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Establishment and Application of 1200-kV Lightning Impulse Voltage Reference Measuring System

Wei Zhao¹, Senior Member, IEEE, Jari Hällström², Imke Splinter³, Alf-Peter Elg⁴, Senior Member, IEEE, and Gert Rietveld⁵, Senior Member, IEEE

Abstract—The National Metrology Institute (NMI) of The Netherlands (VSL) developed a new 1200-kV reference measuring system for on-site calibration of lightning impulse (LI) voltage measuring systems. Improvement of the low-voltage grounding loop and triaxial signal transmission reduced oscillation ripples and enhanced the shielding of environmental high-frequency interference. Calibration and measurement capabilities are realized in the test voltage (U_t), front time (T_1), and time to half-value (T_2) with uncertainties of 0.7%, 3.0%, and 1.5%, respectively, up to 600 kV and 1.2%, 5.0%, and 3.0%, respectively, up to 1200 kV for direct comparison calibration. With additional linearity experiments, VSL is now able to provide LI voltage calibrations on-site up to 3000 kV. The VSL system was used as the reference for calibration and tuning of a 4000-kV LI divider to improve its accuracy performance. A measurement campaign was held to compare different LI measuring systems and research the linearity of the measuring system up to 3000 kV. The comparison results confirmed the good performance of the VSL 1200-kV reference measuring system and also indicated that the 4000-kV measuring system was improved after calibration and tuning with the VSL reference system.

Index Terms—Front oscillation, impulse test, lightning impulse (LI) voltage, measurement standard, oscillation ripple, reference measuring system, uncertainty.

I. INTRODUCTION

LIGHTNING impulse (LI) voltage measuring systems used in high-voltage (HV) test laboratories need to be calibrated periodically to ensure the test voltage amplitude and waveform shape satisfy the requirement of related standards, e.g., IEC 60060 [1], [2]. Measurement results traceable to calibration and measurement capability (CMC) of a National Metrology Institute (NMI) ensure nationwide consistency and

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international equivalence. Several NMIs have established LI voltage reference measuring systems to support the quality and technology development in electrical power grids [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13]. Recent development of extra-high-voltage (EHV) and ultrahigh-voltage (UHV) power grids put challenging demands on the development and improvement of adequate NMI LI reference measuring systems.

Driven by this demand, the 19ENG02 FutureEnergy project aimed to realize metrology solutions for grid component testing and condition monitoring required for successful implementation of future UHV transmission grids. To achieve this aim, a new UHV metrology infrastructure for reliable and traceable LI voltage measurements was created, up to and beyond 2500 kV. Measurements were performed up to 3000 kV with recommendations on criteria to meet to go beyond [14].

As part of the FutureEnergy project, the NMI of The Netherlands (VSL) built a 1200-kV LI voltage reference measuring system for calibration of industrial LI test systems. Combined with additional linearity tests, VSL can provide LI calibration services at customer's premises up to 3000 kV. VSL, the Technical Research Centre of Finland (VTT), and Delft University of Technology (TU Delft) worked together to characterize and fine-tune a 4000-kV LI generation circuit and divider.

This article is an extension of the proceedings paper [15], [16]. It introduces the establishment and on-site application of the VSL 1200-kV LI voltage reference measurement system. First, it describes the schematic and setup of the reference system, the improvement on the grounding, the characterization of system accuracy, and the propagation of measurement uncertainty. Second, it introduces the improvement on the 4000-kV LI generator to produce smooth LI waveforms without front oscillations and to optimize waveform repeatability especially at low voltages. Finally, it discusses the fine-tuning and improvement on the 4000-kV LI divider with the VSL reference system, an international LI comparison campaign, the analysis of the comparison results, and the linearity tests for LI dividers up to 3000 kV.

II. VSL 1200-kV LI REFERENCE MEASURING SYSTEM

A. Schematic and Setup

The VSL LI reference system consists of an HV divider with triaxial transmission cable (Belden 9888), an impulse

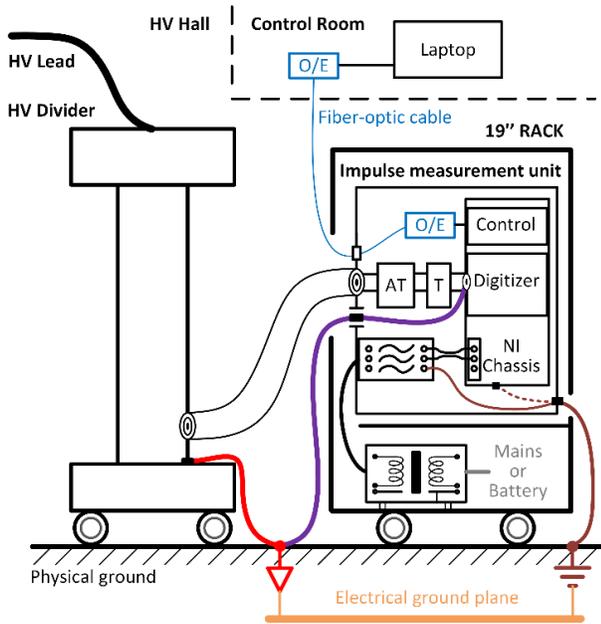


Fig. 1. Schematic of the VSL LI reference measuring system consisting of an HV divider and a measurement rack.



Fig. 2. VSL 600-kV measuring system (left) and VSL 1200-kV measuring system comparison tests with a 3600-kV LI measuring system in the TU Delft HV laboratory (right).

measurement unit, and analysis software (Figs. 1 and 2). The voltage divider is of a resistive type with two stages, each with a rated voltage of 600 kV, developed by the National Institute of Metrology of China (NIM, China). The two stages can be used separately for two 600 kV measuring systems or stacked to realize a 1200-kV measuring system. The divider output has a triaxial connector for electromagnetic compatibility and noise shielding.

The impulse measurement unit is developed by the Research Institutes of Sweden (RISE). The input triaxial connector is converted into coaxial signal transmission in the measurement unit, and the signal is then fed through an attenuator and termination resistor into the digitizer. A 12-bit digitizer (NI PXI-5124) with 145-MHz bandwidth and 200-MS/s sampling rate is used for waveform recording, satisfying the requirement of IEC 61083-1 [17]. The analysis software is designed according to the waveform parameter definition in IEC 60060 [1] and verified according to IEC 61083-2 [18].

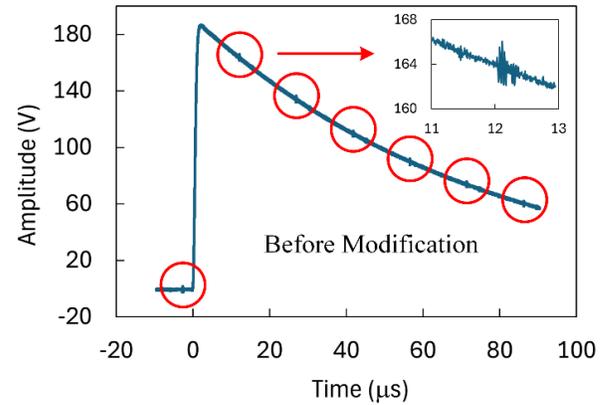


Fig. 3. Recorded LI waveforms with original grounding configuration.

The measuring circuit is grounded at the HV divider to the grounding plane in the HV hall, indicated with the red-colored grounding wire in Fig. 1. The lower terminal of the digitizer's BNC input is grounded through the triaxial cable at the divider side. In addition, another copper foil colored purple is added next to the triaxial cable, which provides another low-inductance path parallel to the cable guard but still keeps the circling area between these two grounding paths small enough to avoid picking up environmental EMC influence.

The safety ground of the 19" rack, the digitizer chassis, and the ac EMC filter are colored brown and grounded to another point in the HV hall. The grounding wire between the NI chassis' grounding point and the safety grounding point of the 19" rack could optionally be disconnected to avoid possible influence picked up by the measurement ground from the safety ground. The safety grounding and measuring grounding points are connected to the electrical ground plane; however, there could be some slight potential difference, but this will not influence the measurement.

The isolating transformer's power supply could be connected to the mains from the HV hall or control room, or supplied by a UPS, and the grounds of the input and output terminals of the isolating transformer are not connected.

B. Grounding Improvement

After the VSL LI reference system was assembled, preliminary tests with a portable 2-kV LI generator revealed some high-frequency oscillation ripples on the measured LI waveforms (Fig. 3).

Following an analysis of the simplified divider schematic and the measuring unit as illustrated in Fig. 4(a), the inductance in the low-voltage (LV) part of the divider was found to influence the step response of the divider significantly, especially the inductance L_2 . It caused the step response to have a strong overshoot [Fig. 4(b)], so the digitizer tends to easily pick up environmental noise or oscillation ripples in the measurement circuit. It does not necessarily result in significant errors in LI measurement, as an LI waveform with front time greater than $0.84 \mu\text{s}$ contains negligible frequency components above 3 MHz [19]. The values of the circuit components given in Fig. 4(a) are estimated, so there may be some difference from the actual values. Stray capacitances in

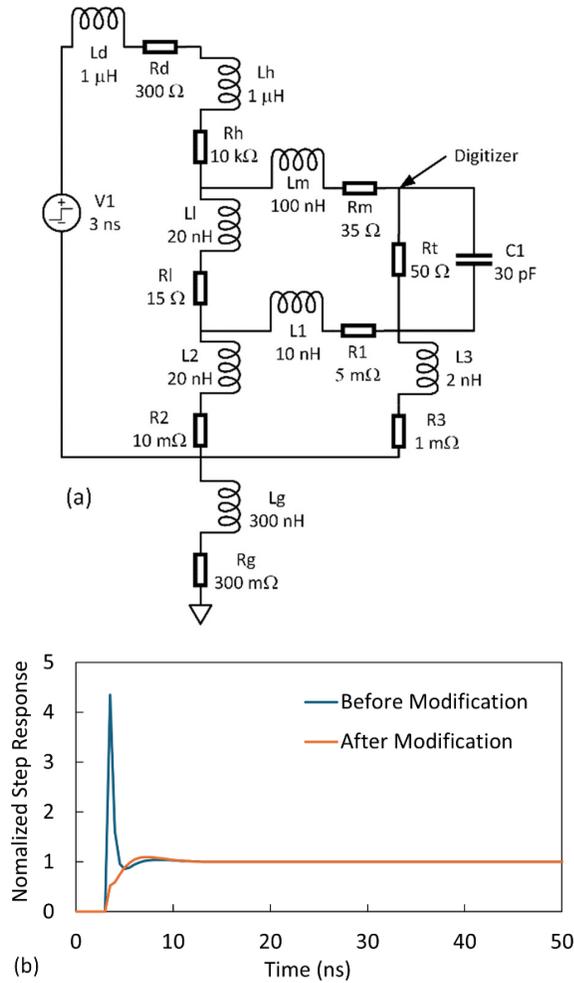


Fig. 4. Circuit simulation analysis on the LI reference divider, with (a) simplified circuit diagram and (b) simulated step response before and after modification of the LV part of the divider.

the divider are ignored, and the model is not precisely the same as the actual divider, but the analysis indicated the key part in the system that needs to be improved, and the difference in the simulation results before and after the modification as given in Fig. 4(b) illustrates the significant improvement resulting from the modification.

Descriptions of components in the model of Fig. 4(a) are as follows.

$L_d R_d$: inductance and resistance of the damping resistor and the copper foil to the HV arm.

$L_h R_h$: inductance and resistance of the HV arm.

$L_l R_l$: inductance and resistance of the LV arm.

$L_m R_m$: inductance and resistance of the matching resistor.

C_1 : capacitance of the digitizer input impedance.

R_t : resistance of the termination resistor.

$L_1 R_1$: inductance and resistance from the LV arm to the guard conductor of the output triaxial connector.

$L_2 R_2$: inductance and resistance from the LV arm to the ground plate of the divider.

$L_g R_g$: inductance and resistance from the ground plate of the divider to the grounding point in the HV hall.

$L_3 R_3$: inductance and resistance from the guard conductor of the output triaxial connector to the ground plate.

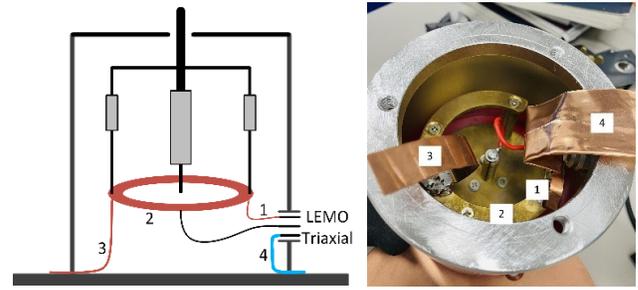


Fig. 5. Change in the grounding in the LI divider with wide Cu foil (blue, "4"), in parallel to the existing ground ("1, 2, 3"), to realize a low-inductance ground for the signal low connection.

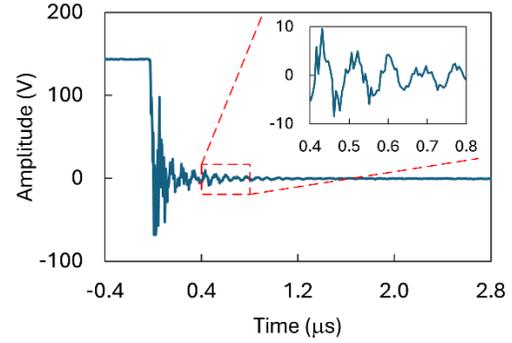


Fig. 6. Measured step response of the LI reference divider after grounding modification shown in Fig. 5.

To mitigate the influence of L_2 , the grounding loop in the divider was changed as shown in Fig. 5. A wide piece of copper foil was added from the output connector of the divider to the grounding plate directly, in parallel with the existing grounding, to significantly reduce the inductance in the output grounding connection, which was estimated to be roughly 2 nH.

Step response tests were performed, and the waveforms were recorded with a digitizer in the measuring system. As Fig. 6 shows, a symmetrical oscillation period was reached within 0.4 μ s. The origin of this oscillation is not known, and not covered by the model in Fig. 4. However, such small oscillations are not a problem, especially if they are symmetrical and the amplitude of the oscillation is only several percentages of the normalized amplitude of the step response (see also Annex C of IEC 60060-2:2010 [2]). Actually, the key performance indicator parameters of the step response, including the experimental response time T_N , partial response time T_a , and settling time t_s are all improved. Especially the settling time t_s is reduced from 220 to 130 ns, which is an important indication of improvement. Convolution of the step response signal recorded before and after the modification with ideal LI waveforms, and the differences are less than 0.02%, both for T_1 and T_2 , indicating that the improvement does not influence the LI measurement values but leads to reduced noise and thus improved accuracy.

In addition, the safety chassis ground and analog signal reference ground in the measurement unit were separated, as illustrated in Fig. 1, to improve EMC shielding and reduce noise influence on the analog ground.

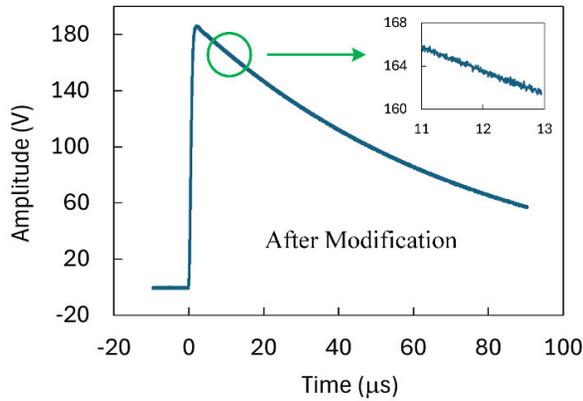


Fig. 7. Recorded LI waveforms after grounding improvement.

LI comparison tests with another divider were performed before and after the modification for verification of the impact of these changes on the LI reference system accuracy. The difference between these two systems in test voltage, front time, and time to half-value measurement changed less than 0.1% before and after the modification. This supports the results from the step response tests that the modification mainly improved the high-frequency robustness but did not change LI measurement values. Fig. 7 is the recorded waveform after the improvement, which is much smoother than the initial waveform. All the oscillation ripples are eliminated, and the high-frequency noise is also reduced.

C. System Accuracy Characterization and Measurement Uncertainty Propagation

Extensive experiments have been conducted in NIM (China), RISE (Sweden), and VSL (The Netherlands) to validate the performance of the individual components and the combined system. The divider, attenuator, termination resistor, digitizer, and analysis software have been calibrated individually following IEC 61083 [17], [18]. The resistances of the components in the measuring system were separately measured and subsequently used to calculate the system scale factor. It was compared with the measured dc voltage scale factor of the system, and the difference is only 0.06%. The step response of the divider was measured and used for convolution with LI waveforms (0.84/60 μ s and 1.56/60 μ s) to check the errors caused by the nonideal dynamic response of the system, which are less than 0.3% for both the front time and time to half-value. Initial checks have been done for the digitizer to verify its performance of nonlinearity, rise time, internal noise influence, and interference influence. Routine tests on the digitizer, together with the analysis software, were performed to calibrate the measuring errors of test voltage (peak voltage), front time, and time to half-value using a standard LV LI calibrator [20]. The temperature coefficient of the divider (0.006%/K), attenuator (0.004%/K), termination resistor (0.004%/K), and digitizer (0.05%/K) were all measured to allow for scale factor correction at nonnominal temperatures.

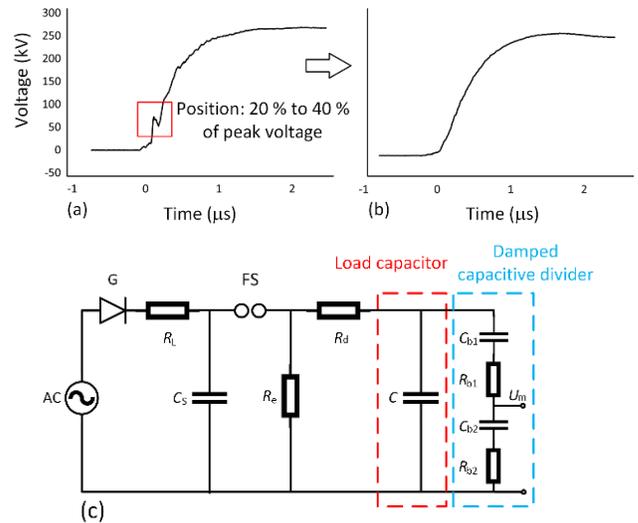


Fig. 8. Front oscillation of the TU Delft 4000-kV generator (a) is significantly reduced (b) by adding a 400-pF HV capacitor as load to the generator circuit (c).

The whole system was calibrated following IEC 60060-2 [2]. Type tests of the system were performed to check the short-term stability (0.02%), ambient temperature effect, proximity effect (0.01% for test voltage, 0.05% for front time, and 0.00% for time to half-value) and the effect of the analysis software (0.02% for test voltage, 0.19% for front time, and 0.03% for time to half-value). Performance tests of the system were conducted to calibrate the scale factor and the time parameter for short front ($\sim 0.84 \mu$ s) and long front ($\sim 1.56 \mu$ s) LI waveforms. Long-term stability was checked by repeating the measurement on the divider, attenuator, resistor, digitizer, and the whole system periodically.

The results of all these tests were used for system accuracy characterization and measurement uncertainty propagation. Uncertainty budgets of test voltage and front time measurement at 600 kV are given in Tables I and II. For explanation of quantities, refer to IEC 60060-2 [2]. In 2023, VSL registered the CMCs in the mutual recognition arrangement database (KCDB) of the International Bureau of Weights and Measures (BIPM), as given in Table III [21].

III. OPTIMIZING THE 4000-KV LI GENERATOR

A. Improved Generator Circuit With Reduced Front Oscillations

In IEC 60060-1, the front time is defined as 1/0.6 times the interval between the instants when the impulse is 30% and 90% of the peak value on the test voltage curve. And in Annex B.3, it introduces the procedure for evaluation of parameters of full lighting impulses, indicating the data to be used for analysis of the front time start from the last sample on the front having a voltage value less than 0.2 times the extreme value [1]. So, front oscillations, especially those between 20% and 40% of the peak value, could significantly influence the front time measurement results. Front oscillations had been proven to strongly influence the consistency of results between reference LI measuring systems from different

TABLE I
600-kV TEST VOLTAGE U_t UNCERTAINTY BUDGET

Quantity		Standard Uncertainty (%)	Distribution	Uncertainty Contribution (%)
u_{ref}	Combined standard uncertainty of the reference system at its calibration	0.22	normal	0.22
u_A	Statistical Type A uncertainty	0.05	normal	0.05
u_{B0}	Non-linearity in the calibration range by direct comparison measurement	0.05	rectangular	0.05
u_{B1}	Reference system Non-linearity	0.12	rectangular	0.12
u_{B2}	Reference system Dynamic behaviour	0.17	rectangular	0.17
u_{B3}	Reference system Short-term stability	0.02	rectangular	0.02
u_{B4}	Reference system Long-term stability	0.05	rectangular	0.05
u_{B5}	Reference system Ambient temperature effect	0.01	rectangular	0.01
u_{B6}	Reference system Proximity effect	0.01	rectangular	0.01
u_{B7}	Reference system Software effect	0.02	rectangular	0.02
u_{cal}	Combined standard uncertainty of the approved measuring system	/	/	0.3
U_{cal}	Combined uncertainty ($k=2$)	/	/	0.6

TABLE II
600-kV FRONT TIME T_1 UNCERTAINTY BUDGET

Quantity		Standard Uncertainty (%)	Distribution	Uncertainty Contribution (%)
u_{ref}	Combined standard uncertainty of the reference system at its calibration	1.00	normal	1.00
u_A	Statistical Type A uncertainty	0.20	normal	0.20
u_{B0}	Non-linearity in the calibration range by direct comparison measurement	0.40	rectangular	0.40
u_{B1}	Reference system Non-linearity	0.80	rectangular	0.80
u_{B2}	Reference system Dynamic behaviour	0.18	rectangular	0.18
u_{B3}	Reference system Short-term stability	0.10	rectangular	0.10
u_{B4}	Reference system Long-term stability	0.20	rectangular	0.20
u_{B5}	Reference system Ambient temperature effect	0.10	rectangular	0.10
u_{B6}	Reference system Proximity effect	0.10	rectangular	0.10
u_{B7}	Reference system Software effect	0.20	rectangular	0.20
u_{cal}	Combined standard uncertainty of the approved measuring system	/	/	1.4
U_{cal}	Combined uncertainty ($k=2$)	/	/	2.8

NMIs [5]. After circuit analysis and experiments, it was found that one reason for front oscillations is that the load capacitor of the LI generator is often omitted when a damped capacitive voltage divider (DCVD) is used as the measurement unit [22]. The oscillation is more obvious if only a few stages of the LI generator are used, e.g., when five stages of a 20-stage 4000-kV LI generator are used to produce test voltages less than 1000 kV. Test results of the TU Delft LI generator in Fig. 8 show that the generated LI waveform shape can be significantly improved by adding a proper load capacitor.

B. Secondary (Tail) Gaps of the LI Generator

The maximum output voltage of the 14-m-high 20-stage impulse voltage generator at the TU Delft is 4000 kV, with 200-kJ respective energy. The generator has secondary (tail) spark gaps in the discharge circuit to improve the efficiency of the circuit (see Fig. 9). The permanently connected tail resistor has a high value (typically optimized for switching impulse voltage). During LI testing, a lower valued tail resistor is connected to the circuit around the time when the peak in voltage is reached. This connection is made using the secondary (tail) gap. These tail gaps do not have a forced

TABLE III
VSL CMCs FOR LI VOLTAGE

Rated voltage (kV)	Test voltage U_t (%)	Front time T_1 (%)	Time to half-value T_2 (%)
Up to 600	0.7	3.0	1.5
600 to 900	0.9	4.0	2.0
900 to 1200	1.2	5.0	3.0

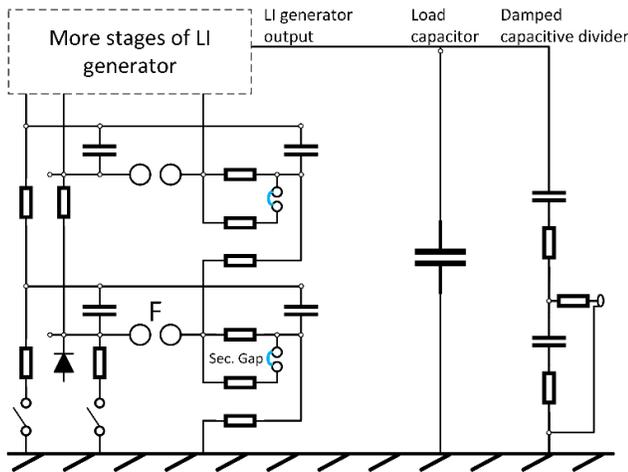


Fig. 9. Principal connection of the TU Delft impulse voltage generator and a damped capacitive divider. Generator secondary (tail) gaps were shorted during the comparison campaign to improve repeatability in impulse shape.

trigger, and the scatter in timing of the sparkover of these gaps leads to variations in the impulse shape. To stabilize the impulse shape, especially to improve repeatability at low charging voltages, these gaps were shorted during this study. In addition, due to the age of the generator, it was charged only up to 90% of the nominal maximum value to reduce the stress on the charging capacitors. Given the loading by the dividers in the tests, the final maximum voltage reached was 3000 kV.

IV. CALIBRATE AND FINE-TUNE THE 4000-kV LI DIVIDER

A. Fine-Tune the 4000-kV Divider

The VSL LI measuring system was used as the reference to calibrate and fine-tune the TU Delft 4000-kV LI divider, by changing different external damping resistors. A resistor with 500- Ω resistance was finally chosen based on the comparison results. Fig. 10 shows the schematic of the calibration setup. The difference in front time (T_1) measurement result of the TU Delft and VSL systems at a test voltage of 570 kV was improved from -17% to 1% by tuning the damping resistor.

B. Comparison Campaign for Verification

In October 2022, a multilateral comparison campaign was performed in the TU Delft HV laboratory, with measuring systems from different NMIs, industrial HV manufacturers, and research institutes. Three kinds of LI dividers were used during the campaign: resistive dividers (R), damped capacitive

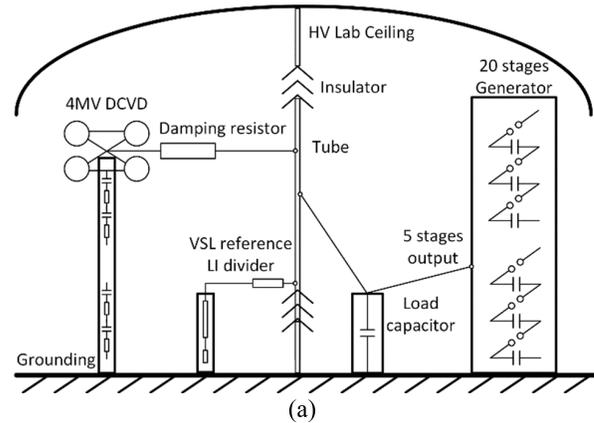


Fig. 10. Calibrating and tuning the TU Delft 4000-kV LI divider, with (a) schematic of the circuit for 4000-kV divider calibration and tuning and (b) photograph of the actual experiment in the TU Delft HV laboratory.

dividers (CR), and universal dividers with a resistive arm in parallel with a damped capacitive arm (RCR).

Fig. 11 illustrates the test voltage comparison result. Most of the dividers agree with the VTT reference system R400 within 0.5%, indicating the accuracy of these LI measuring systems and the good arrangement of this comparison campaign. The agreement of the R600 (600 kV) and R1200B (1200 kV) VSL reference systems with the reference R400 (400 kV) is better than 0.2% for both the positive and negative waveforms,

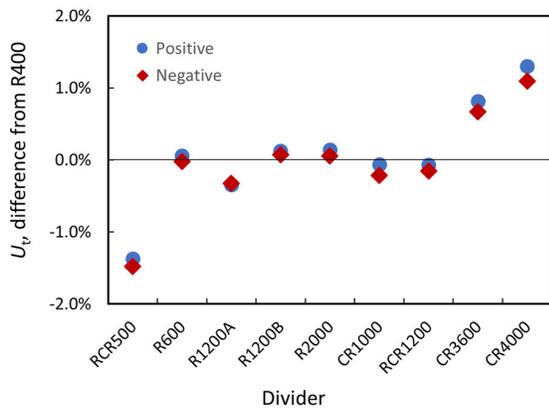


Fig. 11. Test voltage U_t comparison results of the 400-kV international comparison campaign (based on [23]). The R400 system is used as reference, to make the link to the worldwide comparison EURAMET.EM-S42 [5].

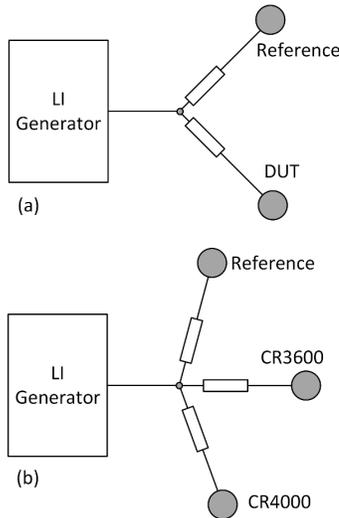


Fig. 12. Top view of the comparison circuit, (a) normal circuit for the comparison test and (b) circuit used for CR3600 and CR4000.

indicating the excellent performance of the VSL reference measuring system.

Three dividers deviate more than 0.5% from the R400 reference system. RCR500 system has an error of -1.5% , because it had been modified by the partner some time ago, and after that it had not been calibrated before the campaign. This test voltage error of -1.5% underlines the importance and necessity of calibration for achieving reliable measurement results during HV tests.

The results of the two dividers, CR3600 and CR4000, have higher errors compared with the other dividers. This is an unexpected result, as both these dividers were calibrated by NMIs before the campaign, and they were expected to agree with the reference divider within 0.5%. The experiment recordings were analyzed, and it was found that there was a special arrangement for these two dividers, different from other dividers. As Fig. 12(b) illustrates, they were connected with the reference divider simultaneously for the comparison tests, which means there are two devices under test (DUTs) connected with the reference simultaneously. For the other dividers, as Fig. 12(a) illustrates, there is only one DUT each time connected to the reference divider, which is usually the

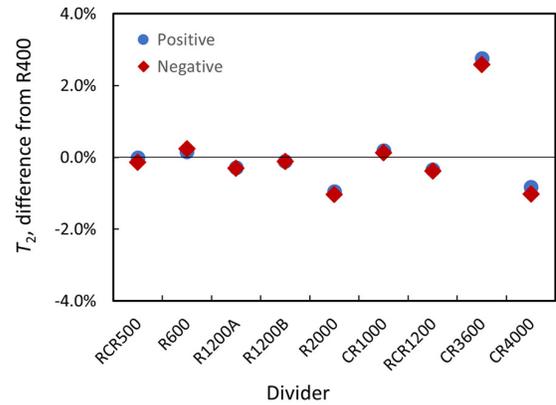
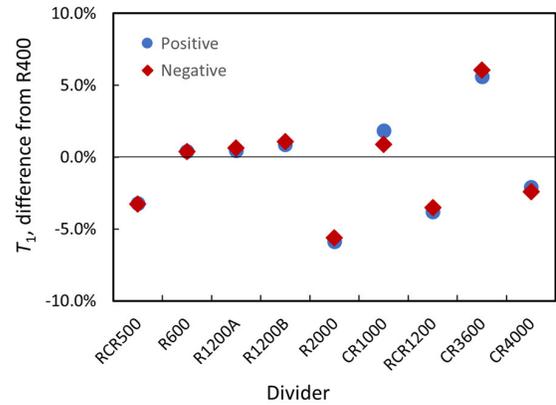


Fig. 13. Front time T_1 and time to half-value T_2 comparison results of the 400-kV international comparison campaign (based on [23]). The R400 system is used as reference, to make the link to the worldwide comparison Euramet.EM-S42 [5].

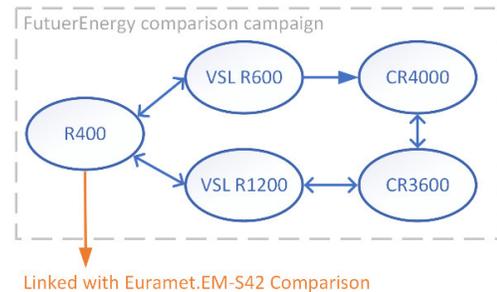


Fig. 14. Schematic of the traceability chain for CR3600 and CR4000 using the VSL 600- and 1200-kV measuring systems.

case during DUT calibration. We thus conclude that the test circuit may have introduced interference between these three dividers and measuring systems, which may be the source of the significant errors.

The front time T_1 and time to half-value T_2 comparison results are illustrated in Fig. 13. The R600 and R1200B VSL reference systems agree with the reference R400 by better than 1% for front time and 0.3% for time to half-value, again indicating the accuracy and very good performance of the VSL reference systems.

C. Revised Comparison Results of CR3600 and CR4000

Since the test circuit may have influenced the CR3600 and CR4000 test results, other comparison test results were used

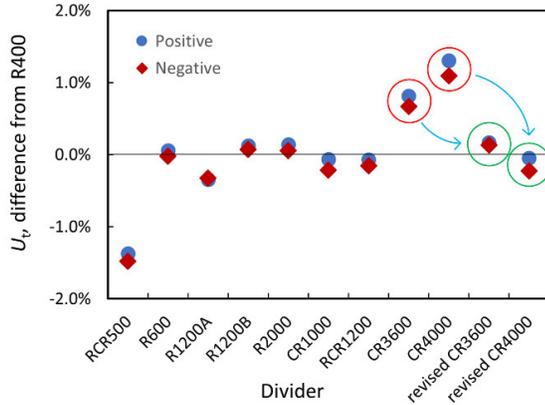


Fig. 15. Revised test voltage comparison results for CR3600 and CR4000, using the comparison scheme of Fig. 14.

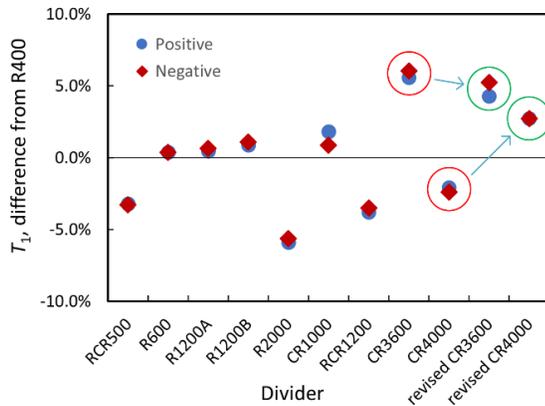


Fig. 16. Revised front time comparison results for CR3600 and CR4000, using the comparison scheme of Fig. 14.

to provide an alternative method to determine these dividers' errors. Fig. 14 illustrates this alternative traceability route to determine the errors of CR3600 and CR4000, based on the comparison between these two dividers with the VSL reference measuring systems.

The revised test voltage U_t errors of CR3600 and CR4000 using the VSL and VTT reference systems are given in Fig. 15. The U_t error of CR3600 is reduced from 0.8% to 0.2%, and from 0.7% to 0.1% for positive and negative waveforms, respectively. The U_t error of CR4000 is reduced from 1.3% to 0.0%, and from 1.1% to -0.2% for positive and negative waveforms, respectively. Thus, the U_t error of both the dividers is significantly improved to a much more reasonable level, given the calibration uncertainty range of the initial NMI calibrations before the comparison campaign.

As Fig. 16 illustrates, the T_1 error of CR3600 is reduced from 5.6% to 4.3%, and from 6.1% to 5.2% for positive and negative waveforms, respectively. The T_1 error of CR4000 is changed from -2.1% to 2.7%, and from -2.4% to 2.7% for positive and negative waveforms, respectively. The difference between CR3600 and CR4000 is significantly reduced by 6%, from 7.7% to 1.6%, and from 8.5% to 2.5%, for positive and negative waveforms, respectively. The T_1 error of CR3600 is not changed too much, but the results for CR4000 show a

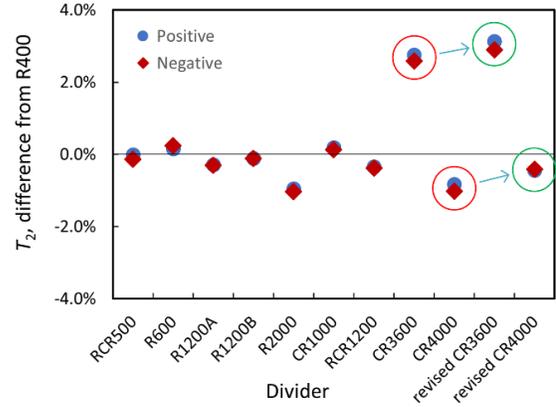


Fig. 17. Revised time to half-value comparison results for CR3600 and CR4000, using the comparison scheme of Fig. 14.

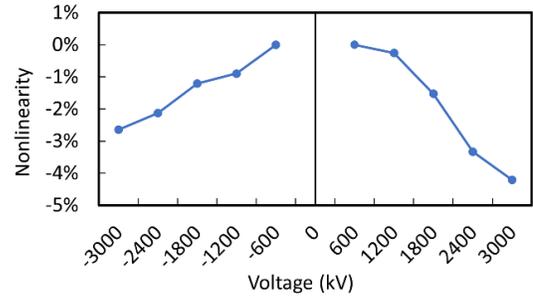


Fig. 18. Initial linearity calibration result of the 4000-kV LI divider for both negative (left) and positive (right) test voltages. The test results at 600 kV are taken as the reference for linearity measurement and thus have zero error.

significant difference, indicating that interference and environmental change influenced the dynamic response of the CR4000 divider more significantly.

Finally, Fig. 17 illustrates that the T_2 error of CR3600 changes from 2.8% to 3.1%, and from 2.6% to 2.9% for positive and negative waveforms, respectively. The T_2 error of CR4000 changes from -0.8% to -0.4% , and from -1.0% to -0.4% for positive and negative waveforms, respectively. Clearly, T_2 errors of both the dividers have not changed too much, showing that the interference has not influenced T_2 errors very much. The higher T_2 error of CR3600 compared with other dividers can be related to the nonideal step response of this divider. Further checks and tuning of this divider to improve the step response and reduce the T_2 error will be part of future work.

The finding that the change in traceability route has more influence on U_t and T_1 but not much on T_2 is an indication that the influence mainly occurred during the rising period of the LI waveforms, which includes more high-frequency components of the signals. The phenomenon may be related to reflections of the signal or to the stray capacitance of the circuit loop.

V. LINEARITY EXPERIMENT

Before the comparison campaign, a linearity calibration of the 4000-kV LI measuring system was performed with an HV dc measurement system monitoring the charging voltage of the LI generator as the reference, and the results are shown in Fig. 18. From 600 to 3000 kV, the scale factor changes -2.6%

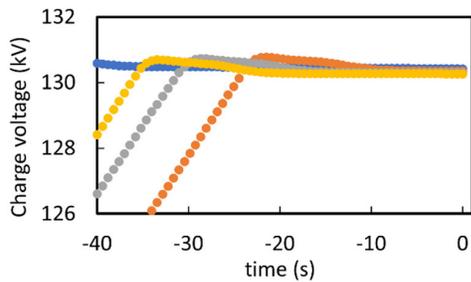


Fig. 19. Four typical stabilization curves of the dc generator charging voltage at 130-kV charging. The generator was manually triggered at $t = 0$ s.

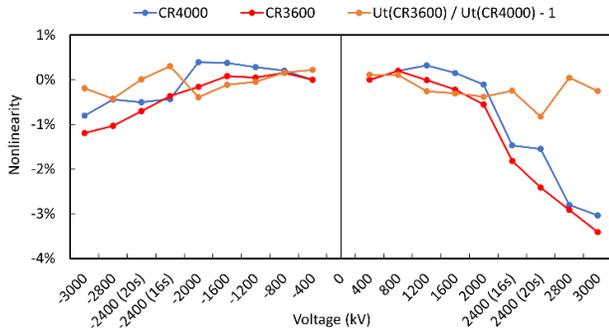


Fig. 20. Change in the ratio between CR4000 and CR3600 test voltage readings and the generator charging voltage (blue and red) as a function of negative (left) and positive (right) test voltages; relative variation in CR4000 and CR3600 test voltage readings after gain correction based on their 400-kV calibration (orange).

for negative waveform, and -4.2% for positive waveform. The HV instruments around the LI generator and divider were then moved further away to reduce proximity effects that affect the linearity performance.

During the campaign, the linearity measurements were repeated with the CR4000 divider and the CR3600 divider. The charging voltage of the impulse generator was measured with a RISE 500-kV universal voltage divider, and the output of this divider was logged continuously at a rate of 0.6 samples/s using a Keysight 34470 multimeter. The actual, applied value for the charging voltage was taken as the last value before the generator was triggered manually, when the charging voltage stabilized to a lower level after the initial peak. Typical charging voltage curves are shown in Fig. 19. The expanded uncertainty for the charging voltage measurement is 0.02% [23].

The linearity results following this procedure are given in Fig. 20, showing that from 400 to 3000 kV, the scale factor of the CR4000 divider changes -0.9% for negative waveforms and -3.0% for positive waveforms. The linearity change and trend are pretty close to the results in Fig. 18, which indicates that the linearity test carried out by VSL, TU Delft, and VTT before the campaign was quite good, but that moving the other HV instruments in the laboratory away from the LI test setup has improved the linearity test results. Furthermore, the similar nonlinearity trend of CR3600 and CR4000 suggests that the nonlinearity is possibly caused by the generator or testing environment (e.g., due to corona discharges), rather than by the measuring systems, which mutually agree within

$\pm 1\%$ up to 3000 kV [23]. And as there are also two different types of measurement (charging voltage versus comparative measurement), other factors may also lead to this difference, which should be further studied in the future.

VI. CONCLUSION

VSL has developed a new reference measuring system for on-site LI voltage calibrations up to 1200 kV by direct comparison and 3000 kV with additional linearity tests. Its accuracy has been verified by an international comparison campaign in 2022 in the HV laboratory of the TU Delft. Based on an uncertainty analysis and the comparison results, VSL has established CMCs of test voltage (U_t), front time (T_1), and time to half-value (T_2) of, respectively, 0.7% , 3.0% , and 1.5% up to 600 kV and 1.2% , 5.0% , and 3.0% up to 1200 kV LI voltage.

With the VSL measuring system as the reference, a 4000-kV LI divider was calibrated and fine-tuned to improve the measurement accuracy in test voltage and time parameters. Furthermore, linearity tests were performed up to 3000 kV, showing results that are likely limited by the generator or test environment. The 2022 comparison also confirmed the good performance of the 4000-kV divider after tuning of the divider and the LI generator circuit, as well as the benefit of calibrations and modifications with the VSL LI reference measurement system.

Future research would further study the UHV lighting impulse voltage linearity and chopped LI voltage waveform measurement.

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