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Empirical Characterization of Cable Effects on a Reference Lightning Impulse Voltage Divider

Jussi Havunen, Stephan Passon, Jari Hällström, Johann Meisner, and Tim Christoph Schlüterbusch

***Abstract*— The effect of measurement cables on impulse voltage measurement system signal transmission has been widely ignored by the high-voltage community. During the last years, the cable length effects have been reported, but the results have not been fully consistent. This article characterizes cable effects on a resistive impulse voltage divider system using three different empirical test methods. The used methods are step response analysis using convolution, low-voltage analysis with an impulse calibrator, and high-voltage impulse analysis with an impulse generator. Results show that with reasonable cable lengths up to 25 m, the time parameter errors increase almost linearly with the cable length. The tested divider system was not sensitive to the tolerance of the 50-Ω termination at the cable end. The cable effect seems to be related to the current flowing through the cable, and the related errors can be reduced using a high-impedance termination at the digitizer end of the cable. Either short cable or high-impedance termination at the digitizer end is recommended for this type of divider. In addition, the results show that the three applied methods produce comparable results.**

***Index Terms*— Calibration, high-voltage techniques, measurement techniques, measurement uncertainty.**

I. INTRODUCTION

LIGHTNING impulse (LI) voltages [1] are used in high-voltage testing to simulate the stress caused by lightning strikes on a test object. Voltage is generated across the test object using an impulse generator, which is based on discharging capacitors to the test object through a resistor network. Voltage across the test object is measured using an impulse voltage measuring system.

Ideally, the output of an impulse generator is a double-exponential waveform (Fig. 1), but its front is typically distorted by different kinds of oscillations [2]. The measured voltage wave shape is described with two time parameters: front time T_1 and time to half-value T_2 [1]. T_1 describes how fast the impulse reaches its peak by linearly extrapolating from the 30% and 90% points on the front. T_2 describes when the curve has decreased to half of its peak value. Standard LI has T_1 of 1.2 μs ± 30% and T_2 of 50 μ ± 20% [1]. These parameters are evaluated from the test voltage curve, which is obtained using a procedure described in IEC 60060-1:2010 [1]. Briefly, the test voltage curve is sum of a fitted double-exponential curve (base curve) and filtered residual curve. The use of this standardized parameter evaluation provides stable results since it filters out the irrelevant frequencies from the recorded voltage and makes the evaluation less sensitive to noise [3].

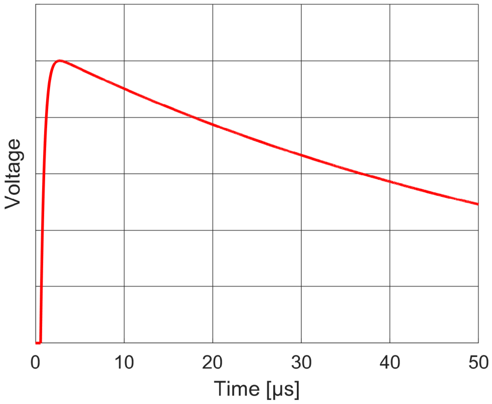

Fig. 1. Example of an ideal double-exponential LI.

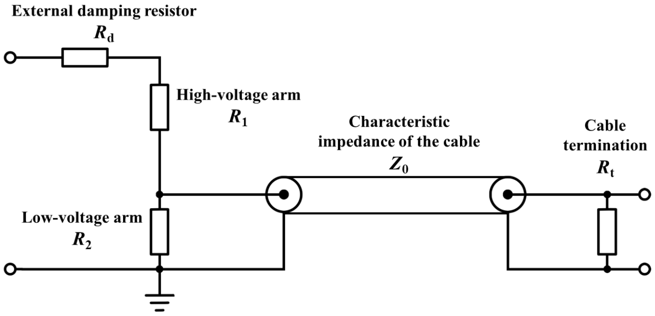

Fig. 2. Basic principle of a resistive voltage divider with cable.

The main parts of an LI voltage measuring systems are a voltage divider, a transient recorder (digitizer) with evaluation software, and a measurement cable that connects the output of the voltage divider to the input of the transient recorder. The voltage divider is usually located near the impulse generator in the high-voltage laboratory, whereas the transient recorder is preferably placed in a shielded control room tens of meters from the dividers to protect the recorder from interferences and to allow safe operation of the instrument. Therefore, long measurement cables are typical.

Voltage dividers used with LI are usually damped capacitive or resistive type [4]. This article is an extension to

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the Conference on Precision Electromagnetic Measurements (CPEM) 2020 proceedings paper [5] and provides experimental results on the cable effect with a resistive divider. The resistive type of divider (Fig. 2) attenuates the input voltage with a factor that is proportional to the resistances of its high-voltage ($R_d + R_1$) and low-voltage (R_2) arms according to the principle of voltage division. The low-voltage arm is connected to the input of the transient recorder using a coaxial or triaxial cable with characteristic impedance Z_0. The cable should be low-loss and well-shielded to provide an accurate and interference free signal. Cable is terminated with an attenuator or transient recorder input (R_t).

Measurement cable acts as a transmission line in LI measuring system. Voltage in a transmission line is the superposition of an incident (V_{0+}) and a reflected wave (V_{0-}). According to transmission line theory [6], voltage reflection in a lossless transmission line can be calculated with voltage reflection coefficient Γ. If a cable is terminated with the characteristic impedance of the cable ($R_t = Z_0$), then the voltage reflection coefficient can be calculated as

$$\Gamma = \frac{V_{0-}}{V_{0+}} = \frac{R_t - Z_0}{R_t + Z_0} = 0. \quad (1)$$

Transmission line is then called matched, and no reflected wave occurs from the incident wave on the transient recorder end of the cable.

If $R_t \gg Z_0$, Γ is close to 1. This means that the reflected wave has the same polarity and almost the same magnitude but opposite direction. If $R_2 = Z_0$, the reflected wave from the transient recorder end is absorbed and no further reflections will occur to the direction of the transient recorder. This is a typical arrangement with damped capacitive voltage dividers.

It is generally assumed that measurement cable of a resistive impulse voltage divider needs to be terminated on both ends with its characteristic impedance to avoid any reflections to the recorded signal. With the divider presented in this study, the termination has originally been applied on both ends of the cable meaning that $R_2 = Z_0 = R_t = 50\ \Omega$. In this case, the cable length has been expected to have no significant influence on the system response [7], [8]. In practice, cables are not lossless, and their electrical properties are frequency dependent making their transient behavior complex to model.

The influence of the measuring cable is often neglected, but the National Metrology Institutes (NMIs) need to be aware of the effect of the measuring cable to ensure small measurement uncertainties of their reference systems. Even though the cable effect has been noted already decades ago [9], it has been largely ignored in high-voltage community.

Sato et al. [10] have performed a theoretical analysis of the cable effect for T_1, which indicates that a coaxial cable slows T_1 significantly (approximately 1% per 10 m). Their theory was also tested with different lengths of RG-58 coaxial cables by generating impulse voltage to the other end of the cable and by measuring the voltage from the opposite end of the cable with a transient recorder. Their measurement results agreed well with their calculations. They also pointed out that the cable length affects to the scale factor of the measuring system due to the additional resistance.

Few years later, Bergman et al. [11] have performed high-voltage (100 kV) impulse voltage measurements with different coaxial cables and cable lengths up to 75 m. In this test, they compared two measuring systems and altered the cable length for the other system. These measurements show that the longer the cable, the longer are T_1 and T_2. In addition, the scale factor of the divider increases when cable gets longer due to the resistance increase in the low-voltage arm. However, their simulation model did not correspond completely to their measurements.

Sato et al. [12] have also tested the cable length effect with different LI evaluations from the 1989 and 2010 versions of the IEC 60060-1 [1]. Their results show that the 2010 evaluation for T_1 is more sensitive to the cable length than the 1989 evaluation.

The experimental comparison of different cable types and lengths has also been carried out with low voltage using an impulse calibrator (IC) [13]. Cable effect was determined by measuring the input and output signals with a reference transient recorder. This examination showed results like previous studies, but the time parameter errors were higher. This might be because the impedance of the calibrator did not correspond to the actual arrangement, where the cable is connected in the low-voltage arm of the divider.

The comparison of different test methods for evaluating the cable effect has also been approached [5]. Results show that the step response evaluation, low-voltage tests, and high-voltage tests provide very similar results for the evaluation of the cable effect.

For damped capacitive dividers, Schelkunoff approach has been used to simulate the effects of the coaxial cables [14], [15]. On the contrary to the resistive dividers, the results showed that T_1 gets shorter when the cable gets longer. Similar simulation model could also be used for simulating the coaxial cable effect with resistive dividers.

The studies with resistive dividers show that T_1 and T_2 are increasing due to longer cable, but the reported magnitudes of the effects are not identical. Simulations and the measurements are also not fully consistent. The comparison of different studies is difficult since there are differences in the test setups and studied cable types. More results and modeling are required to fully understand the phenomenon. According to preliminary simulations, the effect is caused by the attenuation of higher frequency components in the cable, which would explain the slower T_1 and T_2 of the measured impulse.

The aim of this study was to provide more consistent results on this phenomenon by characterizing the effect of the measuring cable length, different cable types, and terminations (R_t) to a measuring system based on a resistive voltage divider. Analyzing methods were: 1) step response evaluation using convolution techniques; 2) direct impulse measurements with low voltages less than 1 kV; and 3) high-voltage measurements up to 400 kV [5]. The results of this study can be used to compare the performance of different cable types, estimate their sensitivity to the terminating impedance at the cable end, and to propose possible improvements to reduce the cable effect with resistive voltage dividers. Additionally, the results will demonstrate how well do the three analyzing methods

Fig. 3. Shielded-resistive type voltage divider (HUT-400). Damping resistor (R_d) with a resistance of 200 Ω is located at the outer end of the fixed horizontal arm.

TABLE I

CABLE PROPERTIES

Cable	Belden 9888	Ecoflex 10 PLUS	RG214
Capacitance [pF/m]	85	78	101
DC resistance, conductor [mΩ / m]	3.9	≤ 3.5	6
DC resistance, shield (inner/outer) [mΩ / m]	3.9/6.9	8.8	3.1
Attenuation at 10 MHz [dB / 100 m]	1.6	1.1	2.1
Velocity of propagation [%]	78	85	66

TABLE II

EFFECT OF THE SG AND MEASUREMENT CIRCUIT

Circuit	Generator	Estimated T_1 error	Estimated T_2 error
Preferred	VTT	0.57 %	0.15 %
Preferred	PTB	0.57 %	0.15 %
Preferred for large dividers	PTB	0.56 %	0.14 %

agree when the same system is characterized with them. Agreement between these analyzing methods is appealing since the exploitation of these methods is not only limited to cable effect and can be used for estimating the overall performance of an impulse voltage measuring systems.

II. INSTRUMENTATION

Analysis was performed for an LI voltage measuring system consisting of a voltage divider, a cable, an attenuator or impedance termination, and a digitizer. Different types and lengths of cables with different impedance terminations were under test.

The resistive reference voltage divider used in this study (HUT-400) [16] has a nominal maximum voltage of 400 kV. The shielded resistive structure makes the divider very insensitive to proximity effects. The nominal high-voltage and low-voltage arm resistances of the divider are 10 kΩ (R_1) and 50 Ω (R_2), respectively. The divider is presented in Fig. 3.

One triaxial and two coaxial cable types were used in this study. All the cable types had a characteristic impedance of 50 Ω and were available with different lengths up to 25 m. The triaxial cable was Belden 9888 with triaxial LEMO connectors. The coaxial cables were Ecoflex 10 PLUS and RG214 with N-connectors. Adapters were used during the tests in case of connector mismatch. Cable properties according to their datasheets are summarized in Table I. The selected cable types are the typical examples of cables used in impulse voltage measurement systems and might not be the best options for this application.

During the low-voltage measurements, the cable was terminated without an additional attenuator. Impedance terminations close and equal to 50 Ω were used to test the requirements for proper matching. Additionally, digitizer's 1-MΩ input was used as a high-impedance termination to study the behavior with impedance mismatch. During high-voltage measurements, three different attenuators with different impedances were used: 50 Ω [17], 1 kΩ, and 2 MΩ.

Digitizer used in the measurements has 12-bit resolution with a maximum sample rate of 200 MS/s and a bandwidth of 150 MHz. This type of digitizer has been found well suitable for impulse measurements [18]. Digitizer was used with 1-MΩ input impedance, and its nonideal step response is corrected by software with deconvolution [19], resulting small errors in LI parameters according to IEC 60060-1:2010 [1]. Digitizer is placed in a shielded cabinet, which allows it to be in the high-voltage area near the divider without the need for a long measuring cable. Data acquisition is performed by using a fiber-optic connection. This setup passes the interference test requirements described in IEC 60060-2:2010 [20].

Test signals were generated by using step generators (SGs), a low-voltage impulse generator, and a high-voltage impulse generator. The used SGs are designed to be used with high-voltage dividers and they are based on a closing mercury-wetted relay, which allows very fast switching [4]. The low-voltage impulse generator was a commercial calculable impulse voltage calibrator, which generates very stable output with smooth impulse shape when the load impedance is constant. The used high-voltage impulse generator was a commercial system, which was used with the same configuration throughout the tests. The stability of the high-voltage impulse generator was measured with another reference measuring system consisting of a damped-capacitive voltage divider [21] and a digitizer [22].

III. TEST METHODS

A. Step Response Analysis Using Convolution

The first approach to study the cable effects was to analyze the step response of the measuring system using convolution techniques [20]. An ideal double-exponential impulse curve ($T_1 = 1.200\ \mu$s and $T_2 = 50.00\ \mu$s) was first analyzed with approved analysis software [3], resulting the reference values for impulse parameters. The time derivative of the measured step response, impulse response, was convolved together with the reference impulse. Convolution was done in frequency domain by multiplying the fast Fourier transforms

TABLE III

SHORT-TIME STABILITY OF THE LOW-VOLTAGE TEST SETUP

Test	T_1 difference	T_2 difference
Original	-	-
30 minutes	0.00 %	-0.01 %
1 day	0.02 %	-0.03 %

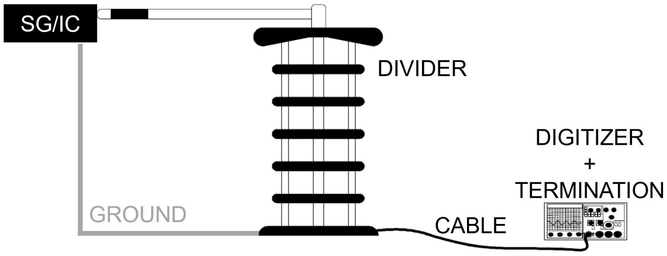

Fig. 4. Arrangement used for step response measurements with SG and low-voltage testing with IC. Impedance termination was placed directly to the digitizer input. Ground was approx. 1-m-wide copper strip.

(FFTs) of the reference impulse voltage and the impulse response [19]. Convolved impulse was then converted back to time domain and analyzed again with the same analysis software. These new parameters were then compared to the reference values received from the ideal curve. Differences predict the systematic errors of the used measuring system.

Generated step voltages were falling steps from approximately 180 V to short circuit. The output of the divider was approximately 0.45 or 0.9 V to the 50-Ω and 1-MΩ terminations, respectively. All the step responses were measured using the same channel and 1 V range of the of the used digitizer. Based on the impulse calibration [23] results of the used digitizer, the expected nonlinearity of the 1 V range is minor and will cause differences less than 0.1% in the time parameters between the 0.45- and 0.9-V impulses.

Every step response is an average of 100 records to reduce the effect of noise. Since the step response of the digitizer is corrected, all the remaining time parameter errors are mainly caused by the voltage divider including the cable.

The effect of the used SG and step response measurement circuit was also tested using the 16-m triaxial cable with 50-Ω termination. Two different SGs marked as “VTT” and “PTB” were used, and two measurement circuits and their names from IEC 60060-2 [20] were used. The preferred arrangement is presented in Fig. 4. Results summarized in Table II show that step response of this system is insensitive to the used circuit and similar results are obtained using both SGs.

SG marked as “PTB” and the preferred arrangement [20] was used in the cable effect measurements. Convolution analysis was performed for three cable types in different lengths using different impedance terminations.

The main benefits of this test method are that the measurement is quite straightforward, and the same step response can be used to evaluate different types of waveshapes. The used voltage level is limited by the used SG, and the step response of large dividers might be dependent on the used arrangement [24].

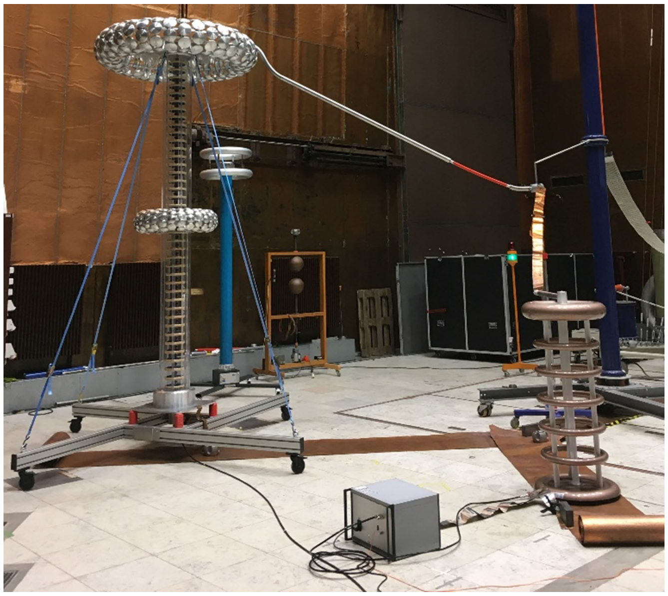

Fig. 5. Measurement arrangement for the high-voltage impulse tests. The system under test (VTT) with its digitizer is on the right side of the photograph. The voltage divider of the other system (PTB) to measure the stability of the generator is on the left side of the photograph.

TABLE IV

UNCERTAINTY ESTIMATION FOR THE LOW-VOLTAGE TESTING

Uncertainty component	T_1	T_2
Repeatability (measured 1-day stability)	0.02 %	0.03 %
Standard deviation of the mean (worst case)	0.03 %	0.02 %
Total standard uncertainty ($k = 1$)	0.04 %	0.03 %
Total expanded uncertainty ($k = 2$)	0.08 %	0.07 %

B. Low-Voltage Testing Using an Impulse Calibrator

A commercial calculable impulse voltage calibrator ($T_1 = 1.2\ \mu$s and $T_2 = 38\ \mu$s) was used to generate the impulses to be measured with the measuring system. The measurement arrangement was similar as with the step responses, and only the step voltage generator was replaced with the calibrator as seen in Fig. 4. Applied test voltage amplitude was similar as with step responses, approximately 160 V, so that the same range of the digitizer could be used. Impulse polarity was negative to correspond to the falling step response measurement.

The IC was used as a stable source. The parasitic capacitance affecting the reference parameters was difficult to measure with low uncertainty due to noncoaxial structure of the circuit. Calibrator output was found to be very stable since the 10-kΩ input impedance of the divider stays constant regardless of changes in its output configuration. Short-time stability was tested by repeating one set of measurements after 30 min and again during the next day. Results in Table III indicate that the calibrator and digitizer worked stably during the measurements and the results should be comparable.

TABLE V
UNCERTAINTY ESTIMATION FOR THE HIGH-VOLTAGE TESTING

Uncertainty component	T_1	T_2
Generator repeatability (typical)	0.10 %	0.10 %
Standard deviation of the mean (worst case)	0.08 %	0.02 %
Total standard uncertainty ($k = 1$)	0.13 %	0.10 %
Total expanded uncertainty ($k = 2$)	0.25 %	0.20 %

Relative overshoot magnitude [1] varied between −0.2% and 0.5% with all the cable and termination combinations during the measurements. Smooth and stable waveshapes provided comparable results with the convolution analysis. However, the T_2 values are smaller in this analysis compared to the two other test methods, which slightly complicates the comparison of the different methods.

The average of ten impulses was used as a result, and the standard deviations for all cable and termination combinations were less than 0.10% for T_1 and 0.06% for T_2. The stability of the test setup, i.e., repeatability of the results, was also taken into account in the uncertainty estimation based on Table III. For all measurements, the relative uncertainty ($k = 2$) is expected to be approximately 0.1% for T_1 and T_2. An example uncertainty estimation is presented in Table IV. Since only differences are being analyzed, the uncertainty related to the absolute error of the digitizer can be neglected.

The main advantages of this test method are that the system is tested with an actual LI wave shape, statistical uncertainties can be very small, and the measurement is straightforward. This test method using the same digitizer has been successfully used together with a damped-capacitive divider and provided very good agreement with the simulated cable effect [15]. The main disadvantage is that the voltage level is quite limited.

C. High-Voltage Testing Using an Impulse Generator

The third approach was to investigate the cable length effect using high-voltage impulses from −50 to −400 kV. Impulse generator was used with the same connections and settings throughout the tests, and only the cables and attenuators of the system under test were changed. Negative polarity was used as in the low-voltage tests.

Instead of the impedance terminations, three different impulse attenuators were used with the cables: 50 Ω [17], 1 kΩ, and 2 MΩ. Different digitizer ranges were used because of different scale factors and test voltages. However, the ranges are kept the same throughout the cable length tests with a certain voltage.

Measurement arrangement is presented in Fig. 5. The shortest 0.5-m cable was not used to keep safe distance between the divider and the digitizer. Voltage was fed from the impulse generator to the system under test (VTT) and to another measuring system (PTB) consisting of a damped-capacitive voltage divider [21] and a digitizer [22]. PTB system was used to check the stability of the impulse generator during the tests. The waveform was reasonably smooth with small overshoot. Time parameters were close to the nominal 1.2 and 50 μs.

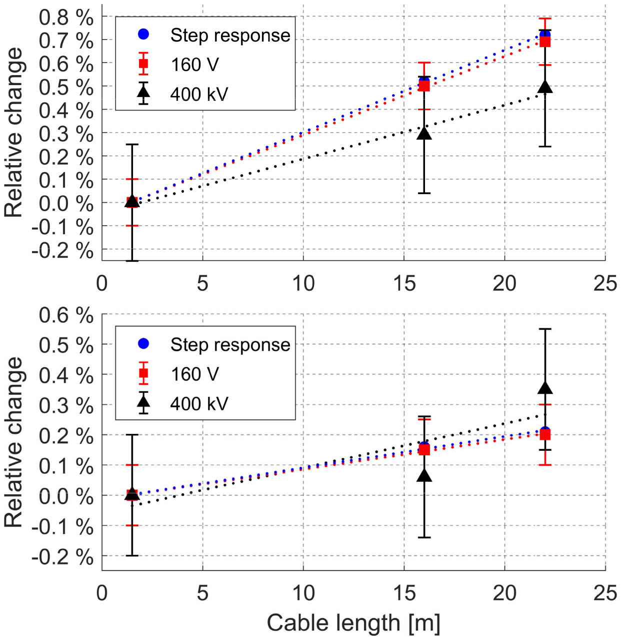

Fig. 6. Changes in T_1 (upper) and in T_2 (lower) with their uncertainties for different cable lengths of Belden 9888 (50-Ω termination).

T_1 and T_2 varied slightly between the different voltage levels due to voltage dependency of the impulse generator. However, measurements performed with the PTB measuring system showed that the stability of T_1 and T_2 with the same voltage levels were typically within 0.1%. In addition to the generator stability, the standard deviation of the applied ten impulses was used. This was based on the standard deviation of the difference measured with PTB and VTT measuring systems. The estimated uncertainty level ($k = 2$) for these results is approximately 0.25% for T_1 and 0.20% for T_2. An example uncertainty estimation is presented in Table V. Since differences are being measured, the uncertainty related to the absolute error of the digitizer can be neglected.

The main disadvantages of this method are that the test setup is the most complicated to be prepared and analyzed, and the uncertainties due to the stability of the high-voltage circuit are higher than with low voltage. Nevertheless, this is the only method that reveals the actual behavior under high voltage.

IV. RESULTS

A. Comparison of the Cable Types

The change in time parameters for different types of cables with 50-Ω termination is presented in Tables VI and VII. Cable lengths were limited to 25 m as reference systems rarely need cables longer than that. Results are shown as relative change to the shortest cable and divided by the length difference to show the relative change per meter. The effects for a 15-m cable can be up to +0.8% for T_1 and +0.3% for T_2.

Results show that the cable effect for T_1 and T_2 is the least significant with Belden, but there are no large differences

TABLE VI

CABLE EFFECT FOR FRONT TIME T_1

50 Ω termination	Relative change of T_1 [%/m]		
Cable	Convolution	Low-voltage test	High-voltage test
Belden 9888			-400 kV
1.5 m	-	-	-
16 m	0.036	0.035	0.020
22 m	0.035	0.034	0.024
Average	**0.035**	**0.034**	**0.022**
Ecoflex 10 PLUS			-200 kV
0.5 m	-	-	-
5 m	0.052	0.048	-
14 m	0.051	0.052	-
16 m	0.050	0.050	0.035
Average	**0.051**	**0.050**	**0.035**
RG214			-400 kV
1.5 m	-	-	-
25 m	0.048	0.043	0.034
Average	**0.048**	**0.043**	**0.034**

TABLE VII

CABLE EFFECT FOR TIME TO HALF-VALUE T_2

50 Ω termination	Relative change of T_2 [%/m]		
Cable	Convolution	Low-voltage test	High-voltage test
Belden 9888			-400 kV
1.5 m	-	-	-
16 m	0.011	0.012	0.004
22 m	0.010	0.010	0.017
Average	**0.011**	**0.011**	**0.011**
Ecoflex 10 PLUS			-200 kV
0.5 m	-	-	-
5 m	0.021	0.019	-
14 m	0.015	0.016	-
16 m	0.016	0.015	0.013
Average	**0.017**	**0.016**	**0.013**
RG214			-400 kV
1.5 m	-	-	-
25 m	0.011	0.012	0.015
Average	**0.011**	**0.012**	**0.015**

TABLE VIII

VOLTAGE DEPENDENCY DURING HIGH-VOLTAGE TESTS

50 Ω termination	Relative change of T_1 [%/m]			
	-50 kV	-100 kV	-200 kV	-400 kV
Belden 9888				
1.5 m	-	-	-	-
16 m	0.022	0.022	0.017	0.020
22 m	0.020	0.024	0.019	0.024
Average	**0.021**	**0.023**	**0.018**	**0.022**
50 Ω termination	Relative change of T_2 [%/m]			
	-50 kV	-100 kV	-200 kV	-400 kV
Belden 9888				
1.5 m	-	-	-	-
16 m	0.008	0.003	0.007	0.004
22 m	0.014	0.016	0.016	0.017
Average	**0.011**	**0.009**	**0.012**	**0.011**

TABLE IX

EFFECT OF 50-Ω TERMINATION BASED ON CONVOLUTION ANALYSIS

	Relative change of T_1 [%/m]		
	45 Ω	50 Ω	55 Ω
Belden 9888			
1.5 m	-	-	-
16 m	0.037	0.036	0.035
22 m	-	0.035	-
Average	**0.037**	**0.035**	**0.035**
	Relative change of T_2 [%/m]		
	45 Ω	50 Ω	55 Ω
Belden 9888			
1.5 m	-	-	-
16 m	0.012	0.011	0.011
22 m	-	0.010	-
Average	**0.012**	**0.011**	**0.011**

between the cable types. Differences are higher with T_1 than with T_2, where the changes are almost identical with all the cable types. This analysis indicates that the cable length is more important than the chosen type. However, high-voltage testing requires cables to be properly shielded, which must be taken into account when choosing the suitable cable.

B. Agreement Between Different Test Methods

Results in Tables VI and VII also show that different test methods give very similar results, and they all are suitable for the determination of the cable effect. The comparison of different methods for Belden 9888 is shown in Fig. 6. Especially, the convolution analysis and the low-voltage impulse measurements have good agreement. This is because these measurements were performed using the same test and grounding arrangements.

Since the test arrangement for high-voltage testing is more complicated, it might be influenced by the used grounding arrangements. Statistical uncertainty is also higher due to the stability of the impulse generator. In addition, the used wave shape was not as ideal as with other test methods. With high-voltage measurements, the effect to T_1 seems to be systematically lower than with other methods, whereas the effect to T_2 is still very similar.

C. Voltage Dependency

High-voltage tests were performed with the same impulse generator configuration and connections covering voltages −50, −100, −200, and −400 kV. Results obtained using Belden 9888 cable together with 50-Ω termination are presented in Table VIII. No sign of voltage dependency for cable effect was observed with any of the tested cables. Differences between each voltage levels were within the experimental standard deviations.

D. 50-Ω Termination at the Digitizer End

The effect of the 50-Ω termination at the digitizer end of the cable was analyzed. In this study, three cable terminations with different dc resistances were used together with the

TABLE X
EFFECT OF DIFFERENT TERMINATIONS BASED ON LOW-VOLTAGE IMPULSE TESTS

	Relative change of T_1 [%/m]		
	50 Ω	1 kΩ	1 MΩ
Belden 9888			
1.5 m	-	-	-
16 m	0.031	0.001	0.001
22 m	0.035	-	-
Average	**0.033**	**0.001**	**0.001**
	Relative change of T_2 [%/m]		
	50 Ω	1 kΩ	1 MΩ
Belden 9888			
1.5 m	-	-	-
16 m	0.012	0.000	0.000
22 m	**0.010**	-	-
Average	**0.011**	**0.000**	**0.000**

TABLE XI
MEASURED IMPULSE TIME PARAMETERS WITH DIFFERENT CABLE LENGTHS AND TERMINATIONS BASED ON LOW-VOLTAGE TESTS

BELDEN 9888	Relative difference from reference [%]	
	T_1	T_2
Reference: 1.5 m and 50 Ω	-	-
1.5 m and 1 kΩ	+0.01	+0.03
1.5 m and 1 MΩ	+0.00	+0.04
16 m and 50 Ω	+0.50	+0.15
16 m and 1 kΩ	+0.02	+0.04
16 m and 1 MΩ	+0.01	+0.04

Belden triaxial cable: 45, 50, and 55 Ω. The results of different terminations using convolution analysis are presented in Table IX.

Results show that that 10% tolerance with the dc resistance of the termination has negligible effect to the performance. Similar results were obtained using low-voltage calibrator, and with Ecoflex and RG214 cables. Reflections caused by the imperfect termination were not detected in the measured step responses or impulses.

E. High-Impedance Termination at the Digitizer End

The use of high-impedance termination at the digitizer end of the cable was analyzed using 1-kΩ and 1-MΩ terminations together with the Belden triaxial cable. The results of the low-voltage impulse test are presented in Table X.

Unexpectedly, the high impedance terminations do show only marginal cable length effects for both time parameters.

Similar results were obtained Ecoflex and RG214, also with the convolution analysis and high-voltage tests using the 1-kΩ and 2-MΩ attenuators.

All the test results indicate that the cable effect of each tested cable type can be reduced by using a high-impedance cable termination at the digitizer end. The use of high-impedance termination with long cable will provide similar time parameters as obtained using the shortest cable and 50-Ω termination, as seen in Table XI.

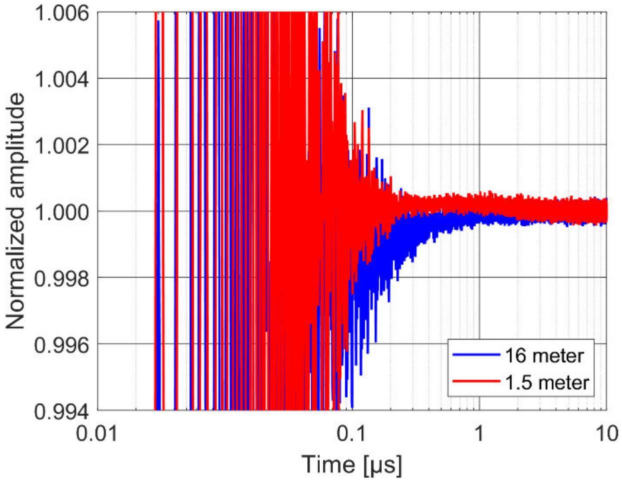

Fig. 7. Measured step response with 50-Ω termination and two different cable lengths. Used cable was Belden 9888 [25].

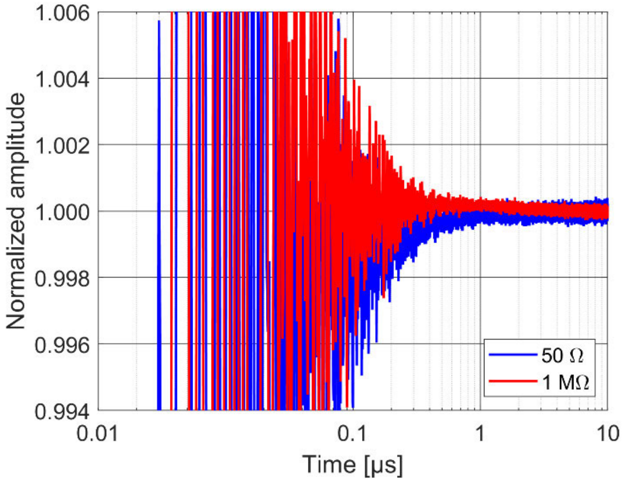

Fig. 8. Measured step response with 16-m Belden 9888 and two different terminations [25].

Further analysis was performed by visually comparing the measured step responses with different configurations. With 15-m cable and 50-Ω termination, the higher frequencies seem to be attenuated, as seen in Fig. 7, as a slower rising edge. However, as seen in Fig. 8, using the high-impedance termination with the 15-m cable improves the divider response to the same level as with the short cable and 50-Ω termination. No notable reflections were visible when the high-impedance termination was used. This means that the reflections caused by the high-impedance termination are attenuated in the cable and absorbed by the 50-Ω termination in the divider.

V. CONCLUSION AND DISCUSSION

A resistive type of voltage divider used for LI measurements was characterized using different types and lengths of cables together with different impedance terminations and attenuators. Characterization was performed with three methods based on convolution analysis of step response and impulse measurements with low and high voltage. All these methods had a good agreement with each other, especially the convolution analysis and the low-voltage impulse measurements, which were performed in the same test setup. The setup used in the high-voltage tests was different and was probably more sensitive to grounding arrangements. Nevertheless, this study suggests that the relatively straightforward convolution and low voltage impulse methods are very considerable ways to determine the measuring system performance instead of the laborious high-voltage comparison.

The performance of the tested cable types was similar throughout the tests. All the tests show almost a linear effect for T_1 and T_2 when the cable gets longer and is terminated with 50 Ω. Results also show that the termination does not need to be exactly 50 Ω since the 45-Ω and 55-Ω terminations work almost the same way. Surprisingly, high-impedance termination seems to make the cable length effect negligible when the cable length is reasonable (less than 25 m). This suggests that high-impedance termination can be used to reduce the cable length effect with resistive voltage dividers when the low-voltage arm and cable are 50 Ω. This can be very tempting option if the used digitizer cannot be used with fiber-optic connection and a short cable.

Results also show that the cable effect is not related to the used voltage level. Instead, the cable length effect seems to be related to the current flowing through the cable because the effect is more visible with low-impedance termination. However, the method is not yet completely known and needs theory and simulation results to support the measured results.

It must be noted that the measurement cable should always be treated as part of the measuring system and the influence of its length is dependent on the used voltage divider.

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