Improvement and uncertainty evaluation of a 1 MV lightning impulse measurement system

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Abstract

This paper focuses on development of an existing 1 MV lightning impulse (LI) measuring system as part of European project for i.a. LI calibration capabilities development. After carefully characterization of the original LI divider a new low voltage arm was designed and built with e.g. improved shielding and also RC circuits for compensating the detected drift in the step response. With the compensation step response was successfully corrected resulting in clear improvements in LI time parameter measurements. However, persistent high frequency noise was present in the step response complicating further fine-tuning of the response. The noise could not much be improved at least partly due to non-optimal damping resistor structure, which is difficult to improve afterwards. After the improvements an extensive uncertainty evaluation was carried out for the original system as well as for two versions of the improved system.

1.   Introduction

Ongoing trends in power production and usage clearly indicate the needs for increased power transmission both over short and long distances. Higher system voltages are thus needed e.g. due to usage of more distributed and distant power production resulting also in needs for improved calibration capabilities. Such development work is carried out also in European Union research project 'Future energy' [1] under which this study was made. This paper focuses on development and characterization of an existing LI measurement system for an European intercomparison campaign, where reference measuring system level uncertainties are needed.

For the improved voltage divider a new low voltage arm and a measuring cable were made. The low voltage arm has compensating branches on a circuit board layout to compensate the frequency dependency of the high voltage capacitors. Together with simulations step response testing is performed to analyze the contributions of different improvements in the system to improve the dynamic behavior of the divider. Uncertainty contributions are studied with different testing setups or estimated.

The different uncertainty contributions for the divider are examined and uncertainty analysis performed using intercomparison measurements with reference measuring system. The resulting uncertainties for peak voltage and time parameters for three different measurement systems are presented and compared. Accuracy of the time to half value is successfully improved with the compensation.

2.   Measuring system for lightning impulses

A high voltage measurement system consists of a transient recorder, a high voltage divider and a measurement cable. For lightning impulses, usually resistive or damped capacitive divider is used. The divider studied in this paper is a damped capacitive CS 1000/670 by Haefely presented in figure 1. The transient recorders used are the Haefely DIAS® 733 and VTT's NI PXI-5124 based system.

Fig. 1 – Damped capacitive 1 MV lightning impulse divider.

The original system uses the divider with the original low voltage arm and a 75 Ω coaxial cable. The coaxial cable travels under the laboratory's floor to the shielded control room where DIAS digitizer is located.

In the development work a new low voltage arm was designed and built for the existing divider to mainly to improve the time parameter accuracy of the original LV

arm. Thus two different modified LI measuring systems are studied in this paper. Both of them are using the existing updated divider consisting of the original HV arm and the new LV arm together with either DIAS or the VTT digitizer. The VTT digitizer's response is corrected via a software [2] and the system uses a 1.2 m measurement cable and a shielded box inside the laboratory, near the divider. That system is intended to be used in the comparison campaign. The DIAS digitizer with a new 50 Ω triaxial measurement cable is studied also since it is a part of the system present at the laboratory.

2.1. Divider modifications

The new divider has a scale factor of approximately 1150. The high voltage arm has 3 capacitors connected on top of each other and a damping resistor inserted to the top of the divider. The capacitors are 2 nF each and the resistor is 230 Ω. The resistive and capacitive scale factors are designed to be the same so the low voltage arm has 0.2 Ω and 792 nF in series. The capacitance and resistance are divided to a printed circuit board to 4 branches in a coaxial arrangement and the board rests on 4 support beams that also act as a ground return. The 50 Ω terminating resistor is placed between the cable connector and the circuit board. The low voltage arm is shown in figure 2
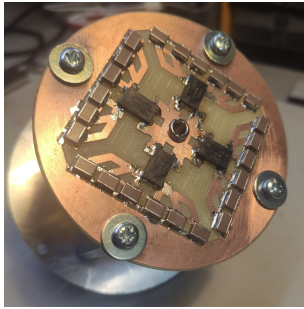

Fig. 2 – The new low voltage arm.

3. Creeping response

The high voltage capacitors have some unidealities. When used in high frequencies, the capacitors' value changes. This is due to change in permittivity [3]. Figure 3 shows how the frequency dependency can be modeled.
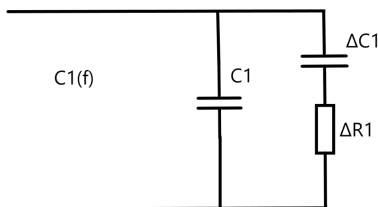

Fig. 3 – Equivalent circuit model of the high voltage capacitor's frequency dependancy.

This frequency dependency is only at the high voltage

arm's oil-filled capacitors that are large in size. The low voltage arm has ceramic capacitors that behave more ideally also over the whole frequency range of LI. This results in the capacitive scale factor to vary slightly with the frequency. The divider factor at the start of the step signal follows the resistive scale factor. After the initial highest frequency transient, the capacitive scale factor starts to dominate which at that freq differs from the resistive one due to the described effect. This effect slowly decays and follows approximately 1st order system's response as can be seen from figure 4.
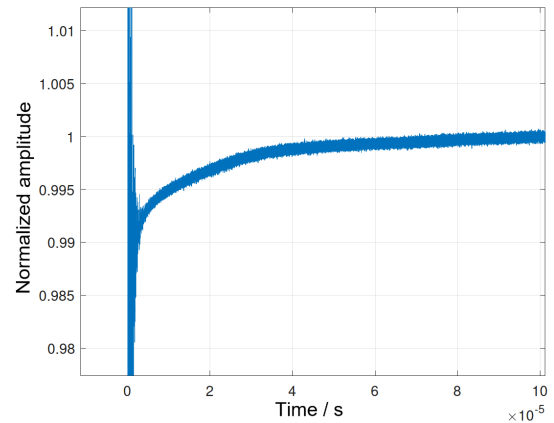

Fig. 4 – Step responce of the divider, zoomed to point out the creeping phenomena.

The figure 4 shows how the creeping follows closely 1st order response which can be modeled with the RC circuit parallel to the capacitance. The step response was fed to the divider with a step voltage generator. The generator connects 300 V_{DC} to ground using a mercury-wetter relay to achieve a connection in less than 1 ns with minimal contact bounce.

In a lightning impulse standpoint this creeping phenomenon results in different scale factor used in the sub microsecond range compared to the scale factor in the tens of microsecond range. So in essence the tail time will have error because of this.

The creeping amplitude

$$\frac{\Delta U}{U} = \frac{\Delta C_1}{C_1 + \Delta C_1}, \quad (1)$$

where $\frac{\Delta U}{U}$ is the relative creeping of the output voltage, C_1 is the high voltage arm's capacitance and ΔC_1 is the change in the high voltage arm's capacitors. The latter part of the equation is the relative creeping of the high voltage capacitance.

The time constant of the high voltage arm

$$\tau_1 = \Delta R_1 \Delta C_1, \quad (2)$$

where ΔR_1 is the resistance in the parallel branch in the high voltage arm. This RC time constant follows the response shown in figure 4 but the slowly increasing phenomena after 50 μs doesn't follow the 1st order

response. This phenomena however has a slope of approximately 0.3 % per 100 μs so it can be considered small in lightning impulse's standpoint.

4. LV arm compensation

To compensate the unideal step response characteristics discussed in chapter 3. the resistive and capacitive scale factors need to be tuned to the same value in all frequencies to achieve ideal step response. This can be achieved by placing similar RC circuit parallel to the low voltage arm's capacitors. This will insert a RC time constant to the low voltage arm that has similar response to that in high voltage arm.

The compensation branch needs to be divided to the PCB to achieve coaxial layout also on terms of the compensation. It could also be divided to each of the single capacitors but that would be taking a lot of space. The final circuit board with the compensation added is shown in fig. 5.
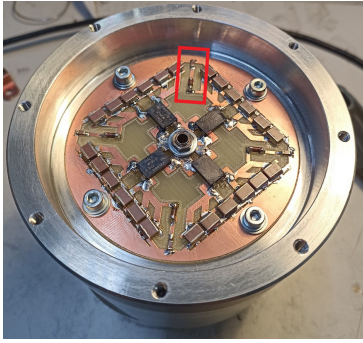

Fig. 5 – Low voltage arm with compensation added to the PCB. One of the four compensation branches is denoted by the red rectangle.

The compensation values can be calculated from the step response. The creeping amplitude corresponds to the change in the capacitance and the resistor value together with that capacitance value corresponds to the the time constant. Those values then need to be transferred to the low voltage side. The creeping amplitude should be set similarly to the HV arm as it appears in the LV arm. The amplitude of the creep

$$\frac{\Delta U}{U} = \frac{\Delta C_1}{C_1 + \Delta C_1} = \frac{\Delta C_2}{C_2 + \Delta C_2}$$
$$\rightarrow \frac{\Delta C_1}{C_1} = \frac{\Delta C_2}{C_2}, \tag{3}$$

is set similarly as in the HV arm, where C_2 is the low voltage arm's capacitance and ΔC_2 is the capacitance in the compensation branch. The ΔC is much smaller than C so the assumption can be made to simplify the equation.

Now that the amplitude of the creeping is set, similar thing should be done to the time constants. The low voltage arm time constant should be also set equal to the high voltage arm time constant. For the low voltage time

constant

$$\tau_2 = \tau_1$$
$$\leftrightarrow \Delta R_2 \Delta C_2 = \Delta R_1 \Delta C_1, \tag{4}$$

where τ_2 is the low voltage arm's creeping time constant.

Now the equations 3 and 4 can be used to get a formula for the compensation branch's values. The ΔC_2 and ΔR_2

$$\Delta C_2 = \frac{\Delta U}{U} C_2 \quad \text{and} \quad \Delta R_2 = \frac{\tau}{\Delta C_2}, \tag{5}$$

where τ is the measured RC time constant of the creep.

The amplitude and the time constant are usually hard to determine since the start of the creeping phenomena is near the transient where many oscillations occur so the initial correction might be set too high or too low. In this case the tuning is an iterative process. If the initial response is, after the correction, less than the final level, then the ΔC_2 should be increased or if other way around, decreased. Then the ΔR_2 is adjusted so that the response is flat enough which depends on the application the divider is used in.

The step response shown in fig. 4 was run through a program that corrects the oscilloscope's unideal step response and the amplitude of the creep is observed to be about 0.6 % and the time constant about 20 μs. This results in compensation branch to have values of 4.8 nF and 3.3 kΩ. When this is divided to the 4 branches the values needs to be multiplied and divided by 4.

After fine tuning the compensation values, the resulting compensation for the new low voltage arm has 1.1 nF and 15 kΩ per branch. The figure 6 shows the old low voltage arm and the new low voltage arm after the compensation has been made.
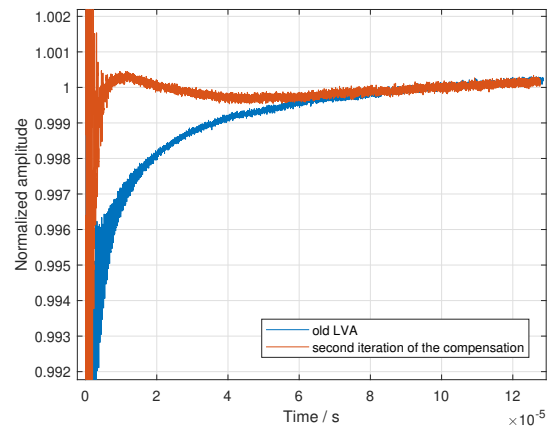

Fig. 6 – Step response of the old low voltage arm and the new low voltage arm after compensation.

The new low voltage arm creeping falls flatter, inside ± 0.1 % of the final unity level. The old low voltage arm's creeping is almost 1 % and has a lot of oscillations in the beginning so it is hard to determine exactly. Both low

voltage arms have a bit upward creeping after the 50 μs mark but that is relatively small. The resulting waveform is not completely flat since the creeping doesn't follow exactly first order response like the compensation does as discussed in the end of 4. chapter.

5.   Oscillatory response

The new low voltage arm exhibits more oscillations at the front as well as a large peak. Figure 7 shows how the divider acts at the sub 2 μs time frame when applying a step voltage to the divider.
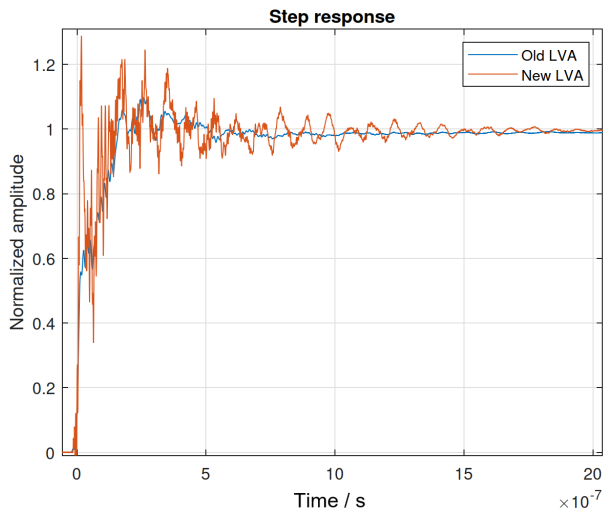

Fig. 7 – Step response of the old low voltage arm and the new low voltage arm zoomed to show the oscillations at the start of the transient.

The reason the old low voltage arm is so slow, might be because the capacitors in the low voltage arm are big in size and might have significant inductance as well as other unwanted effects in them.

The big peak at the beginning could be caused by the stray capacitance directly coupling to the low voltage arm since the plate structure supporting the high voltage arm is rather large in size and is not shielded in any way. To combat this a setup with metal plates connected to ground was introduced to shield the support structure. This capacitive coupling would then be connected to the ground instead of the low voltage arm directly.

Different earthing conditions were investigated. The laboratory's grounding point was moved to a different point with minimal inductance and additional grounding was connected at the connector terminal in the control room end of the measurement cable.

The low voltage arm is connected to ground via aluminium beams that support the low voltage arm. These support beams were bypassed with copper foils to minimize their inductance as well as to minimize the current loop size. Also a testing with different outer shielding was done by connecting copper foil inside and outside of the low voltage arm's plastic housing.

The damping resistor is bifilarly wound but it still has significant inductance of about 7 μH. The inductance in the high voltage arm was matched by placing another inductance in the low voltage arm. This damping resistor forms together with stray capacitances to earth an oscillating LC circuit which is hard to match in the low voltage arm. So other solution is to make an impact on the LC circuit in the high voltage arm by either minimizing the inductance or distributing a part of the damping resistance in between the high voltage capacitors. The high voltage resistor was changed to a lower inductive one of carbon foil type. The distribution of the damping resistor between the 3 capacitors was also made however the lowest connection point couldn't be used since it would need additional adjustments to guarantee that the divider wouldn't fall over. These resistors were used only in low voltage step tests because they cannot handle high voltage impulses. Ideally the distribution of the resistor would be made inside the capacitor units.

All the studied modifications to minimize the high frequency interference in the measured waveform did not result in any significant improvement. The interferences are assumed to be caused by unidealities in the high voltage arm.

6.   Uncertainty analysis

Different uncertainty contributions[4] are needed for the uncertainty analysis. The long term standard uncertainty was calculated from previous calibration certificates. Some of the standard uncertainties were examined with comparison measurements with the reference measurement system of VTT. Temperature effect was estimated by measuring the capacitance of the high voltage arm while varying the temperature. For the proximity effect standard lightning impulses were fed to the divider while varying the position of the divider.

6.1.   Ambient temperature

The effect of ambient temperature variations was studied by disconnecting the divider's capacitors and measuring individual capacitor's value while altering the temperature. The capacitors were put to a room with controllable temperature and humidity and the measurement of capacitance was taken with an LCR meter. The resulting temperature frequency dependency is shown in figure 8.

All the three capacitors have similar slope but one has slightly lower offset from the average. This offset may be e.q due to different production batch but is not an issue since the only interesting part is the slope.

The capacitors have approximately 0.34 pF/K of temperature dependency and the low voltage arm's capacitors have temperature dependency stated in the data sheet as ±30 ppm. The capacitance in the low voltage arm can be assumed to change in the same direction as in the high voltage arm although the this
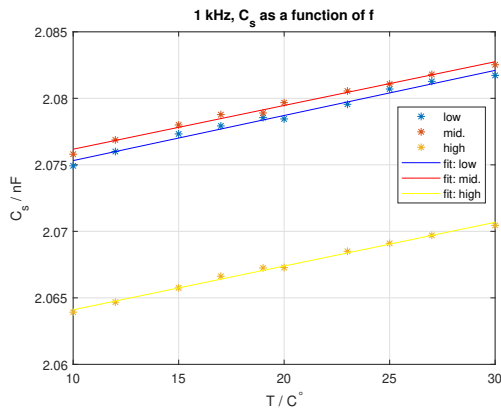
Fig. 8 – Capacitance value for the each three individual high voltage capacitors in the high voltage arm with function of temperature.

standard uncertainty is mainly governed by the high voltage arm characteristics. This results in standard uncertainty of 0.02 %.

6.2. Proximity

The proximity effect was measured by firing +200 kV standard front lightning impulses to the divider while altering the divider location in the laboratory. The figure 9 shows how the scale factor changes while moving the divider. Zero point is the normal divider location, in between the LI generator and the grounded lab wall, about 3 meters to each of them. The final ±2 m points mean 2 meters away from the zero point so about 1 meter away from the grounded wall and generator. In practise the divider cannot be used that close to wall or generator.
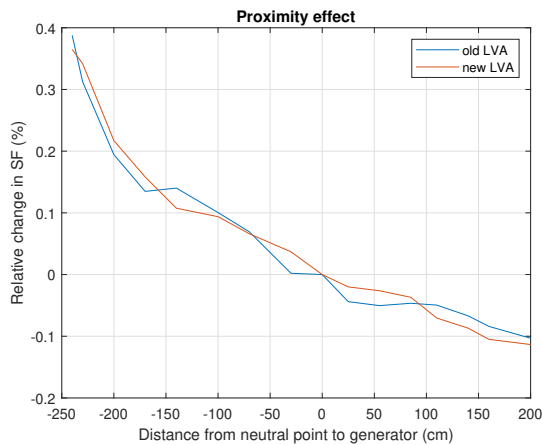

Fig. 9 – Change in the scale factor as a function of location. The zero distance indicates the optimal position for the divider which set so that it is 3 meters away from both the wall and the generator.

The old and new divider constructions behave similarly. This is because the low voltage arms have scale factors of similar magnitude and the stray capacitive effect is mostly from the top of the divider to the grounded or energized object. From the figure it can be seen that the

proximity of a grounded object has a larger effect. The uncertainty for the proximity effect is 0.11 %, provided that the nearest grounded or energized object is over 2 meters away from the divider. The divider is over 3 meters tall and as a "rule-of-thumb" should be placed as far from the near by objects as the divider's height is but usually this is unachievable when there is a real equipment being tested.

6.3. Dynamic effect

The dynamic effect was studied by firing lightning impulses of different shapes. The front time was set to the nominal and ±30 % of the nominal. The more flat the step response of the divider is more ideally it behaves under pulses with different front times. The type B uncertainty for peak voltage is 0.15, for front time is 1.51 and for time to half value is 0.15 with the new DIAS 733 based setup and with the NI digitizer 0.20, 1.10 and 0.21 respectively.

6.4. Long & short term stability

Long term stability can be calculated from multiple performance checks or calibrations with a Gaussian distribution. Other method is to use 2 calibrations and a rectangle distribution is assumed. Short term stability needs to be determined by measuring the divider scale factor before and after it has been in intensive use. This should cover the heating of the divider during testing period. This effect is more severe in resistive dividers.

The type B uncertainty contribution of long term effects is 0.47 % and is taken from 2019 and 2020 calibration certificates. The short term effect is hard to measure safely and accurately. The short term contribution is assumed to be 0.07 %.

6.5. Non-linearity

The scale factor is taken as the mean of the voltage levels used in the calibration. The real scale factor of the system deviates from the mean a bit when changing the voltage level. The uncertainty can be calculated by the largest scale factor deviation from the mean with type B uncertainty. The non-linearity of the scale factor is 0.16 and 0.23 for the DIAS and the NI digitizer setups respectively.

6.6. Digitizer

The National Instrument PXI-512 digitizer has uncertainty of 0.1 % for the front time, 1 % for the T_1 and 0.5 % for the T_2. These are stated in the calibration certificate so they have approximately 95 % coverage factor i.e. $k = 2$.

The DIAS® 733 system by Haefely has stated the uncertainties (k=2) as 1 % for the peak voltage and 2 % for the time parameters. This is however the uncertainties according to the old standard. The software is updated to give the parameters by the definitions in the newest standard afterwards. The uncertainty can be assumed to

be the same to be on the safe side.

6.7. Combined expanded uncertainty

The expanded uncertainty

$$u_{total} = 2\sqrt{\sum_{i=1}^{n} u_i^2},\qquad(6)$$

where n is the number of different uncertainty contributions and u_i is a single standard uncertainty contribution that is either estimated or measured and calculated. The peak voltage has many more uncertainties added since the time parameters have no f.ex temperature dependency.

The expanded uncertainty calculation needs also the uncertainty of the reference system. The used reference system has uncertainties stated to be 0.5 %, 2 % and 1 % for the peak voltage, front time and time to half value, respectively.

The old system's uncertainties are assumed to be the same as in the new system with DIAS digitizer excluding the dynamic component which is calculated from previous calibration certificate to be 0.23, 1.22 and 1.04 % for the peak value, T_1 and T_2, respectively. The resulting expanded uncertainty is 1.7, 3.1 and 3.1 % of the peak value, T_1 and T_2 respectively for the old system.

The calculated uncertainties for the peak voltage are given in the table 1 and for the time parameters in the table 2.

Table 1 – Uncertainty evaluation of the peak value for the new system.

	DIAS $U_T(\%)$	NI $U_p(\%)$
$U_{ref_{k=2}}$	0.5	0.5
u_{B1}	0.35	0.35
u_{B2}	0.15	0.20
u_{B3}	0.07	0.07
u_{B4}	0.47	0.47
u_{B5}	0.02	0.02
u_{B6}	0.11	0.11
u_{B7}	0.5	0.05
$U_{k=2}$	1.7	1.4

Table 2 – Uncertainty evaluation of time parameters for the new system.

	DIAS $T_1(\%)$	NI $T_1(\%)$	DIAS $T_2(\%)$	NI $T_2(\%)$
$U_{ref_{k=2}}$	2	2	1	1
u_{B2}	1.51	1.10	0.15	0.21
u_{B7}	1	0.5	1	0.25
$U_{k=2}$	4.2	3.2	2.3	1.2

7. Conclusions

The main problem with the voltage divider is its high voltage arm. The damping resistance is not divided along the diver column as it ideally should be and is only placed on top of the high voltage capacitors. This together with the unidealities of the capacitors and decreased inductance of the low voltage arm results in high oscillations when the divider is fed with high transients. The oscillations on the front result in high uncertainties for the front time.

The old measuring system has about 1-2 % of error in the time to half value. This is because of the high voltage capacitors' behavior under fast transients which is successfully corrected in the new low voltage arm by compensation circuit.

The expanded uncertainties of both the original measuring system and the new system fulfill the requirements of reference measuring system (1 % and 5 % for the peak and time parameters, respectively [4]). However, although the uncertainty of T2 was improved with the new LV arm, the high frequency oscillations resulted in increased uncertainty of T1.

Acknowledgment

8. References

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