Simulation Based Design of a New Capacitive Probe for Very Fast Voltage Measurements on High Voltage Cables

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Abstract – In this paper, an electromagnetic simulation based design of a new capacitive field probe for measurements of very fast voltage transients in high voltage cables is presented. The novelty of the sensor is its very simple design and its adaptability regarding the input/output ratio of the capacitive divider. This is achieved by additional surface-mounted device (SMD) capacitors placed on a printed circuit board (PCB) within the sensor case. To transfer the received voltage signal to a measurement device, a subminiature version A (SMA) connector is mounted on the PCB. This allows the direct connection of a standard oscilloscope to the sensor for voltage measurements up to 600 kV. Several sensor designs were examined and compared by full wave simulations prior to its fabrication. The most important findings of the correlation between sensor shape and sensitivity are presented in this paper as design guidelines. For the most promising sensor, a mathematical optimization formulation was developed to find the ideal sensor dimensions. Finally, real measurements with a commercially available spark gap switch are shown as to prove the proper function of the sensor.

***Index Terms*— capacitive field probe, high voltage measurements, very fast transients, electromagnetic wave simulation.**

I. Introduction

INDUSTRIAL X-ray sources are used for a broad range of applications such as non-destructive testing, gauging, detection of material and design flaws, sterilization of food or airport baggage scanners. X-ray tubes are powered by high voltage DC sources with up to 600kV for high dose applications. The X-ray tube is usually connected to the high voltage generator tank by a high voltage cable of several meters length depending on the application. During the manufacturing of the X-ray source, the X-ray tubes have to be pre-conditioned by several flashovers in vacuum. The breakdown in vacuum occurs very quickly and produces a high dv/dt in the voltage applied to the vacuum tubes. In order to measure the transient voltage during the breakdown, a voltage probe has to be applied to the high voltage cable next to the X-ray tube. Conventional voltage probes need a galvanic connection to the potential-carrying conductor and cannot be used for the measurement in shielded high voltage cables, since this would require the destruction of the cable's shield and main insulation. Therefore, a non-invasive capacitive field sensor has to be used instead. The main requirements for a capacitive field probe are the voltage divider ratio, the safe operation which requires shielding of the sensor, and the undisturbed transmission of the measured signal.

Several sensor designs can be found in literature [1]-[3] for specific applications. However, these designs exhibit either a low bandwidth or a voltage divider ratio, which is too low for the direct connection of the oscilloscope to the sensor. This paper presents the simulation-based development of an optimized, adaptive cable sensor, which overcomes most of the described problems.

II. Equivalent circuit

When a capacitive sensor is mounted onto a coaxial cable, it usually forms two capacitances. The capacitance C_1 describes the coupling capacitor to the inner conductor and C_2 is the capacitance of the sensor to ground. These capacitances can be calculated easily by an electrostatic field simulation. Regarding the divider ratio, the real measurement setup contains at least two more capacitances. This is on one hand C_3, a transient voltage suppression (TVS) diode due to safety reasons and on the other hand the SMA cable (C_4). As the length of the cable changes for different measurement setups, the PCB allows to add six more SMD capacitances C_2' in the predefined slots to change the divider ratio depending on the rated voltage. Altogether, the equivalent circuit can be drawn as in Fig. 1 and the total divider ratio is defined as:

$$\frac{1}{u} = \frac{C_1}{C_1 + C_2 + C_2' + C_3 + C_4}. \quad (1)$$

If the values from Table 1 are used, the division rate amounts to approximately 1/700. This value can be increased many times by further SMD capacitors.

III. Simulation-based Design

As the divider ratio can be changed afterwards, the sensor's own behavior and effects due to traveling waves in the coaxial cable must be studied in detail. Here, the electromagnetic simulation is very helpful and offers new possibilities for the sensor sensitivity optimization [4],[5]. In Fig. 2, the most promising

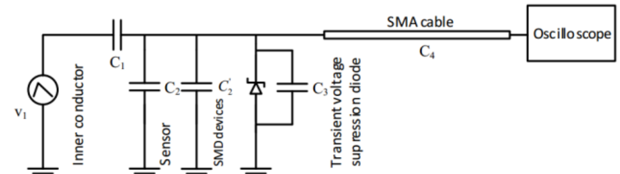

Fig. 1 Equivalent circuit of measurement set up

TABLE I
Calculated Parameters for equivalent circuit

Capacity	Value [pF]	Based on
C_1	0.247	Comsol simulation
C_2	10.77	Comsol simulation
C_2'	0	No SMD capacitors are added
C_3	80	Data sheet
C_4	82	Data sheet

designs are shown on the left. The ring sensor design has already been used in the past [2], [3] and is also considered here. The idea of the conical sensor is to smoothly change the wave impedance from the point of impact of the incident wave to the 50Ω SMA connection. This should reduce reflections and minimize distortion of the traveling wave in the coaxial cable. Lastly, the cylindrical design is considered because of its simple manufacturability. They are compared by their so called S-parameters [6]:

$$S_{11} = 20\times\log\left|\frac{V_1^-}{V_1^+}\right|[dB] \quad \text{if } V_2^+ = 0,$$
$$S_{21} = 20\times\log\left|\frac{V_2^-}{V_1^+}\right|[dB] \quad \text{if } V_2^+ = 0 \qquad (2)$$

where S_{11} is the reflection coefficient calculated by the division of the incident wave V_1^+ at port 1 and its reflection V_1^- at the same port. S_{21} is the forward voltage gain and is accurate only if there is no wave reflected back from the sensor port 2 (V_2^+). V_2^- represents the transmitted wave at port 2. Since the test-rig is a 3-port, S_{21} represents the forward gain input to sensor and S_{31} the input to output behavior of the experimental setup.

If one compares the receiving characteristic of the three sensors in Fig. 2, the following details should be noticed: In case of the ring sensor, there is a large dip in the forward gain at 1.97 GHz. Since a sensor with a bandwidth of at least 1.5 GHz is required, it is not an appropriate solution. A more detailed parameter variation in COMSOL Multiphysics® has shown that by changing the height or width of the ring sensor band, the resonance couldn't be removed. The conical design on the other hand shows a very smooth forward gain and seems to be a possible solution. However, due to manufacturing cost and feasibility issues it has to be ruled out. Finally, the cylindrical design combines the intended wideband behavior and can be manufactured very easily and cost effectively.

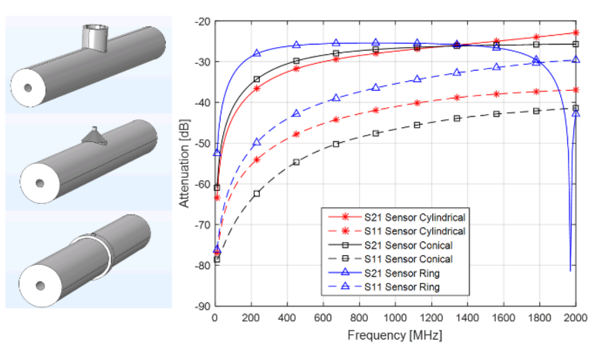

Fig. 2. Frequency behavior of most promising sensors

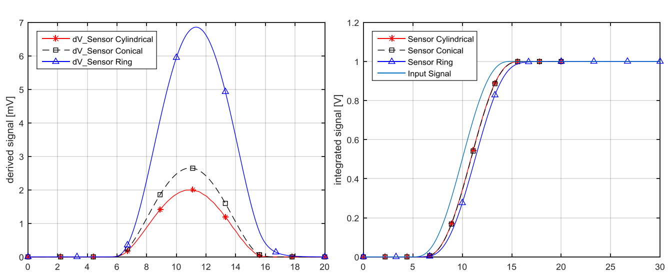

Fig. 3a. V-dot behavior of the test sensors, Fig. 3b. Integrated signals

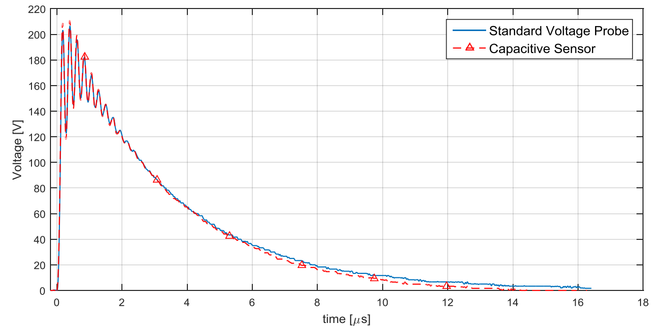

Fig. 4. Comparison of standard voltage probe and new capacitive sensor

To obtain a comprehensive picture, the sensor must be analyzed in time domain as well. For the correct interpretation of the measured signal, it is important to know, if the sensor operates in the V-dot- or V-mode. This means the output voltage v_2 is either proportional to the derivative of the input signal dv_1/dt [4] or simply to v_1. Studying the received voltage signals of the three sensor types in Fig. 3a, it becomes clear that the sensor must operate in the V-dot mode as the applied voltage source was implemented as a 1V step function with 10 ns transition time. The graph shows that the different geometries have a considerable influence on the received signal behavior and amplitude. In Fig. 3b, the signals are integrated and standardized for a comparison to the original input signal. Depending on the design, the signals behave very differently. More detailed evaluations and conclusions, which led to the final design, will be given in the full paper.

IV. Parameter Optimization Formulation and Measurements

After quantifying the best sensor shape by simulations, the detailed dimensions of the sensor geometry were improved by an optimization formulation for a set of constraints. These are the divider ratio, the geometrical boundaries, and the maximum reflection factor. This mathematical approach will be presented in the full paper. First measurements (Fig. 4) done with a small lightning impulse (LI) generator show an excellent agreement with a standard 50Ω probe for measurements up to 500 MHz. Further measurements up to 160 kV with a spark gap generator will be shown in the extended version of this paper.

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