Design and Verification of a Calculable Composite Voltage Calibrator

J. Havunen[1], J. Hällström[1], J. Meisner[2], F. Gerdinand[2], A.-P. Elg[3]
[1] *VTT Technical Research Centre of Finland Ltd, Espoo, Finland*
[2] *PTB Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*
[3] *RISE Research Institutes of Sweden, Borås, Sweden*

Abstract

Components used in the power grid need to be tested to verify they can withstand specified voltage stresses. Composite voltage test according to IEC 60060-1:2010 is a test method where impulse voltage is applied simultaneously with AC or DC voltage to the same terminal of the test object. To provide traceability to instruments used for composite voltage measurements, low-voltage calibrator based on combining existing calibrators was developed. The developed composite voltage calibrator can generate lightning and switching impulses together with DC and AC. The calibrator design is based on a series connection of a DC/AC calibrator and a calculable impulse voltage calibrator. Maximum impulse voltage peak is 330 V whereas the DC/AC voltage can be within 1000 V. Reference parameters for composite waveshape are calculated based on the applied voltage, charging voltage of the impulse calibrator, internal impedance of the impulse calibrator, and the input impedance of the device under calibration. The main uncertainty components of this composite voltage calibrator are the uncertainties related to the separate calibrators and the uncertainty of the load impedance needed for the parameter calculation.

1. Introduction

High-voltage cables, transformers, etc. need to be tested to verify they can withstand the specified voltage stresses present in power grid. Composite voltage test according to IEC 60060-1:2010 is a test method where impulse voltage is applied simultaneously with AC or DC voltage to the same terminal of the test object [1]. DC voltage with superimposed impulse voltage is used for example in testing of DC cable systems. AC voltage with superimposed voltages can occur for example in testing of components that need to be energized during impulse testing.

Test voltage is typically generated using a high-voltage AC or DC source together with an impulse generator. Blocking elements or sphere gaps are used to protect the sources from each other.

Test laboratories typically use a measuring system based on a universal voltage divider to measure the composite voltage. This measuring system is typically calibrated separately with DC, AC, lightning impulse (LI) and switching impulse (SI). However, this approach does not provide metrological traceability to the actual composite voltage measurements. Therefore, calibration should be performed using actual composite voltages to prove their performance.

One of the tasks of European Union funded research project 19NRM07 HV-com² [2] is to develop traceable reference instrumentation for composite voltage calibrations. So far, there has not been composite voltage calibrators available for low-voltage applications. Composite voltage calibrators have been developed in this project to be used for characterization of digitizers and attenuators. One approach for a composite voltage calibrator has been using an arbitrary waveform generator together with linear high-voltage amplifier [3]. Another approach is to use existing DC/AC calibrators and impulse calibrators in series. This paper describes the design, test results and uncertainty estimation for this type of series connection of calibrators.

2. Main components

Aim was to develop a composite voltage calibrator based on existing DC/AC and impulse voltage calibrators. These calibrators would be connected in series according to Fig. 1. The main benefit for this approach is that no new hardware needs to be developed.

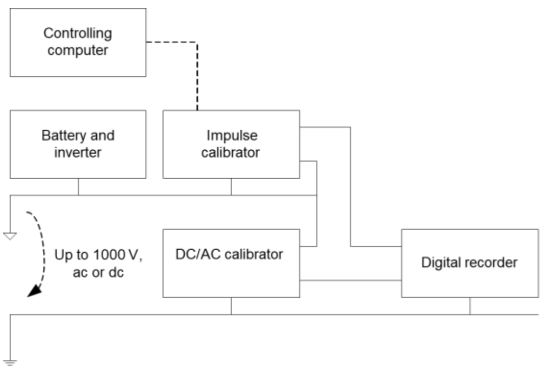

Fig. 1 - Series connection of the DC/AC calibrator and impulse calibrator. Impulse calibrator needs to be battery-powered if DC/AC ≥ 250 V.

2.1. DC/AC calibrator

DC or AC up to 1000 V can be generated using any commercial calibrator which is calibrated, and its output uncertainty is known. Typically, calibrators used for multimeter calibrations have one or two orders of magnitude smaller uncertainties than needed in this approach. If AC composite voltages need to be generated, then the calibrator should have an input or output connector that can be used to synchronize the impulse peak with the AC phase.

2.2. Impulse calibrator

Calculable impulse voltage calibrator is used for generating LI and SI voltages [4]. This calibrator uses a DC voltage source for charging a single stage impulse generator. Charging voltage is measured using a multimeter. Impulse parameters are dependent on the calibrator's internal component values and the load impedance (C_L and R_L). This calibrator can generate LI and SI up to 330 V to a high-impedance load. This is typically enough to calibrate all ranges of a commercial transient recorder when its direct input is used. Output uncertainties (k = 2) for test voltage are less than 0.2 % and less than 1 % for time parameters [4]. Block diagram of the calibrator is presented in Fig. 2. Circuit diagram is presented in Fig. 3. Commercial versions of such calibrator are also available.

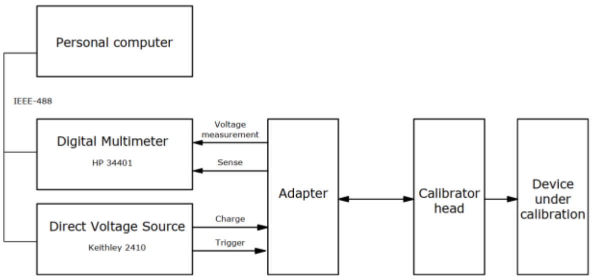

Fig. 2 - Block diagram of a calculable impulse voltage calibrator.

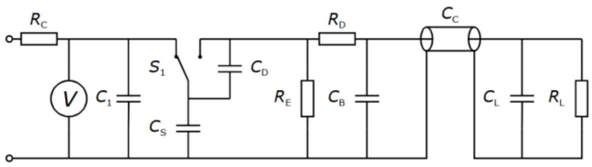

Fig. 3 - Circuit diagram of a calculable impulse voltage calibrator head and device under calibration.

3. Practical implementation

Impulse voltage calibrator is placed inside a metal cabinet connected to laboratory ground. Inside walls of the cabinet are electrically isolated so that the instruments inside the cabinet are isolated from ground. Cabinet protects user from electrical shocks and helps to reduce external interferences to the generated signal.

If the DC/AC calibrator output voltage is less than 250 V, the impulse calibrator can be run normally from the standard grounded 230 V power outlet and copper connection for control can be used. If the DC/AC calibrator output is more than 250 V, then the impulse calibrator must be floating. This is because of the limitations related to the voltage source of the calibrator (common voltage to protective earth). This means that battery-operation and optical connection for control is needed. A standard 12 V car battery together with an inverter and EMC filter is placed inside the cabinet to power the calibrator. An optical GPIB-USB cable is used for the control. DC/AC calibrator can be powered using normal grounded 230 V power outlet.

Connections between the DC/AC calibrator, impulse calibrator, and calibrator output is presented in Fig. 4. A separate connection box is used where the DC/AC signal is connected to the impulse calibrator ground. This connection box is placed inside the metal cabinet. DC/AC ground is connected to the output ground. Impulse calibrator signal is connected to the output signal. This kind of arrangement generates AC/DC voltage with a superimposed impulse (LI or SI). Signal is delivered to the input of the digitizer or attenuator with a coaxial cable.

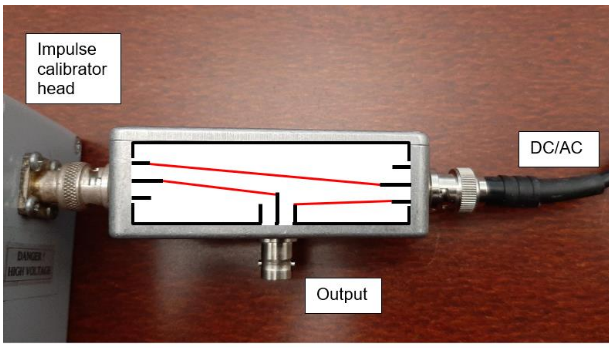

Fig. 4 - The connection box for DC/AC calibrator, impulse calibrator, and output. Both BNC connectors for calibrators are isolated from the connection box.

The metal cabinet is placed near the used DC/AC calibrator so that the connection from the calibrator to the connection box is short as possible. It was noted that the used inverter caused interferences (100 kHz) with constant amplitude, see Fig. 5. Interferences are not a problem since the battery-operation is required only with higher test voltages where the relative interference level is very low.

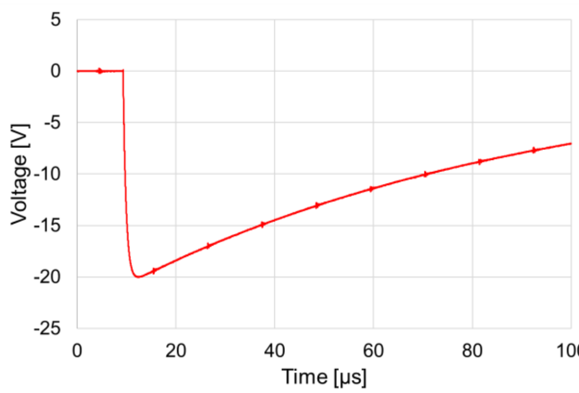

Fig. 5 - Interferences in the output signal when system is battery-operated, and DC/AC (0 V) is applied. [5]

Currently, the authors have only been able to trigger the impulse to random part of the AC waveform (50 Hz). The timing implementation of AC and impulses has not yet been carried out, so the following results are only considering DC composite voltages.

4. Reference parameters

According to the IEC 60060-1:2010, the parameters that need to be evaluated from the composite waveforms are the relevant parameters of the two superimposed voltages, for example impulse parameters and DC parameters. Additionally, the value of the composite voltage, and the time difference (Δt) between AC peak and impulse peak need to be evaluated. Evaluation of Δt is not needed with DC composite voltages. [1]
The basic circuit diagram of the composite voltage calibrator for DC is presented in Fig. 6. The DC level of the composite calibrator output is not directly the DC calibrator output voltage because of the voltage division between the resistors of the impulse calibrator head and the device under calibration. These component values are known, and this effect can be corrected. For example, if test objects R_L is 1 MΩ, R_E is 4208 Ω, and R_D is 448 Ω, then the DC level is influenced by almost 0.5 %. With AC, similar influence can be observed due to the capacitances of the impulse calibrator and device under calibration.

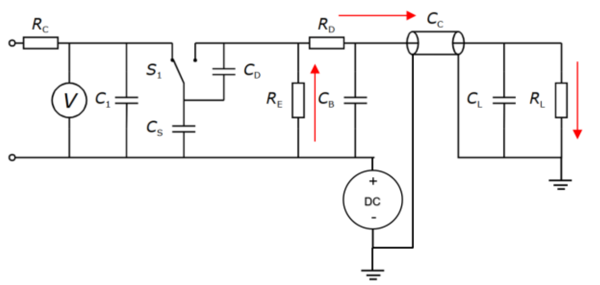

Fig. 6 – Circuit diagram of composite voltage calibrator for DC. Current is flowing from the DC calibrator through the calibrator head and digitizer input.

Since the impulse voltage calibrator is calculable, the impulse time parameter evaluations (T_1/T_p and T_2) are already based on both the resistance and capacitance values of the calibrator head and the device under calibration [4]. They are not affected by the additional DC/AC source connected in series. Normally, the impulse voltage peak (U_t/U_p) is calculated based on the component values and the charging voltage of the calibrator. However, when additional DC/AC voltage is applied it will influence the impulse voltage peak. This effect is more visible with SI than with LI due to different component values inside the calibrator head. This effect can be calculated with mesh analysis, but the equation is complex and solving it numerically will be challenging. Proposed solution is to use circuit simulator (Fig. 7) to calculate the impulse voltage peak based on the DC/AC voltage, component values and the charging voltage of the impulse calibrator.

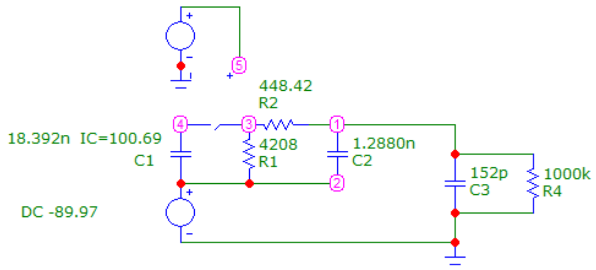

Fig. 7 – Circuit simulator model for LI calibrator head when it is used as part of a composite voltage calibrator. Reference time parameters for this circuit are 1.75 µs for T_1 and 61.5 µs for T_2.

Internal component values for each impulse calibrator are calibrated frequently so simulation model with fixed component values can be used for each impulse calibrator head. Input information for the model is:

1. Input impedance of the device under calibration.
2. Value of the DC/AC voltage (calibrator reading). With AC, also the phase/trigger position of the impulse is needed.
3. Measured charging voltage of the impulse calibrator circuit (provided by the impulse calibrator software).

After transient simulation a result file is generated which can be used to calculate the reference parameters for DC/AC, impulse peak voltage, and value of the composite voltage. Calculated impulse time parameters can be obtained directly from the impulse calibrator software [4].

5. Uncertainty estimation

Calibration results obtained using this calibrator are traceable to the International System of Units (SI) via Finnish national measurement standards of resistance, capacitance, and DC voltage. Estimated uncertainties for DC+LI is presented in Table 1. The used test setup is the one presented in Fig. 7.

Table 1 – Uncertainty budget for composite DC+LI.

Parameter	Expanded uncertainty (k = 2)
DC voltage	0.01 %
Test voltage U_t	0.05 %
Front time T_1	0.46 %
Time to half-value T_2	0.29 %
Value of composite voltage	0.06 %

The DC voltage uncertainty is based on the measurement uncertainties related to measuring the resistor values and the DC calibrator output voltage. If the DC calibrator output uncertainty is 0.01 %, and all the resistances from impulse calibrator and load have been measured with an uncertainty of 0.1 %, the expanded uncertainty (k = 2) for the composite DC voltage is 0.01 %. This is mostly dependent on the uncertainty of the DC calibrator.

Test voltage (U_t) uncertainty is mainly based on the impulse calibrator uncertainty which consists of the impedance measurements of the calibrator and load [4]. The applied DC voltage will affect to the impulse peak mostly when the DC voltage magnitude is high. However, if the DC calibrator output voltage is known with an uncertainty of 0.01 %, the influence caused by that tolerance will be negligible effect on the U_t uncertainty. Therefore, it is justified to use the nominal uncertainty of the impulse voltage calibrator.

The time parameter uncertainties are based on the calculable impulse voltage calibrator uncertainty [4]. Simulations have shown that the DC value do not affect the time parameters, or the effect is negligible.

In the worst case, the uncertainty related to the value of the composite voltage is combination of DC level and impulse voltage uncertainty. This leads to uncertainty of 0.06 % for the value of composite voltage.

6. Test results

The composite calibrator was tested with AC and impulse voltages (both LI and SI) to check that the output signals were reasonable. As described earlier, due to the challenges related to timing of the impulse voltage further characterization has not yet been performed.

DC tests were carried out to test the functionality of the composite calibrator at maximum voltage. A high-impedance attenuator was used together with a digitizer to measure the output. Examples of the measured signals are given in Fig. 8 and Fig. 9. The composite calibrator worked as expected at maximum voltages.

The developed composite voltage calibrator was used to characterize a digitizer used as a reference in impulse voltage measurements. Dynamic behaviour of the digitizer is corrected using deconvolution [6] and gain corrections based on separate impulse and DC calibrations are used. Example of calibration results for LI is given in Table 2. Each result is an average of ten measurements. Related calibration uncertainties are as given in Table 1 without the statistical (Type A) uncertainties. Standard deviations for each parameter were less than 0.03 %.

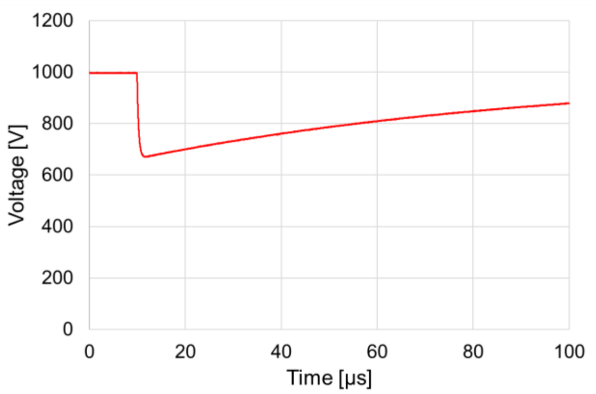

Fig. 8 – Composite voltage calibrator output measured with an attenuator and digitizer. DC voltage was +1 kV and LI voltage was -330 V. [5]

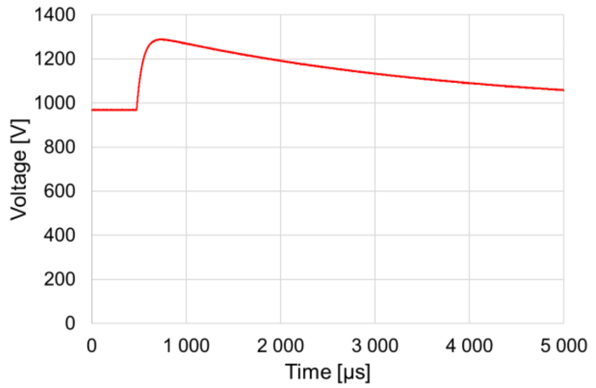

Fig. 9 – Composite voltage calibrator output measured with an attenuator and digitizer. DC voltage was +1 kV and SI voltage was +300 V. Measured DC level is less than with LI because of the higher voltage loss inside the SI calibrator head. [5]

Table 2 - Calibration results with DC+LI.

Digitizer range [V]	DC [V]	LI [V]	DC error	U_t error	T_1 error	T_2 error
100	0	90	-	0.08 %	0.02 %	-0.02 %
100	-45	90	0.04 %	0.09 %	0.05 %	0.02 %
100	-90	90	0.01 %	0.11 %	-0.01 %	0.02 %

Reference digitizer and the calibrator showed excellent agreement. It can be noted that the impulse parameter errors stay relatively constant with or without the applied DC voltage. These results support the uncertainty estimation.

6. Future work

The hardware and software of the presented calibrator are capable to work also with AC composite voltages. To generate composite voltages with adjustable Δt, the timing control of the impulse application has still to be developed.

Performance of different composite voltage calibrators and low-voltage measuring systems will be compared in the HV-com² project in 2022-2023 [2]. This comparison will provide important support for national metrology institutes by verifying their new composite voltage measurement and calibration capabilities.

7. Conclusions

Composite voltage calibrator was developed by connecting existing DC/AC calibrator and calculable impulse voltage calibrators in series. The calibrator is able to generate reference composite voltages with DC/AC up to 1 kV whereas the LI/SI is 330 V. Reference values are calculable, and they are based on calibrator output voltage, internal component values of the calibrators, and input impedance of the system under calibration. The estimated uncertainties for DC+LI composite are less than 0.1 % for voltages, and less than 0.5 % for time parameters. Tests against reference measuring system are supporting the claimed uncertainties. The developed calibrator can be used to provide traceability to low voltage measuring systems used for composite voltage measurements.

8. Acknowledgements

This project 19NRM07 HV-com² has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

9. References

[1] High-voltage test techniques – Part 1: General definitions and test requirements, Standard IEC 60060-1, Edition 3.0, 2010.

[2] 19NRM07 HV-com² website. Accessed: 4.3.2022. [Online] Available: https://www.ptb.de/empir2020/hv-com2/home/

[3] H. Saadeddine, M. Agazar and J. Meisner, "Reference Calibrator for Combined and Composite High Voltage Impulse Tests" in Proceedings of 22nd International Symposium on High Voltage Engineering (ISH), 2021.

[4] J. K. Hallstrom, Y. Y. Chekurov and M. M. Aro, "A calculable impulse voltage calibrator for calibration of impulse digitizers," in IEEE Transactions on Instrumentation and Measurement, vol. 52, no. 2, pp. 400-403, April 2003, doi: 10.1109/TIM.2003.810714.

[5] Dataset, https://doi.org/10.5281/zenodo.6523846.

[6] J. Havunen, J. Hällström, A. Bergman and A.E. Bergman, "Using Deconvolution for Correction of Non-ideal Step Response of Lightning Impulse Digitizers and Measurement Systems", in Proceedings of 20th International Symposium on High Voltage Engineering (ISH), 2017.