HIGH VOLTAGE TOPOLOGIES FOR VERY FAST TRANSIENT MEASUREMENTS

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Abstract: High voltage equipment is subjected to several types of electrical stress during operation, why testing by transient wave shapes is routinely performed. The fastest transient which air insulated equipment are exposed to is lightning impulse (LI) with front times round 1 µs, for which traceability of measurement systems are widely available. Puncture testing of insulators have front times around 200 ns, where presently traceability is just being established. Measurement systems are also being developed by National Metrology Institutes (NMI) for traceable calibration of sensors used in Gas Insulated Switchgear (GIS) where front times below 10 ns are common. We refer to front times below this as Very Fast Transients (VFT).

This paper presents advantages and disadvantages of various divider designs to be used for VFT measurement systems. Many of these are a heritage from lightning impulse measurement systems. Several divider designs are studied to investigate the contribution on uncertainties in both amplitude and time parameters in a measurement system. Four resistive designs based on ceramic bulk resistors, bifilar wire winding, a resistive liquid and thick film SMD resistors have been characterized and compared with a small damped capacitive divider.

Step response measurements have been used to characterize several dividers in different geometrical configurations, looking at the transient response out of a wave propagation point of view with analysis of loop sizes, field distributions and proximity effects. The findings are that and minimizing skin effects and inductance in the dividers are essential for a fast response and settling.

Convolution of the step responses with ideal reference curves showed that more development is needed to eliminate oscillations in the step response. Further improvement of the geometries and impedance matching is needed to achieve acceptable errors for VFT with front times  $T_f$ below 10 ns.

1 INTRODUCTION

High voltage equipment is subjected to several types of electrical stress during operation. Factory tests are defined to ensure that the equipment will perform satisfactorily in service. Testing with standard lightning impulses, according to IEC 60071, using impulses exceeding the nominal voltage in the grid is well proven and used method with established traceable calibration services.

Measurement of transmitted overvoltage test for instrument transformers with 0.5 µs front time at 1 kV according to IEC 61869, currently lacking traceable calibration services for HV has recently been developed [16]. Puncture testing of insulator discs according to IEC 61211 with 0.2 µs front time has recently been developed providing traceability of peak voltage measurement [11]. The need to correctly measure faster impulses, i.e. transients, during testing is pushing metrology to even faster rise times.

For measurement of transients in Gas Insulated Switchgear (GIS), measurement systems with rise times less than 10 ns are needed. Development of traceability for transients with rise times even below 10 ns and voltages up to 100 kV is ongoing at national metrology institutes [1], using transient recorders with latest technology with higher dynamic range and fast enough settling time [9]. Another major obstacle for traceable measurement at high voltage is the design of a divider with a fast response, which involves attention not only to the physical size of the voltage divider but also the topology of the measurement circuit.

2 DIVIDER TYPES

In this work we focus on different divider designs, and their uncertainty contribution in amplitude and time parameter measurements. New divider designs have similarities to dividers used for LI measurements, but in most cases quite different approaches are used to improve the response time and minimize the overshoot at the front.
We have studied seven different dividers. Two dividers typically used in LI measurements are wire-wound resistive dividers, as shown in Figure 1, and mixed resistive capacitive divider shown in Figure 2. The newly developed dividers are: a divider for puncture testing using ceramic resistive components shown in Figure 3, a wire-wound resistive divider shown in Figure 5, a salt solution resistive divider depicted in Figure 6, a divider with Surface Mounted Resistive devices (SMD) in Figure 4, and a damped capacitive divider in Figure 7.

2.1 Lightning impulse dividers

A commercial resistive divider for LI measurements [12] is shown in Figure 1. The shape of the corona ring has proven to be important for linearizing the field distribution along the stack, crucial for achieving a good step response. This type of divider is designed for LI measurements up to c.a. 500-700 kV [13].

Figure 1: Wire wound resistive divider

A damped-capacitive divider is shown in Figure 2 [2] and is an optimum damped $RC$ divider of Zaengl design [14]. The damped-capacitive divider is mainly designed and used for ultra-high voltage measurements. Results show an experimental response time $T_N$ of 5.8 ns, a partial response time $T_\alpha$ of 13 ns and a settling time $T_s$ of 190 ns [2]. Due to the size of the measuring circuit, parasitic inductances in combination with the capacitance give oscillations, which is evident from the 190 ns settling time.

The designs of the LI dividers are well proven for measurements of wave fronts down to 0.5 µs, for testing of HV equipment. However, the dimensions of these are probably too large to achieve fast enough step-response for shorter front times needed for VTF measurements (1-10 ns front time) where the dimensions of the high voltage circuit become important.

2.2 Fast transient dividers

For fast transient measurement the signal propagation path needs to be shortened by reducing the size of the HV circuit, which also lead to lower inductance. This is achieved by building smaller dividers paying attention to the reduction of the flashover voltage or confine the HV circuit in a protective gas like in GIS. We limit this study to designs for applications in air, but an example of GIS application is described in [4].

2.2.1 Ceramic disc resistive divider

This divider was originally designed for puncture testing with 200 ns rise time in a previous study [3].

Figure 2: Optimum damped $RC$ Mixed divider.

Figure 3: Divider with ceramic bulk resistors in a 200 kV configuration. The step generator can be seen attached to the right on the coaxial cable.

Here, compared with the original design, the number of ceramic bulk disk resistors stacked in the high voltage arm has been reduced. The maximum voltage of the modified divider in Figure 3 is 200 kV instead of 600 kV, and the HV arm resistance is 1600 Ω. The disks are 25.4 mm high, have 50 mm outer diameter and a 20 mm diameter through hole. The low voltage arm has a 4.7 Ω resistance, giving a scale factor of 680.

In this divider we focus on minimizing mutual inductance by using a coaxial symmetry in both the HV and LV arm. The design is based on the work of M Aro [5]. The ceramic discs have no measurable inductance, the skin depth is large e.g. 180 mm @ 100 MHz giving a high effective relative conducting cross section of 96%. However, the
scale factor of the divider is voltage dependent. A modified version of this divider design has also been used in an ongoing project for calibration of VFT sensors in GIS [4].

2.2.2 Thick film SMD divider

The coaxial design of the ceramic divider in Figure 3 eliminates much of the inductance. One way to further minimize the skin effect is to use film resistors with preferably thin film. A divider was built with SMD in a coaxial arrangement as shown in Figure 4.

Figure 4: SMD thick film resistors mounted in a coaxial arrangement designed for measurements up to 200 kV with pulse widths up to 500 ns.

In selection of SMD resistor values, there is a trade-off in optimizing the response time, which is hampered either by stray capacitance for large values, or by stray inductance for lower values. Also, the maximum sustainable pulse energy and/or field strength limits the resistor selection.

An optimum is found in the 100 Ω to 300 Ω range. The HV arm was built using ten resistors, each 100 Ω, soldered parallel in a circle, stacking 50 such units to obtain a HV resistance of 500 Ω. The low voltage arm comprises of ten 10 Ω resistors in parallel in a coaxial arrangement, thus obtaining a scale factor of 501.

2.2.3 Wire wound divider

An alternative to discrete resistors is to use a bifilar winding of resistive wire to reduce the mutual inductance. This has been used in the design of the compact divider in Figure 5. The divider is built using a bifilar winding of 140 μm thick Manganin wire forming a high voltage resistance of 5 kΩ. The wire thickness brings skin effect to a low value, e.g. with an effective relative conducting cross section of 56% at 100 MHz.

For large dividers as the ones in Figure 1 and 2, the influence of capacitive coupling to surroundings needs to be taken care of. This can be done either by grading the winding or capacitance in the HV arm or by using a toroid as shown in e.g. Figure 1.

Figure 5: Wire wound resistive divider designed for measurements up to 200 kV with time-to-half values up to c.a. 60 μs.

The toroid in Figure 1 makes the field along the HV stack more linear and reduces capacitive coupling to the surroundings. The effect of the toroid ring for this divider is discussed in the step response test section.

2.2.4 Salt solution divider

The high dielectric constant of water, together with added salt to reduce the resistivity, make the salt solution (CuSO₄) divider a candidate for measurement of fast transients. However, the conclusion in earlier work was that the divider scale factor was dependent on temperature, and it was not stable [6]. The design shown in Figure 6 use a copper sulphate solution to adjust the HV resistance value.

Figure 6: Resistive salt solution divider designed for measurements up to 200 kV with time-to-half values up to c.a. 60 μs.

The fluid is contained in a 2.5 mm thick layer between two PMMA tubes to minimize the inductance and skin effect. With the saturated CuSO₄ solution a high voltage resistance of 1.7 kΩ is achieved. The skin depth is e.g. 28 mm at 100 MHz and using a thin layer design concentric geometry the effective relative conducting cross section is 97%. In Figure 6 the divider is shown with toroid and a guard ring.
2.2.5 Damped-capacitive divider

A miniaturized version of the damped capacitive divider in Figure 2 is the last candidate for VFT measurements. The divider is shown in Figure 7.

Figure 7: Damped capacitive divider 100 kV with time-to-half values up to c.a. 60 µs.

3 STEP RESPONSE

3.1 Step generator and digitizer

Traditionally a mercury wetted relay has been used to study the response on dividers for LI. Relay design producing steps down to 400 ps fall times has been reported [7]. Figure 8 shows the step response of the resistive LI divider of Figure 1 measured with a 75 Ω cable and termination. The rise time is 8 ns which is a bit too slow for VFT measurements.

Figure 8: Step response of SMR500 LI divider. 8 ns rise time.

In VFT measurements we use 50 Ω termination to increase the bandwidth and avoid reflections at the recorder end of the measuring cable. In the low ns time domain, the reflections resolved by the propagation time in the cable will clearly be observed and have an impact on measurement uncertainties.

A special avalanche technique is used to shorten the rise time of the step [8] below 100 ps. The developed step generator utilizes a strip-line technique to match with 50 Ω cable impedance. A reference step response from the digitizer used here is shown in Figure 9.

Figure 9: Step response of the PXIe-5164 digitizer with a rise time of 1.45 ns and 4.6 ns settling.

However, since most of these dividers are mixed RC dividers and cannot be loaded with 50 Ω, the typical input impedance of a recorder used with those is 1 MΩ. This often leads to a reduced bandwidth.

3.2 Step response setup

The step generator [8] shown in Figure 10 is attached as close as possible to the HV circuit of the divider as shown in Figure 3.

Figure 10: Avalanche step generator [4]. A d.c. voltage is applied from the right, output on the left.

3.3 Divider step responses

In Figures 11 to 15 the step responses are shown for the dividers shown in Figures 3 to 7. A fast response is important for a VFT divider; however, overshoot and oscillations lead to a slow settling time, and higher measurement uncertainty [10].

The ceramic disk divider in Figure 3 has a 4.7 ns rise time as shown in Figure 11. The 200 kV version in Figure 3 is more compact and has better step response than larger versions [3], indicating the importance of a compact structure for VFT applications.

The bifilar wire wound divider in Figure 5 performs best with the corona ring linearizing the field but causing more capacitive coupling from the HV arm to earth. This causes the faster oscillations observed on the front of the step response shown in Figure 12.
When we look at the step response of the SMD resistive divider in Figure 14, the rise time of 6.2 ns is the same as for the CuSO₄ liquid divider without corona ring. The overshoot is the lowest of all dividers, which makes the geometry and components of this divider one of the better for VFT measurements. The settling time is the best among the resistive dividers and is discussed more in section 4.

The step response and settling of the damped-capacitive divider of Figure 7 is shown in Figure 15 in the next section.

4 SETTLING TIME AND ERROR ESTIMATE

The settling time of the dividers gives a first hint of the shortest front time that could be used without contributing too much to $U_p$ and $T_1$ uncertainty [10].

The resistive dividers we have presented respond quickly but have oscillations after a step, which makes it difficult to use them for short front times below 10 ns. The measured settling times are 60 ns for the wire wound divider, 20 ns for the salt solution divider, 17 ns for the SMD divider and 22 ns for the ceramic PIKA divider.

The damped-capacitive divider has a rise time almost as fast as the resistive dividers (6.3 ns), but it is settling much faster (7.5 ns shown in Figure 15).

Figure 11: Step response of the ceramic resistive divider of Figure 3. 4.7 ns rise time at 50 Ω. 200 kV configuration without corona sphere and coaxial guard tube.

Figure 12: Step response of the wire wound divider of Figure 5. 9.5 ns rise time green, 18 ns rise time red and blue.

The response time of the wire wound resistive divider in Figure 5 is a little faster than for the larger commercial resistive divider in Figure 1, but oscillations and overshoot are large.

The salt solution divider has a faster response without corona and/or guard ring as shown in Figure 13. Here, we reach 6.4 ns rise time with much less overshoot than for the wire wound and the ceramic disk divider.

Figure 13: Step response of the salt solution divider of Figure 6. 8.4 ns rise time with corona ring and guard, 6.4 ns rise time without corona ring and/or guard.

Figure 14: Step response of the SMD divider of Figure 4. 6.2 ns rise time.

The step response and settling of the damped-capacitive divider of Figure 7 is shown in Figure 15 in the next section.
The errors introduced by the dividers can be determined by convolving the step responses with ideal test data curves [15]. Results are shown in Table 1 for the two fastest dividers.

### Table 1: Errors of damped-capacitive (Zaengl) and SMD dividers after convolution

| Ref. curve | \(U_p\) error [%] | \(T_1\) error [%] | \(U_p\) error [%] | \(T_1\) error [%] |
|------------|-------------------|-------------------|-------------------|-------------------|
|            | Zaengl           | SMD               | Zaengl           | SMD               |
| 2/50 ns    | +0.5             | +280              | +7.4             | +119              |
| 4/50 ns    | +2.4             | +103              | +4.4             | +17.4             |
| 5/50 ns    | +2.5             | +69.2             | +1.9             | -0.0              |
| 7/50 ns    | +1.3             | +30.0             | +0.9             | -9.7              |
| 10/50 ns   | -0.14            | +1.6              | -0.1             | +0.1              |

### 5 CONCLUSIONS

The advantages and disadvantages of various divider designs for use in VFT measurements have been compared. The divider design has impact on uncertainties in both impulse amplitude and time parameters measurement. A low inductance in a divider is essential for a fast response. However, skin effect also must be considered. The wire wound divider with a slower step response and large overshoot must be tuned further to be qualified for VFT measurements.

The fastest rise time is obtained using the ceramic disk divider, followed by the liquid divider and the SMD. The liquid divider does not have a stable scale factor and it must be calibrated before and after use. The ceramic disk divider has an excellent energy withstand, but its drawback is a voltage dependence, although it is repeatable and can be corrected for. The SMD divider design has the lowest overshoot among the resistive dividers, it could have a small voltage dependence, and it has potential to become fast enough for VFT measurements. The small damped capacitive divider has a fast response but most important of all, also a fast settling time.

A first test using convolution of the step responses with ideal reference curves showed that more development is needed to eliminate oscillations in the step response. Further improvement of the test setup geometries and impedance matching is needed to achieve low uncertainty for measurement of VFT with front time \(T_1\) below 10 ns.

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