Proc. 10th Int. Symp. on High Voltage Engineering (Montreal), Vol. 6, August 1997

UHF Couplers for GIS - Sensitivity and Specification

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Abstract

A novel calibration system is used to measure the sensitivity of UHF couplers used for partial discharge (PD) detection in gas insulated substations (GIS). The technique employs a gigahertz transverse electromagnetic (GTEM) test cell to generate a subnanosecond electric field step at the coupler aperture. The frequency response of the coupler is obtained from its time-domain response using FFT processing. Results for internal and external couplers are presented and the effect of the coupler mounting recess is investigated. A possible approach to formulating specifications for UHF couplers is then described.

1. Introduction

Partial discharges (PD) in gas insulated substations (GIS) can be detected by the UHF signals they generate [1,2]. To afford maximum protection to the GIS, a UHF monitoring system must be capable of detecting low levels of PD. A means of ensuring that the UHF couplers used to extract the PD signal from the GIS are sufficiently sensitive is therefore required. A measurement system with this capability would also allow optimisation of the coupler output voltage in response to a given UHF electric field. To a limited extent, this can be achieved by mounting the coupler on a chamber containing a PD source and recording changes in the UHF spectrum that result from design modifications [3]. However, the true response of the coupler can be masked by resonances in the test chamber. To overcome this difficulty, a test procedure has been proposed [4] which measures coupler sensitivity in terms of a frequency dependent effective height $H_e(\omega)$. The transfer function is expressed as an effective height (m) because it is the ratio of the coupler output signal (V) to the incident electric field (V m^{-1}). This definition relates well to the model for PD excitation of UHF signals [5] which defines the electric field at the coupler in terms of parameters of the PD source.

In [4], a TEM line was used to generate an electric field step travelling over the coupler aperture. However, the field uniformity was degraded by reflections at the junction of the taper and the uniform central section of the line. This problem will be common to any approach that uses a tapered section connected to a uniform TEM line [6,7]. For the TEM cell, this difficulty has been overcome by using only the tapered part of the line. The spherical wavefront then sees no discontinuities over the length of the cell. This structure has been called the GHz TEM cell, or GTEM. A practical coupler calibration system using a wire-septum GTEM has been constructed to demonstrate the technique [8]. This paper presents several coupler frequency response measurements and discusses some of the issues involved in specifying UHF couplers for GIS.

2. Calibration technique

The calibration system is shown in Fig. 1. A voltage step (risetime < 300 ps) is applied to the cell input. This voltage appears between the septum and the body of the GTEM and a step electric field propagates towards the cell output. As this field passes over the coupler aperture in the top wall of the GTEM, it provides a broadband excitation for the UHF coupler. By first measuring and storing the incident electric field normal to the cell wall on the coupler axis, the coupler transfer function can be determined using the FFT.

Square plates are used to mount different couplers on the GTEM. The incident electric field is measured using a 25 mm monopole probe with a known response [5]. During

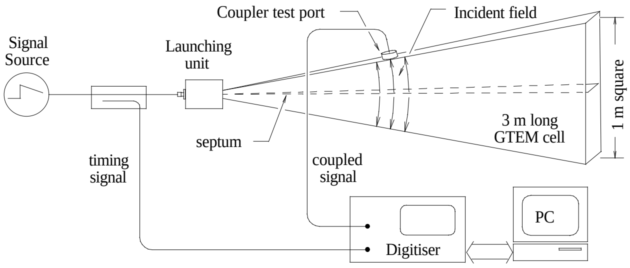

Fig. 1 Block diagram of the coupler calibration system.

this measurement, a flat mounting plate is fitted to the GTEM with a central hole (∅4 mm) for the probe. The coupler test aperture is located at the mid-point of the 3 m GTEM. A reflection-free window of 10 ns is therefore available for the measurement before the reflection from the open end of the cell arrives. Consequently, most of the coupler response to the step excitation must be contained within a 10 ns period for an accurate measurement to be obtained. This requirement is satisfied by most of the couplers that have been tested on the system.

The signal processing used to determine the frequency response of the coupler can extend the measurement bandwidth beyond the normal limits of the test equipment. A description of the methods that can be used to achieve this is given in [9]. The basis of the procedure is to use identical test equipment and cables for both the incident field measurement and the coupler response measurement. Let the spectrum of the incident electric field be denoted by $E(\omega)$ and the frequency response of the test equipment by $U(\omega)$. If $R(\omega)$ is the FFT of the recorded signal from the probe, whose known transfer function is $P(\omega)$, then

$$R(\omega) = P(\omega)\,E(\omega)\,U(\omega) \tag{1}$$

If $C(\omega)$ is the FFT of the signal recorded when a coupler with transfer function $H_e(\omega)$ is tested on the GTEM cell,

$$C(\omega) = H_e(\omega)\,E(\omega)\,U(\omega) \tag{2}$$

By taking the ratio of (2) and (1), $H_e(\omega)$ can be determined without a knowledge of $E(\omega)$ or $U(\omega)$ as

$$H_e(\omega) = C(\omega)\,P(\omega)\big/R(\omega) \tag{3}$$

Using this approach, a measurement system bandwidth of 2 GHz has been achieved [8].

3. Results

When the 25 mm probe is mounted on the GTEM, the measured frequency response of this probe 'coupler' can be compared with its theoretical effective height. This is illustrated in Fig. 2. The difference between the two traces is a measure of the repeatability of the measurement.

An important aspect governing the performance of a coupler is its mounting configuration because this determines how well the coupler responds to UHF fields in the GIS. Couplers are normally located in a recess, or externally on the GIS so that they are removed from regions of high electric field. As this also makes them more remote from the UHF fields, couplers should be tested on a plate that replicates the mounting configuration on the GIS. Results for one internal and one external coupler are presented below, illustrating how the coupler mounting affects its frequency response and sensitivity.

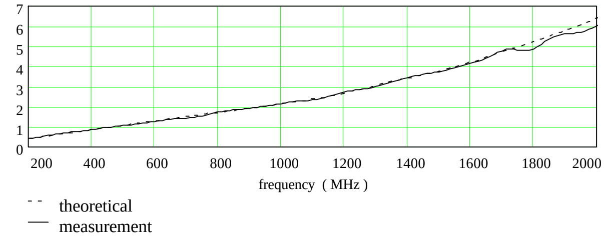

Fig. 2 Theoretical and measured sensitivity of the 25 mm probe.

Fig. 3 shows an internal disc coupler of the type described in [3]. The coupler is an aluminium disc, insulated from the ground plane by a polypropylene sheet and held in place by six insulated screws. The UHF signal is taken from the centre of the disc. To simulate a coupler recess, tubes of internal diameter 300 mm and depths d = 50, 100 and 150 mm were used (see Fig. 3). The plate on which the coupler was mounted could also be fitted directly to the calibration aperture so that the ground plane of the coupler was level with the inside of the GTEM wall. This arrangement corresponds to d = 0 mm. The frequency response of the coupler at four recess depths is shown in Fig. 4. When d = 0 mm, the effective height of the coupler is stable at around 4 mm for frequencies below 600 MHz. At these frequencies, the coupler simply acts as a capacitive divider. As the frequency increases above 600 MHz, the effects of resonance within the coupler structure become apparent. The peak in sensitivity at 925 MHz is in good

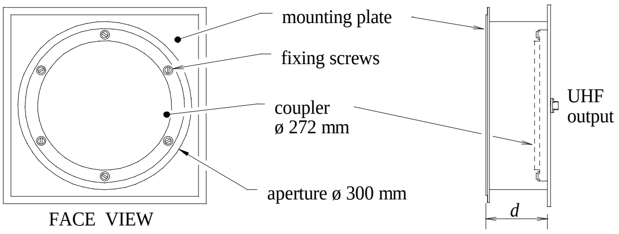

Fig. 3 Mounting the internal coupler for calibration.

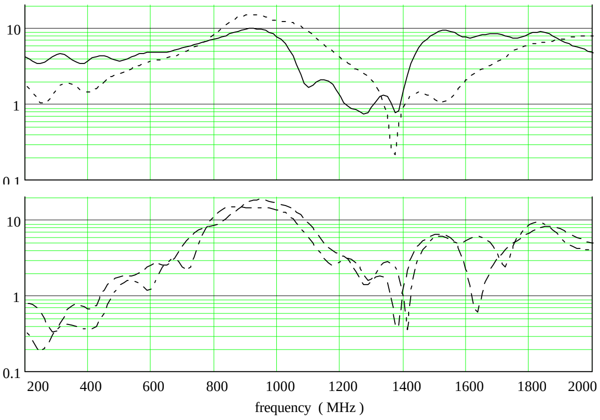

Fig. 4 Sensitivity of the internal disc coupler at several recess depths d.

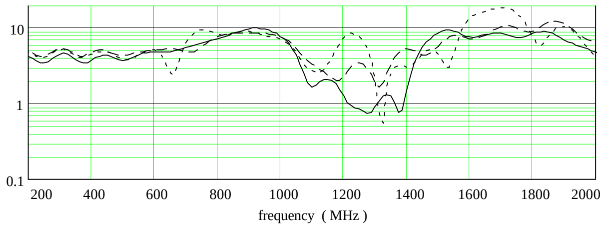

Fig. 5 Effect of mounting screws on the frequency response of the internal disc coupler.

agreement with the first resonance (905 MHz) and peak in the PD spectrum (931 MHz) measured for this coupler in [3]. The main consequence of increasing the depth of the recess is reduced sensitivity at low frequencies. The lowest frequency at which the 300 mm diameter recess can act as a waveguide supporting a propagating electromagnetic mode is 585 MHz. This cut-off frequency is the main reason for reduced sensitivity at lower frequencies.

Fig. 5 shows the effect of the brass mounting screws on the response of the coupler when $d = 0$ mm. The solid curve is the normal sensitivity from Fig. 4 with six screws. The second curve shows the response when only two brass screws at diametrically opposing positions are used. The third curve was obtained when two nylon (i.e. insulating) screws were used. Below 600 MHz, the sensitivity is very similar in all cases, following the pattern of a capacitive coupler. In this region, the sensitivity is lowest when six brass screws are used because the capacitance of the disc to the ground plane is slightly increased by their presence. At frequencies above 1000 MHz, the mounting screws make a significant difference to the sensitivity of the coupler because the distance between the screws approaches a quarter wavelength. Resonances within the structure are complicated by the non-uniform dielectric beneath the disc.

An external coupler for 132 kV GIS is shown in Fig. 6. In this case, the window on which the coupler is mounted has an internal diameter of 90 mm. The cut-off frequency in this tube is $f_c = 1950$ MHz and relatively small lengths can cause significant attenuation [10]. Using the test configuration of Fig. 6(a), the frequency response was measured at $d = 10$, 24 and 61 mm. The results are given in Fig. 7, which again shows attenuation of the signal increasing at lower frequencies as the tube becomes longer. At frequencies below cut-off, the attenuation can be expressed as [11]:

$$\alpha(f) = 8.69 \cdot (2\pi f/c) \cdot \sqrt{(f_c/f)^2 - 1} \qquad \text{dB m}^{-1} \qquad (4)$$

Modifying the curve for $d = 10$ mm in Fig. 7 to allow for this theoretical attenuation based on additional lengths of 14 and 51 mm, the frequency responses shown in Fig. 8 are obtained. The curves in Fig. 8 are quite similar to those in Fig. 7, showing that the calibration results correspond well with expectations based on this simple first-order analysis.

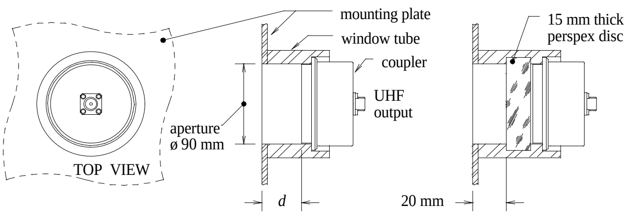

Fig. 6 Mounting the external coupler for testing.
(a) Investigating the effect of the tube length d.
(b) Investigating the effect of a dielectric window.

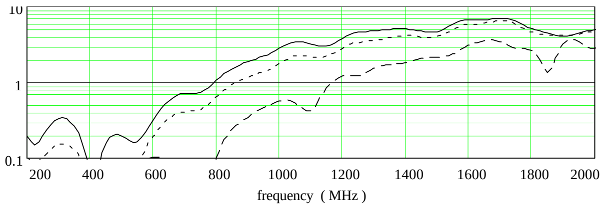

Fig. 7 Effect of the window tube length d on the frequency response of the external coupler.

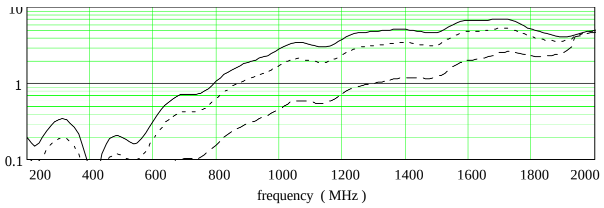

Fig. 8 Theoretical effect of varying the window tube length, based on attenuation of the TE_{11} mode below cut-off.

The effect of adding a dielectric window (Fig. 6 (b)) inside the coupler recess is shown in Fig. 9. The perspex window ($\varepsilon_r \approx 4$) was 15 mm thick, so its addition also increases the tube length. Although the sensitivity of the coupler decreases at frequencies below 900 MHz when the window is added, there is little change at higher frequencies. When the additional attenuation introduced by a 15 mm increase in d is added according to (4), the coupler is found to be more sensitive when the window is present than it would be on a tube of equal length without the window. This is because the relative permittivity ε_r of the window reduces the signal wavelength, making the electrical diameter of the tube appear larger by a factor $\sqrt{\varepsilon_r}$.

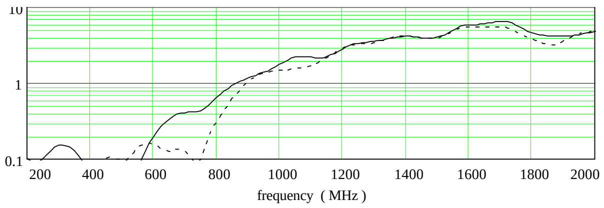

Fig. 9 Effect on the external coupler's frequency response of adding a 15 mm thick perspex window.

4. Specifying UHF couplers

Provided couplers are constructed to a reasonable tolerance, their performance should be consistent. However, in the design stages, or during tendering for installation of a GIS monitoring system, the required coupler response should be specified to ensure adequate sensitivity and allow comparison between different manufacturers. The effective height is a useful measure of the sensitivity of a UHF coupler and a specification could be formulated to define H_e over the frequency range of interest. The measurements that have been presented show that a definition of the coupler mounting arrangement must form an important part of the test specification. Referring to Fig. 10, the test conditions should specify a recess depth d and diameter D for the coupler aperture that are representative of those on the GIS. The distance between the ground plane and the septum of the GTEM may also be specified as $s \geq s_{min}$ so that the field distortion caused by the coupler aperture is not excessive. Variations in the incident electric field strength over the coupler aperture must be restricted, and a tolerance of ± 2 dB at any frequency in the measurement bandwidth is suggested. This value is typical of the uniformity that can presently be achieved in GTEM cells of modest size.

To allow for the effects of the coupler recess, it may be necessary to specify different minimum values for H_e in different frequency ranges. An alternative approach would be to specify a minimum and a mean value for H_e to allow greater flexibility in coupler design. As an example, Table 1 shows a specification that has been proposed on the basis of results from proven couplers.

Table 1 Coupler specification for a 420 kV GIS, with test conditions d = 50 mm, D = 300 mm, $s \geq 0.25$ m.

Frequency range	Minimum effective height $H_e(min)$	Mean effective height $\overline{H}_e$
500 - 1500 MHz	2.0 mm	6.0 mm

5. Conclusions

A coupler calibration system has been demonstrated by testing internal and external UHF couplers for GIS. The effect of the recess in which the coupler is mounted has been investigated, showing that it acts as a high-pass filter. The cut-off frequency is inversely proportional to the recess diameter, and the attenuation at frequencies below cut-off increases with the recess depth. The mounting screws of disc couplers modify the coupler response at sufficiently high frequencies by introducing complex resonances. Where a coupler is mounted externally at a window, the presence of a dielectric material (pressure window) reduces the attenuation by lowering the cut-off frequency in the window tube. When such windows are specifically included to facilitate UHF PD monitoring in GIS, it may therefore be advantageous to make the window as thick as possible, so that it occupies most of the window tube.

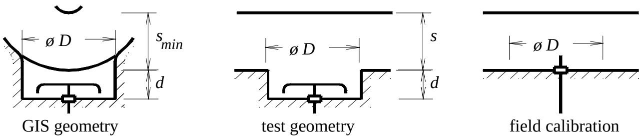

Fig. 10 Defining the test conditions for a UHF coupler.
(a) Dimensions of the GIS.
(b) Coupler mounting in the calibration system.
(c) Measuring the incident field on the coupler axis.

Specification of coupler sensitivity in terms of an effective height has been discussed and an example given showing how a coupler might be specified.

Acknowledgement

M D Judd wishes to thank the EPSRC for supporting this research, under grant number GR/L34785. P F Coventry wishes to thank The National Grid Company plc for support and permission to publish.

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