|---|
| Fig. 7(a) | 1 | 116 | 0 | 0.91/51 | 0.1 | 1.5 | -0.2 |
| | 2 | 164 | 0 | 1.26/52 | 0.3 | 0.7 | -0.3 |
| | 3 | 208 | 0 | 1.60/53 | 0.2 | 0.3 | -0.3 |
| Fig. 7(b) | 4 | 116+206 | 0 | 2.34/55 | 0.2 | 0.2 | -0.3 |
| Fig. 7(c) | 5 | 59 | 105 | 0.87/52 | 0.1 | 2.3 | -0.2 |
| | 6 | 116 | 206 | 1.51/54 | 0.2 | 0.8 | -0.2 |
| Fig. 7(d) | 7 | 208 | 0 | 0.83/51 | -0.2 | 1.2 | 0.0 |

Table VI. Divider D700v2 connected with 30 m RG214

| Connection | Test NO. | $R_d$ (Ω) | $R_b$ (Ω) | waveform (μs) | $\Delta U_t$ (%) | $\Delta T_1$ (%) | $\Delta T_2$ (%) |
|---|---|---|---|---|---|---|---|
| Fig. 7(a) | 11 | 116 | 0 | 0.93/51 | -0.4 | 3.8 | -0.1 |
| | 12 | 164 | 0 | 1.26/52 | -0.6 | 3.8 | 0.3 |
| | 13 | 208 | 0 | 1.61/53 | -0.5 | 1.7 | 0.0 |
| Fig. 7(b) | 14 | 116+206 | 0 | 2.33/55 | -0.4 | 1.4 | 0.0 |
| Fig. 7(c) | 15 | 59 | 206 | 0.89/53 | -0.6 | -2.6 | 0.1 |
| | 16 | 116 | 206 | 1.50/54 | -0.5 | 3.0 | 0.1 |
| Fig. 7(d) | 17 | 285 | 0 | 0.99/51 | -0.4 | 3.1 | 0.0 |

# 4. Conclusion

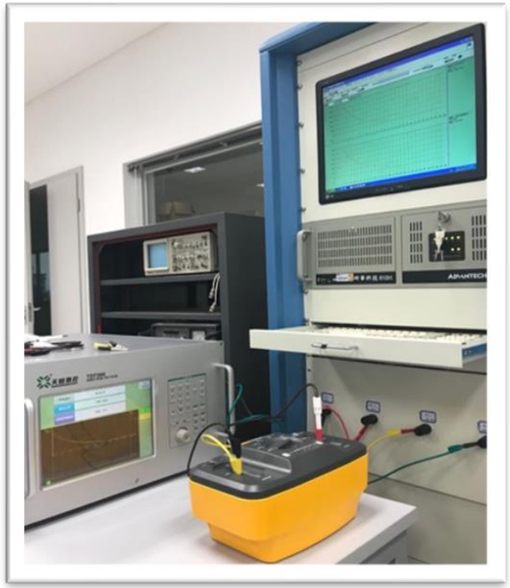
- Resistors in the damped capacitive divider has been proved to be responsible for the voltage step and oscillation on the front of lightning impulse voltage.
- The waveform parameters measured by two resistive reference standard systems were influenced by the shape of the waveform and also the oscillation on the front. It could introduce another component to the uncertainty of the result during comparison test.
- It is recommended to use impulse capacitor with low equivalent series resistance instead of damped capacitive divider as the load capacitor. This would eliminate this common cause of oscillation on the front of lightning impulse voltage waveform.
- Please contact for any discussion, zhaowei@nim.ac.cn

# $2^{nd}$ Part, 5 minutes

- Self Introduction
  - *Future collaboration and calibration,* wzhao@vsl.nl
- Preparation for LI comparison campaign in October 2022
  - Tuning the LI generator to generate smooth LI waveforms
  - Tuning the damping resistor of TU Delft for the 3500 kV

# Self Introduction

- 2014 to 2022, NIM China, Built reference system in HV area



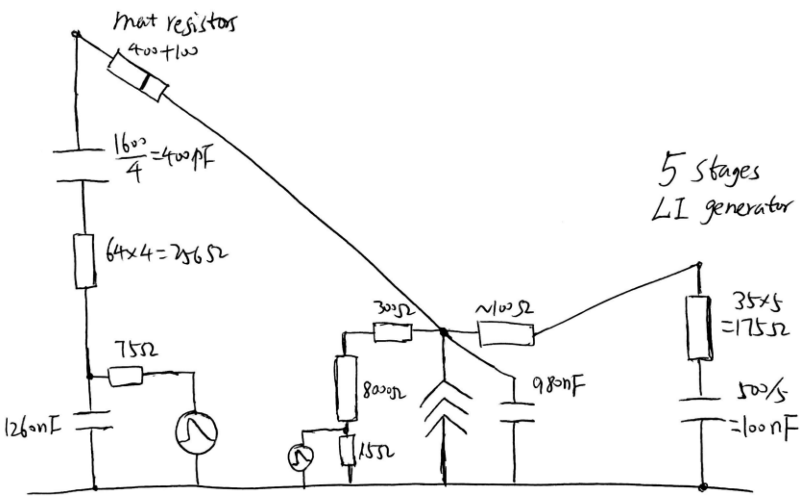
Impulse energy

Lightning Impulse voltage

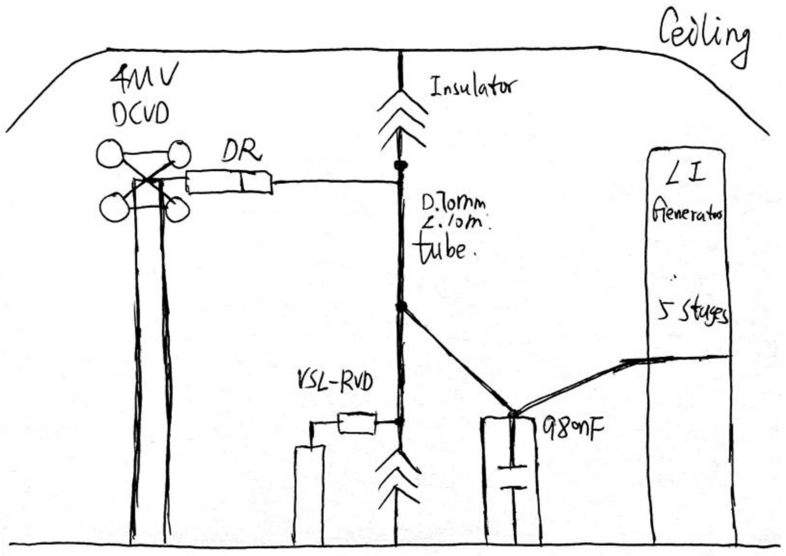
Load loss measurement

- **2022 to now, VSL Netherlands, Power and Energy metrology**

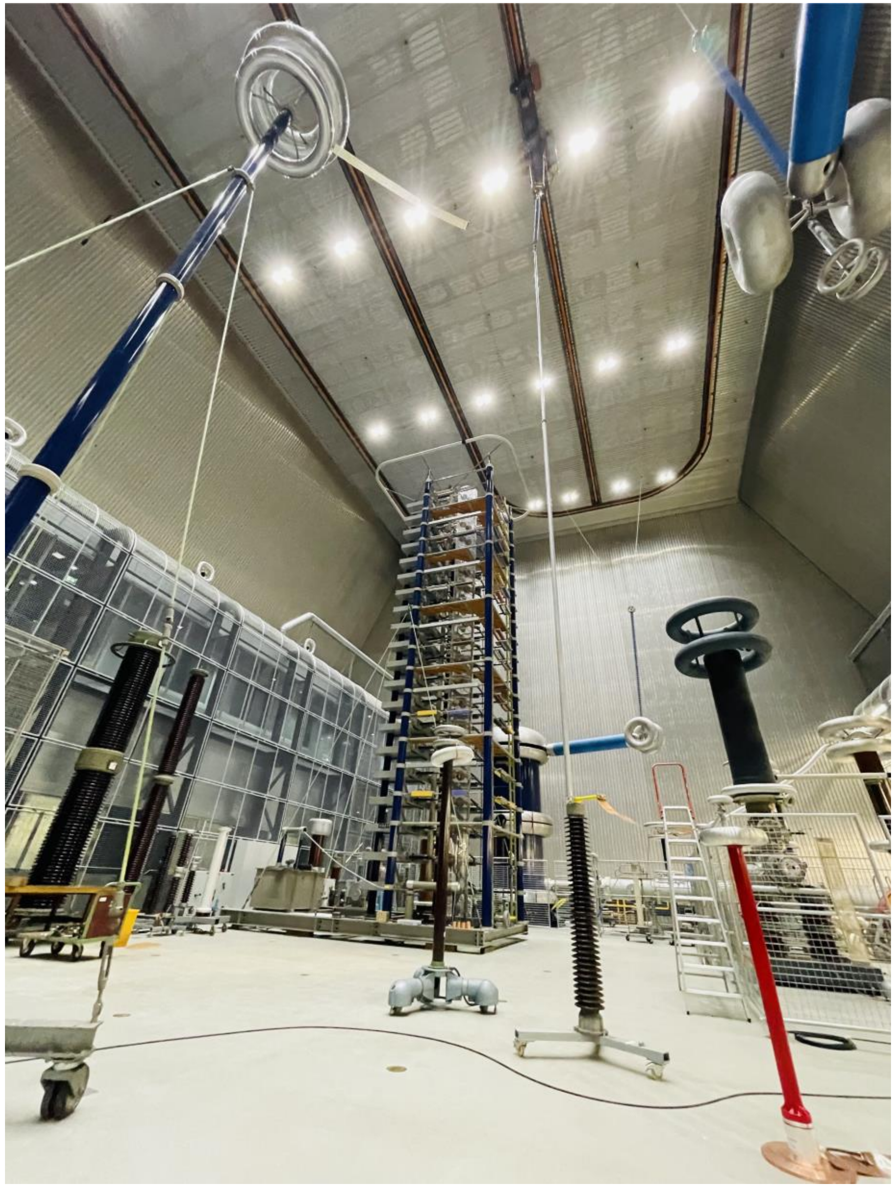
# Check and Improve the waveform of the LI generation



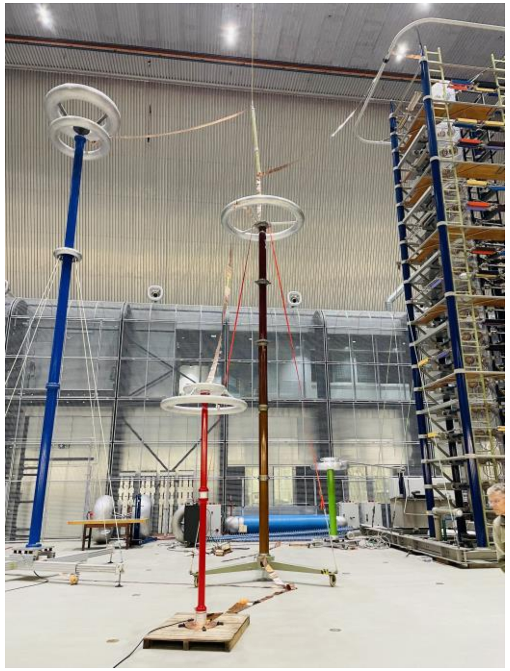

Triangle loop




Rectangular loop

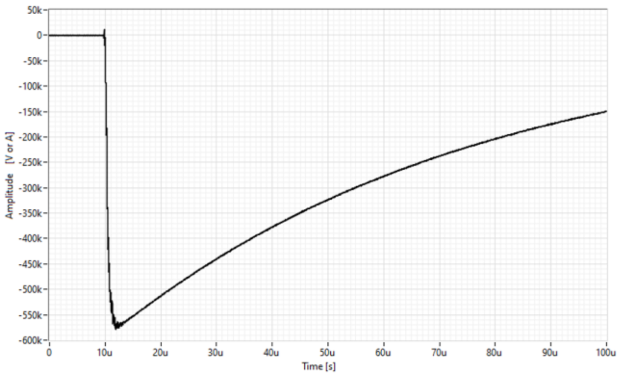


VSL 1200 kV LI system



VSL 600 kV LI system

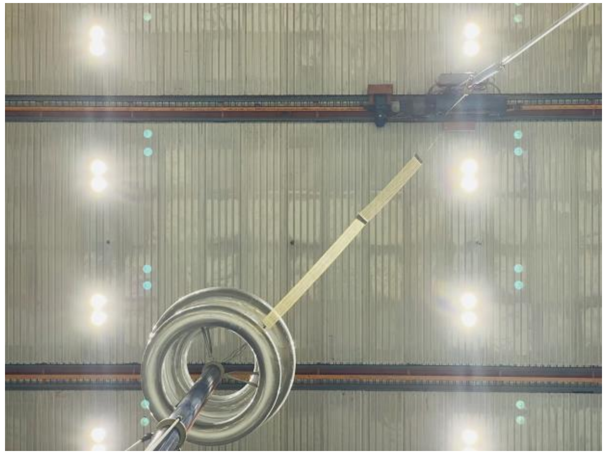
# Tuning the 4000 kV DCVD of TUD




smooth LI waveform

| STD | | | | | DUT | | | | | Error of DUT | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Record ID | Ut(kV) | T1(us) | T2(us) | b'(%) | Record ID | Ut(kV) | T1(us) | T2(us) | b'(%) | dUt(%) | dT1(%) | dT2(%) | db'(%) | |
| 13 | 270.6 | 1.444 | 47.93 | | | 263.6 | 1.176 | 47.69 | | -2.6 | -18.6 | -0.5 | | Triangular setup and Trial test |
| 15 | 272.2 | 1.312 | 47.51 | | | 264.9 | 1.094 | 47.30 | | -2.7 | -16.6 | -0.4 | | Short-circuit DR |
| 18 | 267.0 | 1.055 | 48.94 | | 50 | 259.2 | 2.450 | 50.61 | | -2.9 | 132.2 | 3.4 | | Damping resistor 200+100+1000 |
| 20 | 270.6 | 0.519 | 47.88 | | 51 | 262.9 | 2.270 | 50.07 | | -2.8 | 337.4 | 4.6 | | Remove 980nF capacitor from load capacitor |
| 23 | 274.8 | 0.768 | 46.97 | | 54 | 268.5 | 1.161 | 47.00 | | -2.3 | 51.2 | 0.1 | | Change DR to 400+200 |
| 25 | 270.2 | 1.301 | 48.18 | | 56 | 262.9 | 1.454 | 48.34 | | -2.7 | 11.8 | 0.3 | | Add 980nF Capacitor as load capacitor |
| 27 | 271.2 | 1.354 | 47.91 | | 58 | 264.2 | 1.259 | 47.85 | | -2.6 | -7.0 | -0.1 | | Change DR to 400 |
| 30 | 270.5 | 1.348 | 48.08 | | 60 | 263.8 | 1.324 | 48.03 | | -2.5 | -1.8 | -0.1 | | Change DR to 400+100 |
| 32 | 276.7 | 1.050 | 47.35 | | 62 | 268.5 | 1.124 | 46.55 | | -3.0 | 7.0 | -1.7 | | Change to Rectangular setupa and trial test |
| 35 | 274.4 | 1.209 | 47.84 | | 65 | 265.4 | 1.235 | 47.25 | | -3.3 | 2.2 | -1.2 | | Change front resistor and try different voltages |
| 37 | 364.1 | 1.223 | 47.88 | | 67 | 351.2 | 1.251 | 47.62 | | -3.5 | 2.3 | -0.5 | | |
| 38 | 454.3 | 1.260 | 48.07 | | 68 | 438.6 | 1.265 | 47.70 | | -3.5 | 0.4 | -0.8 | | |
| 39 | 544.5 | 1.265 | 48.19 | | 69 | 525.7 | 1.268 | 47.81 | | -3.5 | 0.2 | -0.8 | | |

T1 measurement improved



Tuning the damping resistor

| STD | | | | | DUT | | | | | Error of DUT | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Record ID | Ut(kV) | T1(us) | T2(us) | b'(%) | Record ID | Ut(kV) | T1(us) | T2(us) | b'(%) | dUt(%) | dT1(%) | dT2(%) | db'(%) | |
| 71 | -401.3 | 1.252 | 47.70 | | 99 | -386.1 | 1.020 | 47.35 | | -3.8 | -18.5 | -0.7 | | Remove DR from DCVD |
| 72 | -401.1 | 1.254 | 47.72 | | 100 | -385.9 | 1.022 | 47.38 | | -3.8 | -18.5 | -0.7 | | N400 |
| 73 | -401.0 | 1.253 | 47.72 | | 101 | -385.9 | 1.021 | 47.38 | | -3.8 | -18.5 | -0.7 | | |
| 74 | -401.0 | 1.253 | 47.73 | | 102 | -386.0 | 1.023 | 47.37 | | -3.7 | -18.3 | -0.7 | | |
| 75 | -401.0 | 1.250 | 47.76 | | 103 | -386.0 | 1.021 | 47.38 | | -3.8 | -18.3 | -0.8 | | |
| 76 | -572.2 | 1.274 | 48.02 | | 104 | -551.6 | 1.055 | 47.48 | | -3.6 | -17.2 | -1.1 | | N570 |
| 77 | -571.9 | 1.274 | 48.00 | | 105 | -551.3 | 1.052 | 47.50 | | -3.6 | -17.4 | -1.0 | | |
| 78 | -572.0 | 1.274 | 48.01 | | 106 | -551.2 | 1.051 | 47.49 | | -3.6 | -17.5 | -1.1 | | |
| 79 | -571.9 | 1.273 | 48.02 | | 107 | -551.3 | 1.052 | 47.51 | | -3.6 | -17.4 | -1.1 | | |
| 80 | -571.7 | 1.275 | 48.02 | | 108 | -551.2 | 1.054 | 47.50 | | -3.6 | -17.4 | -1.1 | | |
| 82 | 400.7 | 1.262 | 47.70 | | 109 | 385.9 | 1.041 | 47.45 | | -3.7 | -17.5 | -0.5 | | P400 |
| 83 | 400.7 | 1.260 | 47.69 | | 110 | 385.9 | 1.039 | 47.43 | | -3.7 | -17.6 | -0.6 | | |
| 84 | 400.8 | 1.266 | 47.69 | | 111 | 386.0 | 1.045 | 47.41 | | -3.7 | -17.4 | -0.6 | | |
| 85 | 400.6 | 1.259 | 47.68 | | 112 | 386.0 | 1.043 | 47.42 | | -3.7 | -17.2 | -0.6 | | |
| 86 | 400.8 | 1.265 | 47.69 | | 113 | 386.1 | 1.048 | 47.41 | | -3.7 | -17.2 | -0.6 | | |
| 87 | 400.8 | 1.261 | 47.69 | | 114 | 386.1 | 1.040 | 47.44 | | -3.7 | -17.5 | -0.5 | | |
| 88 | 572.3 | 1.294 | 48.00 | | 115 | 551.2 | 1.070 | 47.76 | | -3.7 | -17.3 | -0.5 | | P570 |
| 89 | 571.8 | 1.295 | 48.03 | | 116 | 551.2 | 1.073 | 47.72 | | -3.6 | -17.1 | -0.7 | | |
| 90 | 571.5 | 1.293 | 48.06 | | 117 | 551.3 | 1.073 | 47.72 | | -3.5 | -17.0 | -0.7 | | |
| 91 | 571.4 | 1.294 | 48.09 | | 118 | 551.1 | 1.071 | 47.71 | | -3.5 | -17.3 | -0.8 | | |
| 92 | 571.1 | 1.292 | 48.09 | | 119 | 551.0 | 1.072 | 47.72 | | -3.5 | -17.0 | -0.8 | | |

Before tuning

| Error of DUT | | | | |
|---|---|---|---|---|
| dUt(%) | dT1(%) | dT2(%) | db'(%) | |
| -3.5 | 0.1 | -0.7 | | Formal tests |
| -3.5 | -0.1 | -0.7 | | P570 |
| -3.5 | 0.6 | -0.7 | | |
| -3.5 | 0.5 | -0.8 | | |
| -3.5 | -0.5 | -0.7 | | |
| -3.5 | -0.1 | -0.8 | | |
| -3.6 | 2.4 | -0.5 | | P400 |
| -3.6 | 2.5 | -0.6 | | |
| -3.5 | 2.4 | -0.6 | | |
| -3.5 | 2.5 | -0.6 | | |
| -3.5 | 2.6 | -0.6 | | |
| -3.5 | 2.1 | -0.6 | | |
| -3.6 | 2.8 | -0.7 | | N400 |
| -3.6 | 2.2 | -0.7 | | |
| -3.7 | 2.1 | -0.6 | | |
| -3.7 | 2.4 | -0.7 | | |
| -3.7 | 2.4 | -0.6 | | |
| -3.6 | 2.6 | -0.7 | | |
| -3.6 | 0.1 | -1.0 | | N570 |
| -3.6 | 1.0 | -1.0 | | |
| -3.4 | 0.7 | -0.9 | | |
| -3.6 | 0.4 | -1.0 | | |
| -3.6 | 0.6 | -1.1 | | |
| -3.6 | 0.6 | -0.9 | | |
| -3.6 | 0.7 | -1.0 | | |

After tuning