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Sensor Response Characteristics for UHF Location of PD Sources

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Abstract--**Ultra-high frequency (UHF) systems are well established for monitoring partial discharges (PD) in gas-insulated substations (GIS) and are increasingly being used on power transformers. Different sensor designs such as disk sensors, spiral sensors, monopoles and dipoles have been used depending on the application. A primary concern is to ensure that the sensitivity of these different sensors can meet the CIGRE requirement for detecting 5 pC partial discharges GIS. Recent work on locating PD in power transformers has focused attention on recording the arrival time of the received UHF signal, which is important for locating insulation defects in three dimensions. An accuracy of 1 ns or better is desirable for time-of-flight measurements to locate a PD source. In some situations, a clear arrival time for the signal can be identified but in other cases the arrival time can be uncertain within a tolerance of several nanoseconds. Therefore, a number of sensors were tested for their speed of response using a transient calibration system. Results suggest that more complex sensor structures have a slower build-up of energy at their output, while simple sensors exhibit less of a 'blurring' effect on the leading edge of the signal.**

Index Terms--**Partial discharges, fault location, UHF, couplers.**

I. Introduction

UHF detection of partial discharges (PD) in GIS and power transformers requires sensitive couplers to ensure detection of signals radiated by small PD sources. However, an additional aspect that has not been studied in detail is the ability of the coupler to give a good response to the initial wavefront of a UHF signal. For example, a small, simple coupler may have a low sensitivity but a good initial response because the energy build-up is not limited by propagation delays within the coupler structure. A more complex broadband coupler may have good sensitivity but require more time for the energy to build up in its output signal. These issues are particularly important in power transformers [1], where accurate measurement of arrival times at a set of couplers is needed for locating PD sources in three dimensions (in GIS the PD location problem is effectively one-dimensional).

In this paper, a number of coupler types have been evaluated to investigate and compare their initial response to a transient electric field with a sub-nanosecond risetime. The original UHF sensor for GIS was a disk coupler [2], while the spiral antenna [3] is an alternative design that has been used for broadband PD detection, particularly in window couplers [4]. The two other couplers tested are a barrier edge coupler for GIS (dipole design) and a probe coupler (monopole design) for power transformer monitoring through an oil valve.

For GIS, CIGRE has proposed a sensitivity check for UHF PD monitoring systems [5] that requires pulse injection into one coupler while detecting signals at other couplers. In the case of transformers, it will be useful to apply pulse injection not only for a sensitivity check [6], but also to test the location capability for each coupler in turn, as was proposed in [7].

The experiment reported here examines the build-up of signal energy at the beginning of the coupled UHF wavefront. Knowledge of the energy build-up characteristics will allow for good design of sensors in terms of their partial discharge location capabilities and their suitability for pulse injection when testing or calibrating PD location systems. Before reporting the experimental work, a discussion on the level of accuracy expected from UHF timing measurements for PD location is warranted.

II. UHF Signal Timing for Locating PD Sources

When locating a PD source using time-of-flight methods, it is usually necessary to determine the arrival times of the signals at two or more sensors and use the time differences to calculate a PD location. For this purpose, it is necessary to know the relative positions of the sensors (in a coordinate system mapped onto the HV equipment under test) and the velocity of signal propagation. In the bulk oil within a power transformer, the velocity of UHF signals has been measured as 2×10^8 m s^{-1} [8]. A more convenient figure to use when discussing PD location in transformers is 20 cm/ns.

Consider a typical UHF signal from PD in a transformer, as shown in Fig. 1, which was recorded using an external coupler mounted on a dielectric window. There will always be some ambiguity about the exact time of arrival of the signal, although in this case it seems reasonable to claim that it could be estimated with an accuracy of better than 1 ns.

Factors that can influence the apparent arrival time are:

- *Noise:* obscures the initial part of the UHF waveform until it attains a level sufficient to be detected.

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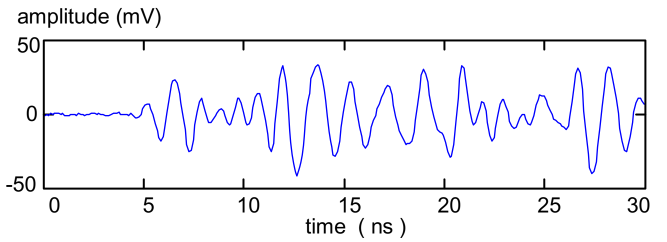

Fig. 1. Example of a UHF signal from partial discharge in a power transformer.

- *Measurement bandwidth:* an approximate relationship for the risetime t_r of a measurement system with a first-order bandwidth of B Hz is $t_r = 0.35/B$. Therefore, if the signals are captured with a bandwidth of 1 GHz, the minimum observable risetime of the coupler output signal would be 0.35 ns (corresponding to 7 cm of signal propagation in oil).
- *Sensor response time:* this is the main subject of this paper, dealt with in the next section.
- *PD current pulse risetime:* a factor easily overlooked when faced with a UHF signal that does not have an obvious start time. Consider an extreme example – it would be unreasonable to expect to locate to within 10 cm a PD source if the current pulse was 10 ns wide. The pulse itself would occupy some 2 m of distance in terms of its radiated electromagnetic transient. What point on such a long current pulse would we consider as being responsible for the "start" of the radiated UHF signal? An idealized Gaussian current pulse is shown in Fig. 2(a). This pulse will radiate an electric field in proportion to the rate of change of current, which is shown in Fig. 2(b). The time-domain waveforms of both will stretch as the current pulse lengthens, the consequence being to make the definition of a time of arrival at a sensor more difficult.

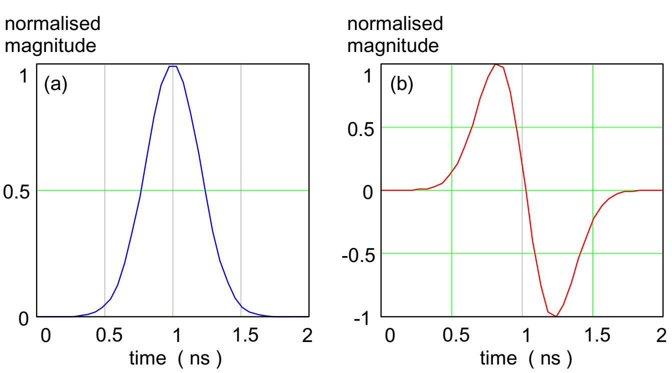

Fig. 2. (a) PD current pulse represented by an ideal Gaussian shape. (b) Time-derivative of the current pulse, which illustrates the form of the radiated electric field.

III. Experimental Procedure

Conveniently for these tests, our UHF sensor calibration system uses a time-domain measurement of step response [9], which is normally used to determine the frequency response of sensors using FFT processing. The coupler to be tested is mounted on a tapered transient test cell, which subjects the UHF coupler antenna to an electric field step of 30 V m^{-1} with a risetime of 300 ps, as shown in Fig. 3.

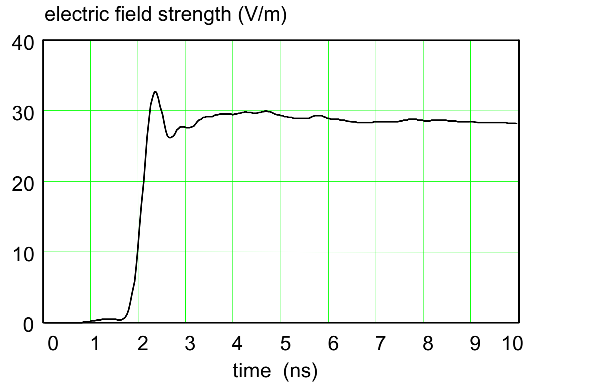

Fig. 3. Time-variation of the step electric field applied in the calibration system.

Four types of UHF coupler were used in the experiments:

- *Window coupler* designed for external mounting on dielectric windows added to power transformer. The structure is a spiral antenna.
- *Internal disk coupler* for use on GIS (conventionally referred to as a capacitive coupler).
- *Barrier coupler* for external mounting on GIS having exposed edges of insulating epoxy gas barriers where UHF signals can escape. This type of coupler uses a dipole element.
- *Transformer probe* for insertion through an oil-valve while a transformer is in service. Due to the restricted diameter, this device is a simple monopole antenna.

The output voltage of each coupler in response to the applied step electric field was recorded using a digitizing oscilloscope with bandwidth of 3 GHz and a sampling rate of 10 Gsamples/sec. 1000 data points were captured over a 100 ns window. Each coupler was mounted in the appropriate manner on the calibration system during these tests. For example, the window coupler was mounted on the dielectric window for which it was designed. Since the calibration test cell is 3 m long and not matched at its output [9], there is a reflection of the incident waveform about 10 ns after it first arrives at the coupler. However, in this paper we are concerned with the first few ns of the response, where the reflection has no influence.

IV. Results and Analysis

Fig. 4 shows the measured step responses of the four coupler types. The disk coupler and the transformer probe have the largest and least complex responses due to their simple structure. The energy content U of the sampled signals can be approximated by a discrete integral (summation) of the form

$$U = \frac{\Delta t}{R} \cdot \sum_{i=0}^{N-1} V_i^2 \qquad (1)$$

where Δt is the time (100 ps) between the samples of coupler output voltage V_i, R is the input impedance of the measurement system (50 Ω), and N is the number of samples in the data (1000). The cumulative signal energy curve can be formulated mathematically as

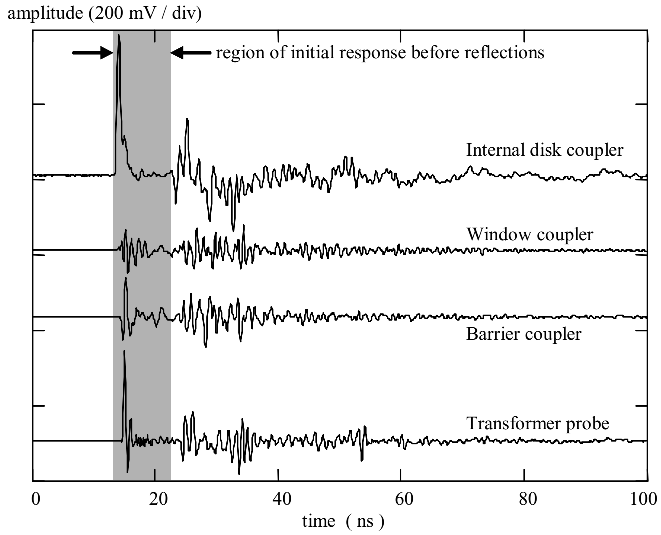

Fig. 4. Measured step responses of the UHF couplers.

$$e_j = e_{j-1} + \frac{\Delta t}{R} \cdot V_j^{\,2}, \qquad j = 1, .. N - 1 \qquad (2)$$

where e_j represents the energy accumulated up to the jth sample.

As illustrated in Fig. 5, the total accumulated energy for the signals in Fig. 4 is in the pJ range, with the window coupler reaching about 0.25 pJ and the internal coupler having the largest response, reaching just over 2.5 pJ. When considering the rates of change of energy at the start of the signal, the sensitivity of the coupler also has an influence, in that the more sensitive coupler will appear to have a greater rate of energy accumulation. Normalising the curves from Fig. 5 so that they represent a percentage of their final value, the energy build-up characteristics at the start of the waveforms become clearer, as shown in Fig. 6.

By fitting smooth cubic curves to the normalised energy data (using the *cspline* and *interp* functions in MathCAD), each of the normalized curves can be differentiated to further compare the rates of change of energy accumulation between the couplers. The resulting curves plotted in Fig. 7 reveal a significant variation in the response characteristics of the couplers. The build-up of energy at the output of the disk and probe structures is faster and more well-defined than that of the window or barrier couplers architectures.

At this point it should be noted that the step responses of all the couplers tested are sufficiently short to allow the start of the signal to be determined with accuracy significantly better than 1 ns. However, since this measurement is in response to a well defined step input, the initial response to a more typical UHF signal may be harder to determine, particularly for the window coupler based on a spiral antenna (the most complex of the four structures).

V. Discussion

From a theoretical and practical viewpoint, we have shown

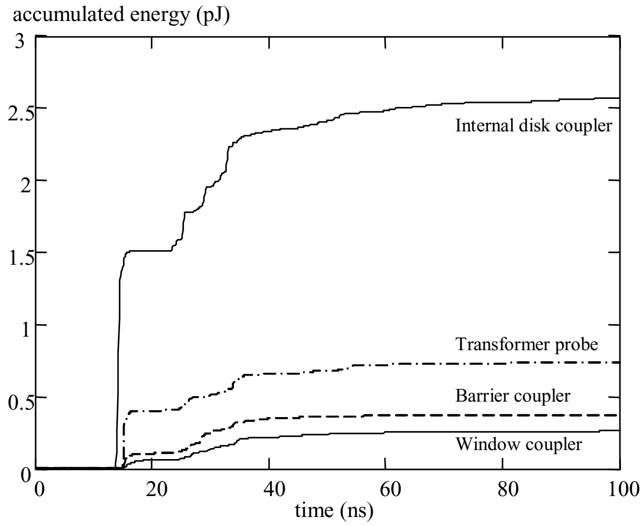

Fig. 5. Accumulated energy curves for the coupler responses of Fig. 4.

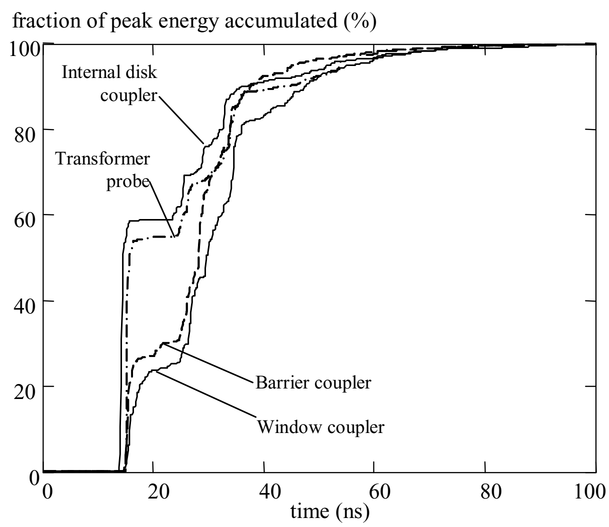

Fig. 6. Normalised form of the energy accumulation curves of Fig. 5, showing energy as a percentage of final value reached for each coupler.

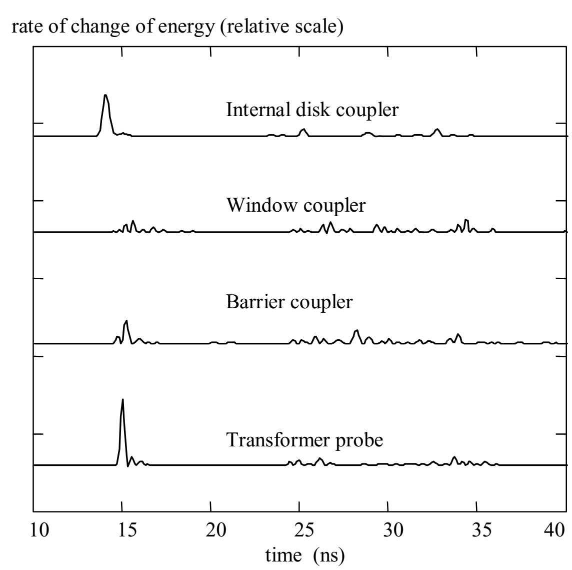

Fig. 7. The differentiated energy curves, showing the rate of change of normalised energy accumulation for each coupler.

that, even in the absence of noise, there are several factors that will limit the risetime of the signal at the output of UHF couplers and these will inevitably cause some uncertainty when attempting to identify the beginning of the UHF signal. Typically, with a good measurement system, these factors should not in themselves degrade accuracy by more than 1 ns. However, the effect of PD current pulse risetime in the case of longer PD pulses will feed through directly to make the measurement of arrival time more challenging.

An alternative to measuring time differences between UHF signals is to measure phase shifts between signals. However, this is only feasible with special multi-element couplers [10]. When conventional couplers are placed in different positions around a transformer tank, the waveforms are too dissimilar to allow cross-correlation to be used to determine the relative time delays.

Comparisons of the step responses of the various couplers have shown significant differences and this is an aspect of coupler design that might be overlooked. A mechanism by which the rate of energy build-up is delayed can be suggested as follows: The UHF signal passes over the coupler with a velocity at the speed of light, but the currents induced in the metal parts of the antenna may not reach its output at the same time. Consider the disk coupler with a central connection shown in Fig. 8, where for simplicity we assume the UHF PD signal to be incident from the left. The signal coupled at the left edge of the disk travels a distance *r* (disk radius) to the centre of the disk in the same direction as the wavefront. However, any signal coupled to the right edge of the disk will need to travel in the opposite direction back to the centre connection, experiencing additional delay due to the extra distance of 2*r* that has been travelled. With a spiral antenna, the extra delays could be significantly higher, as currents in the arms may have to travel much further to reach the centre.

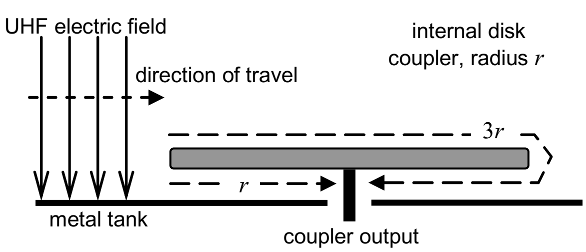

Fig. 8. Example of different delays experienced by the UHF signal wavefront due to different propagation paths in a disk coupler of significant size.

Since the UHF couplers tested are passive, linear devices, the principle of reciprocity must hold. This allows us to make some comments about their potential for use in pulse injection. Pulse injection might be used to simulate a PD source so as to test the accuracy of PD location calculations using other couplers on the equipment. A real PD source will typically involve a large current flowing over a very short distance, and may well approximate a "point" source. UHF couplers are comparatively large (so as to have sufficient sensitivity), and this allows us to use much lower currents for pulse injection. However, even if a pulse with very short risetime is applied to a large structure, it is unlikely that the risetime of the overall radiated field will be comparably small because of the distributed time delays between the input pulse and the different parts of the coupler that can radiate. For this reason, we have preferred to use short monopole antennas for the purpose of PD simulation [11], where the propagation delay from one end of the antenna to the other is minimal compared with the risetime of the applied pulse.

VI. Conclusions and Future Work

Timing the arrival of UHF signals from partial discharges in power transformers is important for PD location purposes. In this paper we have identified four factors that can affect this measurement: noise, measurement bandwidth, sensor response and the PD current pulse shape. Sensor response is a factor that might be overlooked. By measuring the step response of some typical UHF sensors, we have shown that there is a small but potentially significant difference in their speed of response. The results suggest that for pulse injection testing of PD location systems, a coupler designed specifically for this purpose may be more suitable than one designed for optimum broadband sensitivity. In future work we will study the design of couplers for efficient pulse injection that will seek to optimize the risetime of coupled UHF signals in order to quantify the accuracy of UHF-based PD location systems.

VII. References

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