DESIGN AND TESTING OF A NOVEL CALIBRATION SYSTEM FOR UHF SENSORS FOR GIS

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Abstract: Different methods of calibrating UHF sensors for gas-insulated substations (GIS) were investigated in the past. According to some methods the sensors are calibrated inside the substation while other methods use dedicated calibration cells to calibrate the sensors outside the GIS. The latest improvement in the design of a dedicated calibration cell was published in 2010 and is using a conical monopole antenna based on a 50 ohm cone antenna. This approach already showed a very high accuracy but the target of a variation in the electric field near the calibrated sensor of below ± 1 dB was not reached. Since then the original calibration cell has been modified in different ways to improve its characteristics. Details of the different modifications are presented in the paper. The latest design with a 100 ohm cone antenna reaches the target in terms of uncertainty. The variation of the electric field at the sensors installation location is below ± 1 dB in an area of 15cm by 15cm. Whenever UHF sensors for gas insulated substations have to be calibrated, the latest cone calibration system is the preferred way of doing so. It is easy to build and to standardise. It has a very low overall uncertainty in comparison with other known calibration systems. In addition it will reduce the cost of calibration.

1 INTRODUCTION

The measurement of partial discharge activity in gas-insulated substations (GIS) is well known and is increasingly used for condition monitoring purposes. A modern way of measuring partial discharges is the ultra high frequency (UHF) method. Using this method, special UHF sensors in the frequency range between 100 MHz and 2 GHz are deployed.

The calibration of the UHF sensors themselves (without being installed in a GIS) opens up a variety of possibilities: Comparison between sensors from different manufacturers, design of online monitoring systems, optimization of sensors and providing additional sensitivity data to the client – especially when older substations are retrofitted with modern UHF sensors.

The calibration of UHF sensors has already a long history and over the time different calibration methods have been introduced. In the 1990s different calibration methods and cells were tested (strip line, triplate, TEM and GTEM cells). All of these calibration methods had advantages, but also several shortcomings. This lead to the design and construction of a novel calibration system, which is based on a monopole cone antenna. The first design of this system and a comparison of already existing calibration methods were published in 2010 [1].

2 ORIGINAL DESIGN

2.1 Design

The basic idea was to configure the calibration system in such a way that the electric field at a sensor location depends only on the distance r to the driving point and on the power P of the attached network analyzer (Figure 1).

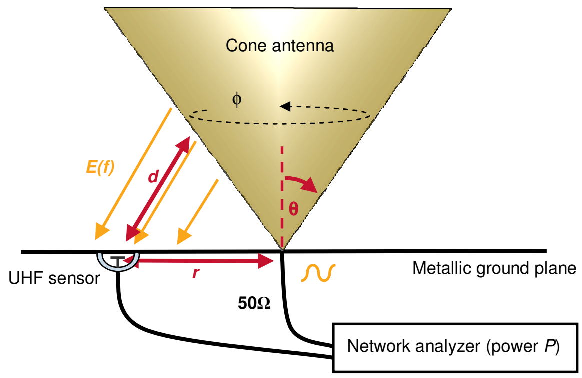

Figure 1: Basic idea: “Design by rule”

The target was therefore that a calibration of the cell is not necessary and only rules for the construction have to be given by related standards. But of course not only the design has to be simple and easy to be standardised there is also a need for a low variation of the incident electric field at the location where the UHF sensor will be calibrated. In addition to not disturb the electric field of the calibration system due to large UHF sensors, the distance d between the conical antenna and the UHF sensor must be as large as possible.

A conical antenna system has in these regards an ideal behaviour. Because of its symmetrical structure the antenna characteristic is very little influenced by installed UHF sensors.

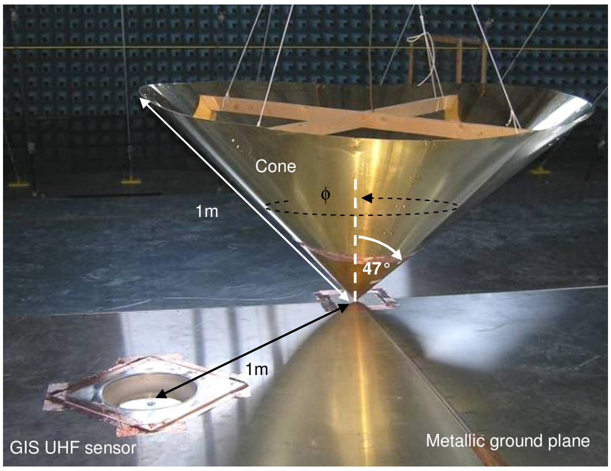

Figure 2: Cone calibration system with installed GIS UHF sensor 1m away from the antenna driving point

The first tested cone calibration system had a cone length of 1m, an opening angle of 47° (50Ω driving point impedance) and a square ground plane size of 4m x 4m (see Figure 2). Such a calibration system can be calculated using the well-known antenna theory. Formulas for the calculation of a spherically capped monopole antenna over an infinite ground plane are for example given in [2].

2.2 Testing

The cone calibration system has been tested using different sensors, at different distances from the driving point and under different angles. Measurements have been taken along the surface of the cone, along the middle axis (see Figure 3), directly on the ground plane where the GIS sensors were installed afterwards and in different directions ϕ around the cone. The distances from the driving point were varied from 10cm to 6m.

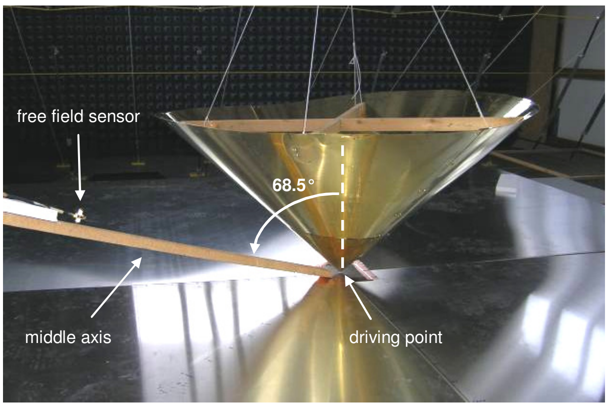

Figure 3: Measurement of the electric field along the middle axis between cone surface and ground plane using a free field sensor from Thomson-CSF

Especially the measurement far away from the driving point gave a good picture of the amount of energy which is transmitted via a transversal electromagnetic (TEM) wave into the open space.
Magnetic field measurements at the ground plane end and near the cones end were used to determine the flowing currents at the ends of the structure.

2.3 Test readings

To prove the accuracy of the electric field at the UHF sensor location 16 measurements were taken on the ground plane in an area of 15cm by 15cm (typical disc sensor size) – one measurement every 5cm. Figure 4 shows the variations of the electric field derivative 1m away from the centre of the cone (installation location of the UHF sensor). The results are within a range of $\pm$ 1.5 dB. A good decoupling between 10 and 20dB between the fields of the r, θ and ϕ axes could be observed.

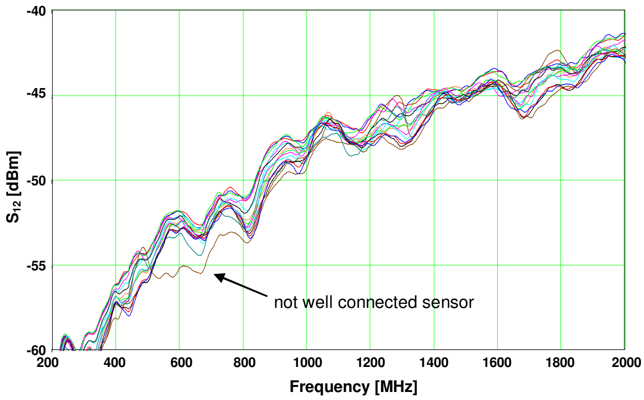

Figure 4: Variations of the relative electric field derivative on the ground plane of the cone calibration cell in a square area of 15cm x 15cm

During the measurements with ground plane electric field sensors their backplane must be well connected with the metallic ground plane of the calibration cell. In Figure 4 one trace with badly connected sensor is shown.

3 MODIFICATIONS OF THE CALIBRATION CELL

To get an even lower variation in the incident electric field further investigations were made. The following chapter shows the different investigations and the modifications are rated in terms of effectiveness, complexity, price and size.

3.1 Tested modifications

The following modifications were tested:

Variations of the ground plane:

- round ground plane with 2m radius
- round ground plane with 1m radius
- quasi infinite ground plane (25m by 10m) (Figure 5a)

Variations of the cone:

- adaptation of the 50 ohm cone to free space (total cone length 2m) (Figure 5b)
- 100 ohm cone with a length of 2m and a round ground plane with 2m radius (Figure 5c)
- 100 ohm cone with a rounded top and a round ground plane with 2m radius (Figure 5d)

Variations of the sensor location:

Different distances of the sensor location from the driving point of the cone antenna were investigated.

3.2 Effects of the modifications on the homogeneity of the electric field

Table 1 summarizes the effect of the electric field homogeneity in the square area of 15cm by 15cm on the ground plane, 1m away from the driving point. In more detail the following effects could be observed:

Size of the ground plane: The measurements show that the variations in the electric field increase with a decrease of the size of the ground plane. The smaller the ground plane the higher are the reflections at the planes ends.

Variation of the cone angle: The higher the opening angle the better is the field homogeneity. But in this case the distance between the cone and the ground plane is reduced and the impact of the sensor itself is getting higher.

The distance between the sensor and the cone should be as big as possible so as to minimize the influence of the installed UHF sensor on the electric field inside the calibration cell. In order for the field enhancement near the sensor to be lower than 10%, the height of the installed UHF sensor should be lower than 1/3 of the height of the septum [3].

On the other hand if the opening angle is decreased the variation in the distance between the cone and the ground plane in the sensor area is increased as well which results in an increased variation of the electric field in the sensor area.

Table 1: Effect of the modifications on the field homogeneity related to the original design.

Modification	Effect
Round ground plane with 2m radius	Negligible effect
Round ground plane with 1m radius	Increase of the field variation
Quasi-infinite ground plane	Negligible effect
Adaption to free space	Increase of the field variation
100 ohm cone with a length of 2m and a round ground plane with 2m radius	Decrease of the field variation
100 ohm cone with a round cap and a round ground plane with 2m radius	Decrease of the field variation

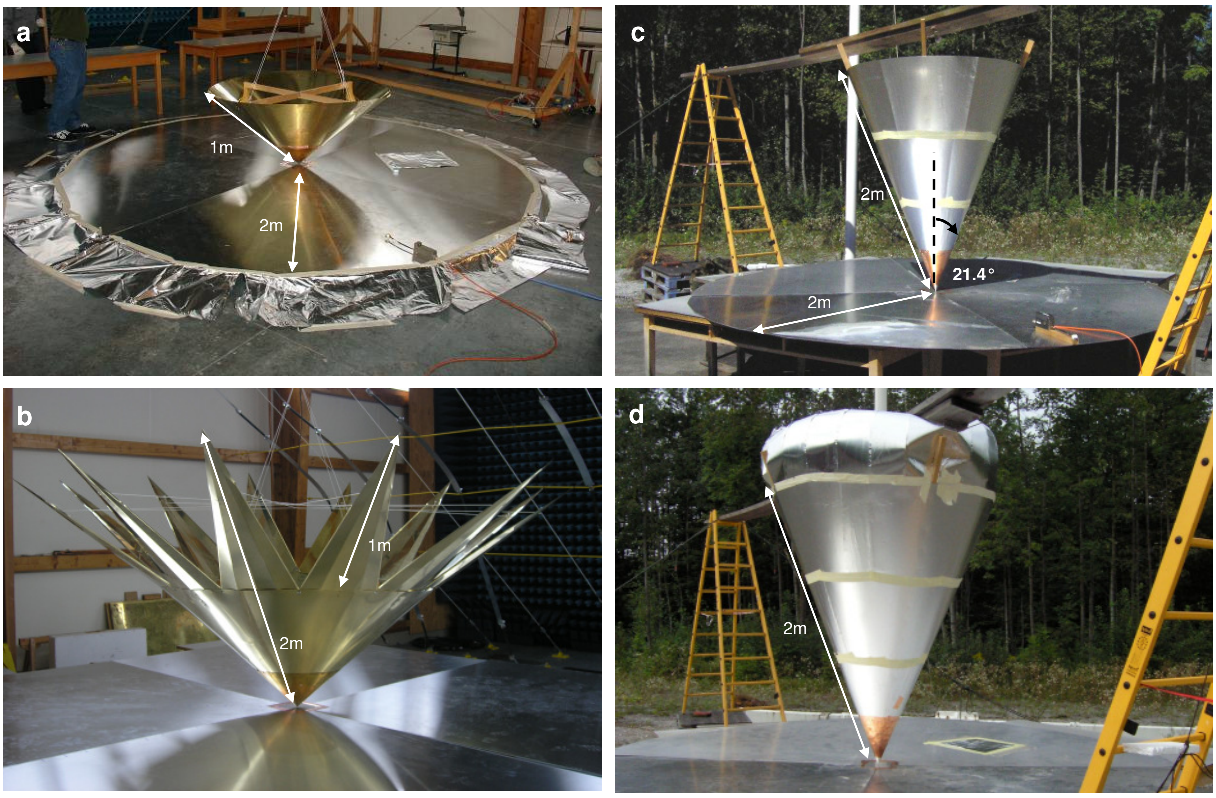

Figure 5: Tested modifications of the original calibration system with a quasi infinite ground plane (a) an adaption to free space (b), a 100 ohm cone (c) and a 100 ohm cone with a round cap (d)

Figure 6 shows the measurement results of $S_{21}(f)$ on the ground plane of the 100 ohm cone. The field variations are in a limit of ± 1 dB. In Figure 7 the measurements are corrected by their distance to the driving point. Figure 7 proofs that most of the field variations are produced by the different distances of the measuring points to the driving point.

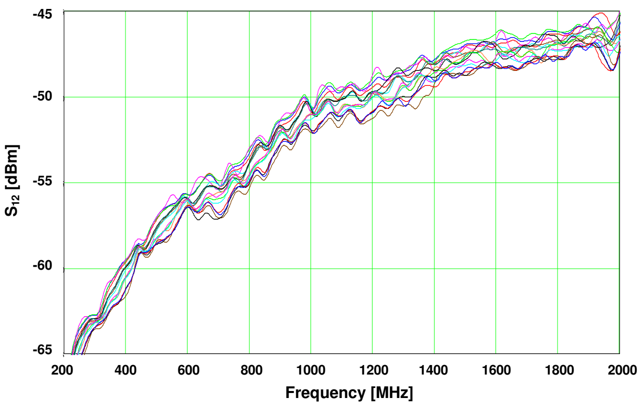

Figure 6: Variations of the relative electric field derivative on the ground plane of the 100 ohm cone calibration cell in a square area of 15cm x 15cm

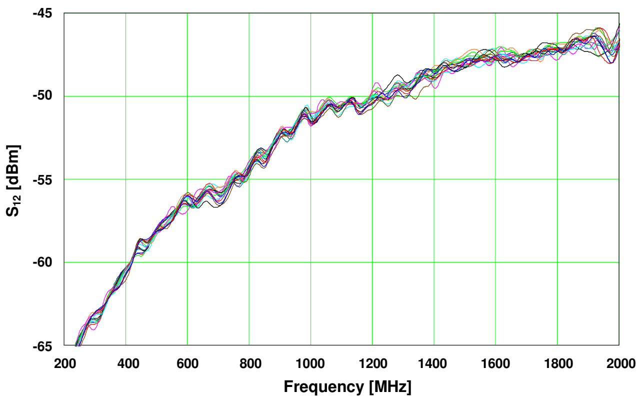

Figure 7: Variations of the relative electric field derivative on the ground plane of the 100 ohm cone calibration cell in a square area of 15cm x 15cm – corrected by the distance r_x/r_0 to the driving point.

Adaptions to free space: Different ways to adapt the antenna to the free space were tested.

First an adaption on the 50 ohm cone antenna system according Figure 5b was tested. It showed an increase of the field variations in the UHF sensor area. It is most likely that the increase comes from standing waves and circulating currents on the cones spikes.
For the 100 ohm cone antenna an adaption of the cones end with a round cap according Figure 5d and Figure 8 was tested. It showed a slightly better behaviour than the 100 ohm cone without round top.

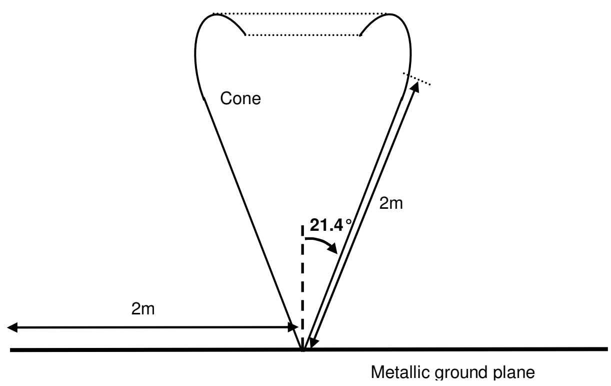

Figure 8: Adaption to free space used for the 100 ohm cone antenna.

Variations in the sensor location: Variations of the distance of the sensor to the driving point of the antenna show the following behaviour.

If the sensor is located too close to the driving point then its size has a non-negligible influence on the field distortion. But if the sensor is located too far away from the centre it will come in a region where the reflecting waves at the ground planes end have a negative influence on the field variation.

3.3 Ranking of the modifications

In Table 2 a ranking of three different calibration systems are presented. The modifications which showed an increase of the field variations or which are not interesting in terms of space or cost are not shown.

Table 2: Ranking of three cone calibration systems

Modification	Original 50 ohm cone	100 ohm cone	100 ohm cone with round cap
Complexity of the calibration system	++	++	+
Ability to be standardized	++	++	+
electric field variation at the sensor location	+	++	++
Price of the test cell	+	+	-
Size of the test cell	+	-	--
Usable to optimize sensors	+	++	++

The best results in terms of uncertainty can be reached by using a 100 ohm cone antenna system with a round cap. But this is not an economic solution. It is therefore recommended to standardize the 100 ohm cone system with an open cone antenna without cap.

4 FINAL DESIGN

According to chapter 3.3 the 100 ohm cone antenna (opening angle: 21.4°) with a cone length of 2m and a round ground plane with a radius of 2m is chosen as the optimum design (see Figure 5c).

4.1 Calculation versus calibration

The Table 3 shows calculated total expanded uncertainties for the two cases where either the system is calibrated in the interesting area with a dedicated electric field sensor (± 21.1%) or if the structure is not calibrated but calculated according to the antenna theory (± 25.3%). It is interesting to see that the differences in the measurement uncertainties are not very big. In case that the cell is calibrated the measurement uncertainty of the sensor itself has a major impact, in case that the cell is not calibrated the dominant parts are the linearity of the cell in respect to the calculation and the uncertainty of the manufacturing of the structure itself.

For the calculations in Table 3 it is assumed that the measurements are performed directly in the frequency domain using a network analyser. In this case the measurement uncertainty of the network analyser is low due to the fact that only relative measurements are performed.

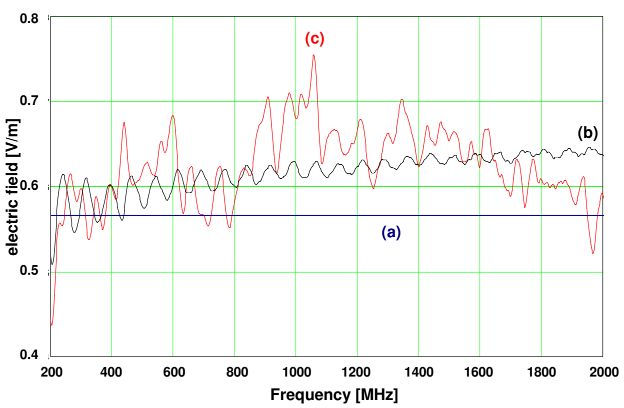

Figure 9: Calculated and measured electric field on the ground plane of the 100 ohm cone calibration cell 1m away from the driving point. (a) is calculated using the formulas (1) and (2), (b) is calculated by using S_{11} and the formulas (1) to (3) and (c) is the measured curve using an electric field sensor.

Figure 9 shows the calculated and measured electric field on the ground plane of the 100 ohm cone 1m away from the driving point. The blue line shows the theoretical value calculated according the formulas (1) and (2). The black curve (b) is as well calculated according the formulas (1) and (2) but instead of setting Z_C to 100 ohm it was calculated out of the measured S_{11} by using formula (3). In this case Z_C is frequency dependant and therefore E as well. The red curve in Figure 9 shows the electric field measured with a sensor of type E1601 from Thomson-CSF.

$$U_C = \frac{Z_C}{R+Z_C} \cdot 2 \cdot \sqrt{P \cdot R} \tag{1}$$

$$E = \frac{U_C \cdot Z_0}{Z_C \cdot 2 \cdot \pi \cdot r} \tag{2}$$

U_C = driving point voltage of the cone antenna (V)
Z_C = input impedance of the antenna i.e. 100Ω (Ω)
R = ref. resistance of the system i.e. 50Ω (Ω)
P = output power of the NWA (W)
E = el. field at the UHF sensor location (V/m)
Z_0 = impedance of free space (≈ 377Ω) (Ω)
r = distance of the UHF sensor from the driving point (m)

$$Z_C(f) = R \cdot \left(\frac{1+S_{11}(f)}{1-S_{11}(f)}\right) \tag{3}$$

$Z_C(f)$ = input impedance of the antenna (Ω)
R = ref. resistance of the system i.e. 50Ω (Ω)
$S_{11}(f)$ = voltage reflection coefficient at the antenna feeder port (1)

Table 3: Measurement uncertainties with and without the calibration of the sensor area

Description of the uncertainty	Uncer-tainty contri-bution (dB / %)	Distri-bution	Standard uncer-tainty with calibration (%)	Standard uncer-tainty without calibration (%)
Field homogeneity in the sensor area	± 1 / 12.2	Gauss	± 6.1	± 6.1
Influence of the surrounding	± 0.2 / 2.3	Gauss	± 1.2	± 1.2
Linearity in respect to the calculation	± 1.2 / 12.2	Gauss	--	± 7.4
Uncertainty of the structure itself (driving point, dimensional accuracy etc)	± 1 / 12.2	Gauss	--	± 6.1
Uncertainty of the network analyzer for relative measure-ments (temperature drift, short term stability, linearity deviation, uncertainty of calibration)	± 0.5 / 5.9	Rect-angular	± 3.4	± 3.4
Mismatch between measuring cables and cone antenna and between UHF sensor and measuring cable	± 0.5 / 5.9	U-shaped	± 4.2	± 4.2
Mismacht between the calibrated sensor and the measuring cable	± 0.3 / 3.5	U-shaped	± 2.5	--
Calibration of the electric field sensor	± 1 / 12.2	Gauss	± 6.1	--
Total expanded measurement uncertainty (2σ)			**± 21.1**	**± 25.3**

If the curve (a) according Figure 9 in the frequency range between 200 MHz and 2 GHz is compared with the calculated electric field of an infinite cone antenna on the ground plane (curve (b)) we see that the correlation is within the range of -10% to +15% at an input power *P* of 10 mW.

It is therefore not necessary to measure the incident electric field with a sensor of known characteristic and the "design by rule" principle is applicable. The incident electric field can be calculated with the given mechanical characteristics of the cone antenna and the system is therefore very easy to standardize.

4.2 Proposed measurement principle

Due to the fact that most of the energy is transmitted via a TEM wave it is recommended to use a network analyser (NWA) and to perform the measurements directly in the frequency domain.

The following steps can be performed to obtain the effective height $H_e(f)$ of a sensor.

- Before the measurements begin the network analyser has to be calibrated together with the measuring cables.
- One of the measuring cables is then connected to the feeder of the cone antenna, the other one to the installed UHF sensor.
- $S_{11}(f)$ and $S_{21}(f)$ are now measured. In order to make sure that the cone calibration system works properly it is recommended to inspect $S_{11}(f)$ and to compare it with the expected values.
- Calculation of the effective height by using the following formula

$$H_e(f) = \frac{U_S(f)}{E(f)} = \frac{S_{21}(f) \cdot \sqrt{P \cdot R}}{E(f)} \qquad (4)$$

where: $H_e(f)$ = effective height (m)
$U_S(f)$ = UHF sensor output voltage (V)
$E(f)$ = el. field at the UHF sensor location (V/m)
$S_{21}(f)$ = insertion loss between cone antenna feeder and UHF sensor output (1)
P = output power of the NWA (W)
R = ref. resistance of the system i.e. 50Ω (Ω)

E(f) can be either calculated using the theoretical formulas (1) and (2), it can be calculated using the measured S_{11} according the formulas (1) to (3) or it can be measured directly using dedicated field sensors.

5 CONCLUSION

We have presented the history and the actual state of a conical calibration system for UHF sensors for GIS applications. Experience shows that this new method for calibrating UHF sensors is necessary in order to overcome the limits in the calibration of large sensors and to suppress the propagation of higher order modes and reflections.

The latest design with a 100 ohm cone reaches the target in terms of uncertainty. Due to the structure of the calibration cell, most of the energy is transmitted through a transversal electromagnetic wave. The variation of the electric field at the sensors installation location is below ± 1 dB in an area of 15cm by 15cm. Compared to other calibration systems like the GTEM cell (typically ± 5 dB) this is very good [1]. The total measurement uncertainty for a UHF sensor calibration in the frequency band between 200 MHz and 2 GHz is about 25%. Because of its structure it is no longer necessary to calibrate the field at the UHF sensor location. This feature makes the system even more interesting because no expensive sensors have to be organized to calibrate the system itself.

The biggest disadvantage of the calibration cell – its size – is a limiting factor. But a reduction of the cone calibration system in its size is not recommended due to the facts that the influence of the sensor itself increases and that the reflections at the cells ends increase as well.

Whenever UHF sensors for GIS have to be calibrated, the cone calibration system seems to be the preferred way of doing so. It is easy to build and to standardise. It has a very low overall uncertainty in comparison with other known calibration systems. In addition, it will reduce the cost of sensor calibration.

6 ACKNOWLEDGMENTS

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7 REFERENCES

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