UHF Diagnostic Monitoring Techniques for Power Transformers

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Abstract

This paper initially gives an introduction to ultra-high frequency (UHF) partial discharge monitoring techniques and their application to gas insulated substations. Recent advances in the technique, covering its application to power transformers, are then discussed and illustrated by means of four site trials. Mounting and installation of the UHF sensors is described and measurements of electrical discharges inside transformers are presented in a range of formats, demonstrating the potential of the UHF method. A procedure for locating sources of electrical discharge is described and demonstrated by means of a practical example where a source of sparking on a tap changer lead was located to within 15 cm.

Progress with the development of a prototype on-line monitoring and diagnostic system is reviewed and possible approaches to its utilization are discussed. New concepts for enhancing the capabilities of the UHF technique are presented, including the possibility of monitoring the internal mechanical integrity of plant. The research presented provides sufficient evidence to justify the installation of robust UHF sensors on transformer tanks to facilitate their monitoring if and when required during the service lifetime.

1. Introduction

Measurement of partial discharge (PD) activity has long been used to assess the condition of high voltage insulation in components such as bushings, capacitors, transformers and switchgear. Many methods are employed, usually based on detecting one or more of the electrical, chemical, acoustic (i.e., mechanical) and RF phenomena that are associated with PD [1,2]. The ultra-high frequency (UHF) method is essentially an RF technique that has evolved as the bandwidth of affordable test equipment and consumer electronics pushes ever upwards. The technology is now mature in its application to gas insulated substations (GIS), with over 15 years of field experience accumulated and many permanent on-line monitoring systems in use around the world. Figure 1 illustrates the basic principles of UHF PD detection.

When electrically insulating materials like oil or SF_6 break down, we can classify the different phenomena as corona, partial discharge or arcing. These words relate something of the physics and intensity of the effects, but on a more basic level the first stage always involves the following process: A medium that was insulating becomes conducting through the liberation of electrons and a pulse of current flows in the insulation. Electrons initially at rest are stripped from the host atom/molecule and accelerated by the electric field (increasing current). Shortly afterwards they come to rest (decreasing current). When electric charges move with anything other than a constant velocity, electromagnetic radiation occurs and these radiated signals begin to propagate away from their point of origin in all directions.

The UHF band covers 300 – 3000 MHz. Whether or not energy from an ionizing event can be detected in this band depends on the risetime and falltime of the current pulse, the magnitude of the current and the signal-to-noise ratio of the measurement system. Roughly speaking, pulses on a nanosecond timescale are necessary for detection by UHF methods. Some of the events that can actually be detected at UHF are usually considered to be much slower than this. Often this is because they have been measured historically using equipment that was bandlimited. Furthermore, there are often superimposed on a large, slower pulse (such as an arc in oil) many small but extremely short current pulses that are associated with the energetic formation of new branches in the discharge channel. Thus, when we “see” these events using a UHF sensor, the “signature” can be quite different to conventional measurements, but just as effective in revealing the activity.

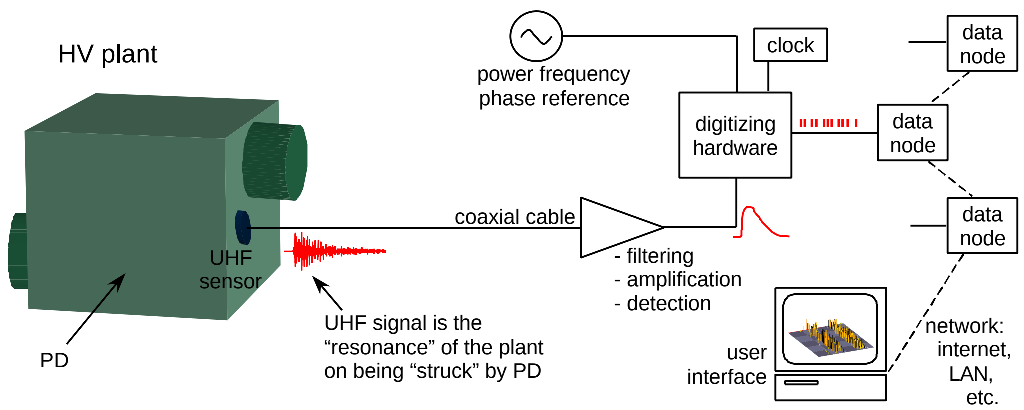

Figure 1: Basic Principles of UHF Condition Monitoring

UHF techniques are inherently suited to metalclad plant for three reasons:

(i) Sensors (antennae) can be built into the metal cladding in such a way that they are naturally screened from external interference that tends to be present around substations (communications masts, corona on overhead lines, etc.,).

(ii) Metal cladding on the plant itself traps the radiated signal. The pulse is reflected around inside and gradually dies away due to conductor losses. As a result, the sensor gets many more "bites at the cherry". In the absence of reflections, the wavefront would never be seen again once it had passed. The result is to greatly increase the pulse energy received by the sensor, improving detection sensitivity.

(iii) UHF detection has a natural propensity to discriminate between electrical discharges in air and materials of higher dielectric strength. Air (being a weaker dielectric) breaks down with what could be described as "softer" pulses, which tend to radiate at VHF (30 –300 MHz) and below. Metalclad plant usually contains the stronger dielectric materials, which tend to ionize more rapidly once they finally succumb to an excessive field.

All of these points are related. For example, the facts that (i) UHF sensors are looking into the plant for PD detection, (ii) are therefore screened from external discharges, and (iii) those external discharges tend to be in air, which the sensor does not respond well to, are all factors that have contributed to the success of UHF methods in relation to GIS. Seeking to obtain the same benefits for transformers is a logical extension of this work.

In this paper, following a brief review of the GIS application, our latest research and site experience on the power transformer application will be reported. We will then describe our vision for the future of this monitoring technique and some of the additional monitoring capabilities (such as mechanical integrity) that are being explored. The authors hope that this work will encourage wider trialling of UHF sensors and the development of a standard sensor for deployment on power transformers.

2. Status of UHF Partial Discharge Monitoring for Gas Insulated Substations

Torness nuclear power station in Scotland was the first to have its GIS equipped for UHF monitoring in 1986. Since then, UHF PD monitoring of GIS has evolved from a novel research topic [3] to a commercially viable technique for on-line plant monitoring that provides real benefits to manufacturers and utilities [4–10]. Large, coaxial GIS busbars are natural conduits for UHF PD signals. In practice, sensors spaced at ~ 20 m intervals along the busbars can satisfy a 5 pC detection sensitivity requirement when the PD source is least favorably placed for detection. Propagation delay from PD source to sensor is less than 100 ns and can be neglected in the process of determining phase position of the PD pulse on the power cycle. This is not the case with acoustic detection systems, where propagation delays can cause a significant and distance-dependent phase shift that precludes phase-resolved analysis unless a separate electrical PD reference signal is available.

PD sources in GIS are located by time-of-flight methods, a procedure that is illustrated in Figure 2. The UHF signals are delayed by 3 ns for each meter they travel along the busbar. A 2-channel oscilloscope with a bandwidth of 500 MHz or more is connected to UHF sensors on either side of the PD source using cables of equal length. If the signals arrive simultaneously at both sensors, the source must be midway between the two sensors. In other locations, any time difference relates directly to the offset from center. By this means, PD sources can be located to within 20 cm (1% of the distance between sensors).

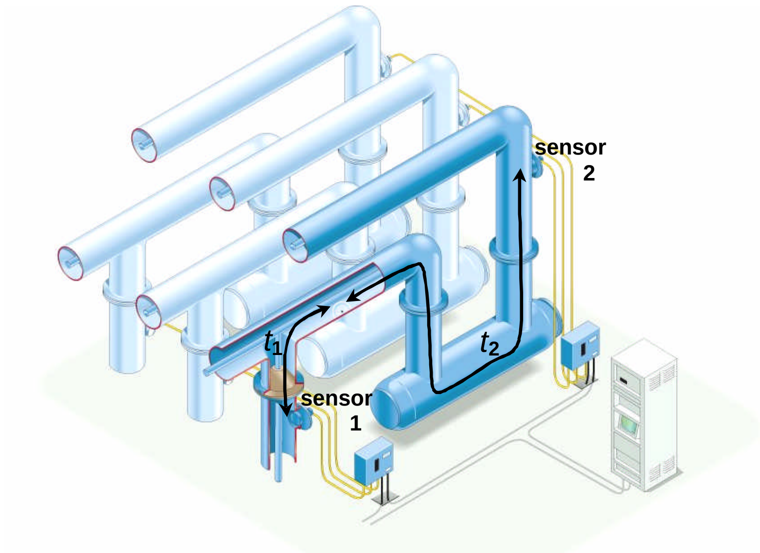

Figure 2: Locating a PD Source in a GIS by the Time-of-Flight Method
(*Image courtesy of Diagnostic Monitoring Systems Ltd*.)

The most common insulation problem found in GIS at commissioning is the presence of free conducting particles. At this stage, UHF monitoring is employed to good effect, allowing free particles to be detected and removed at reduced test voltages, thereby avoiding the risk of particle-induced flashover that can cause costly secondary damage. CIGRE commissioning tests for GIS were revised in 1998 to allow for testing at lower voltage levels when PD diagnostics are employed [11]. CIGRE has also defined a sensitivity verification procedure for both UHF and acoustic PD detection in GIS [12]. In the UK, the National Grid Company (now NGT) issued a sensitivity specification [13] for UHF PD sensors. A sensor that meets this specification will be capable of detecting PD levels of less than 5 pC. The requirements set out in the NGT document have been widely adopted by power utilities around the world in relation to GIS.

3. Applying the UHF Technique to Power Transformers

3.1 Condition Monitoring of Power Transformers

We do not intend to debate the economics of continuous on-line PD monitoring for power transformers in this paper. Clearly, dissolved gas analysis (DGA) is likely to remain the workhorse for identifying transformers that are suffering from internal electrical discharging. DGA can provide some information about the nature and severity of the PD [14]. However, knowing the exact location of PD of arcing (difficult to obtain on the basis of DGA results alone) would be a great help to the engineers and specialists responsible for making decisions about remedial action.

Our aim is to encourage the enabling of new technologies (through the installation of UHF sensors) that will permit the detection, location, analysis and monitoring of PD in a transformer once the need to do so has been established by routine methods or system events giving cause for concern. This would require that transformers are equipped with robust, passive UHF sensors and coaxial cables linking them to connectors at a bulkhead that can be accessed while the transformer is operational. The main technical challenge faced when installing these sensors (either at the manufacturing stage or for retrofitting) is the design of the sensor, which in effect becomes an integral part of the transformer tank.

3.2 Capabilities of a UHF Transformer Monitoring System

Little data is available on the value of PD monitoring for power transformers. Conventional electrical methods are difficult to apply in the field with any useful sensitivity because of electromagnetic interference from surrounding plant. The deployment of UHF monitoring systems will provide reliable data for assessing the value of continuous on-line PD monitoring. The key functionalities of a UHF system in relation to the transformer monitoring task are its abilities to:

(i) Separate each discharge pulse on the basis of its point of origin in the tank and thereby feed the data into separate streams for subsequent analysis.
(ii) Calculate for each data stream the point of origin within the transformer tank.
(iii) Analyze each data stream separately in terms of phase-resolved measurements for pattern recognition.
(iv) Record temporal variations and longer term trends in discharge activity that could be analyzed to establish causative factors.
(v) Provide simultaneous monitoring of other components such as load tap changers (LTCs).

All of this data could be mapped through a remote graphical interface (an impression of which is given in Figure 3), providing a powerful tool that could reduce the frequency of site visits and would be capable of functions such as live viewing or replay of discharge activity in real time.

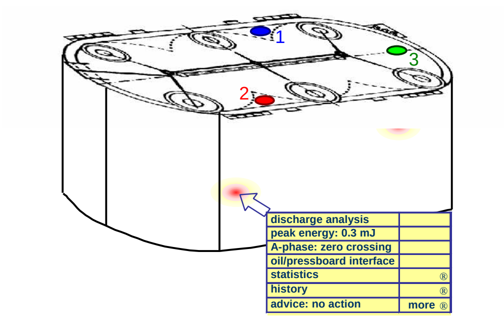

Figure 3: Graphical Interface for Accessing Transformer Monitoring Information

3.3 Sensor Design and Placement

UHF sensors for transformer applications have evolved from those that have proved successful in GIS applications. In many cases, retrofitting of UHF monitors to GIS has involved making use of existing apertures in the metal cladding through which the UHF signals can escape. Typically these are glass pressure windows (sometimes found near disconnectors to permit visual inspection of the contacts) and exposed barrier edges [15]. During the research phase, we have used a window-mounted UHF sensors because they can be removed without opening the tank. However, there is no reason why a robust internal sensor should not be permanently fitted. Internal sensors are commonly installed on new GIS, which are manufactured to extremely rigorous standards.

Retrofitting UHF sensors to transformers requires hatch plates on top of the tank. A new set of plates is made up which incorporate the necessary dielectric windows. Figure 4 shows the assembly and testing of one such sensor. A brief outage is required during which the transformer oil is lowered just enough to allow replacement of the hatches without exposing the windings to air.

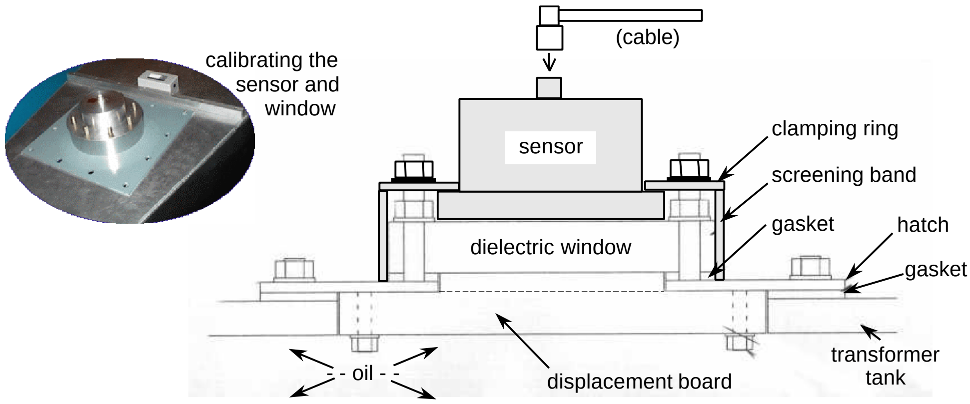

Figure 4: UHF Sensor Assembly on a Transformer Hatch Cover

Crucial to the acceptance by manufacturers of UHF monitoring is the design of a reliable window or internal sensor that that will not compromise the integrity of the tank during the transformer's lifetime. This is a design issue that manufacturers are best placed to address. In many respects, PTFE is an excellent choice of material. Although it is relatively soft, it could form the front layer in contact with the oil or displacement board with a strengthening layer of some other material behind. Cast resin windows are another option not yet explored. Alternative sensor designs that will not require a window are also being studied.

3.4 Locating PD sources

Two UHF sensors are sufficient for locating PD along GIS busbars by giving an indication of the plane on which the PD source must lie. However, in a transformer, at least three sensors are needed if the PD source is to be located to a point rather than to the intersection of a parabolic surface with the tank. Even with three sensors, there is potential for ambiguity between mirror image points on either side of the plane passing through the sensors. However, if all three sensors are located on top to the tank, this effect is unlikely to be an issue.

Since the materials in the transformer tank are diverse, simple triangulation is not the best way to interpret differences in signal arrival times at the sensors in terms of the origin of the signal. Instead, we calculate the most direct electromagnetic path between two points, taking into account the major internal components through which the signal will not propagate. The approach we have adopted is to construct a numerical model of the transformer materials within a rectangular volume large enough to contain the whole tank. A 5 cm grid is used. Each point is given a code to define whether or not UHF signals can pass through it and what their propagation velocity is in that material [16]. Initially, this task appears quite onerous, but actually the level of detail required is not excessive [17]. The transformer assembly is defined in terms of a set of cylinders and boxes of different materials. A pre-calculation takes place, yielding a Propagation-Time-Matrix (PTM) format [17] for each sensor in just a few minutes of computer processing time. This calculation stage only needs to be carried out once for each transformer of a different design.

As PD data is acquired, the predefined PTMs for each sensor pair are interrogated to identify points that match the measured incoming time differences to within a specified tolerance. Points scoring a good match are highlighted on a 3D internal view of the transformer. The PTMs can also be used to trace the predicted most direct path from the PD source to each sensor so that the engineer can check that these are realistic, as shown in Figure 5.

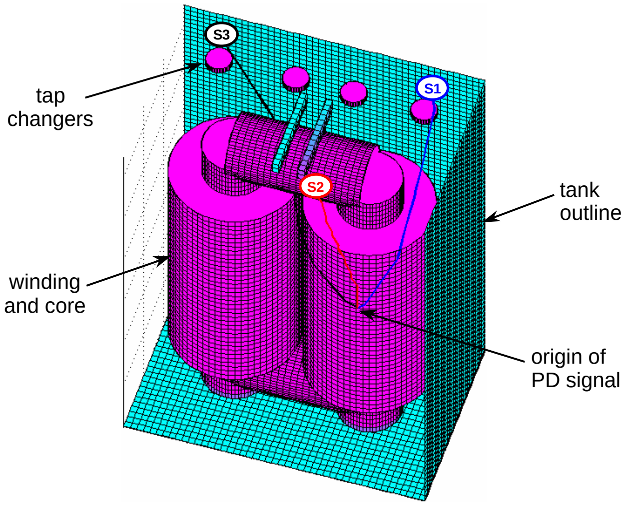

Figure 5: Single Phase Transformer Model Indicating Shortest Signal Paths from PD Source to Sensors

4. Case Studies on Power Transformers

4.1 Grid Transformer

Initial promising results with UHF monitoring on transformers were obtained during a series of tests on a 1000 MVA, 400 – 275 kV unit at Neilston substation near Glasgow, Scotland. These results have been fully reported elsewhere [18,19,20]. The transformer in question has been decommissioned, but not yet dismantled. This task should take place later in 2004, at which time we hope to be able to verify our predictions. Nevertheless, these tests gave rise to a new set of principles for analyzing UHF signals from discharges in transformers that differ from the methods used in GIS. The analysis of UHF signals from sensors on the transformer tank will be reviewed here to illustrate how we can monitor several discharge sources simultaneously and locate each one automatically.

Figure 6 shows in simple form the problem to be addressed. Several sources of transient signal are located inside a metal tank. These may be PD sources, intermittent arcs, or entry points for interference from outside the tank. The different signal paths between each PD source and each of the sensors correspond to different signal transfer functions. Each exhibits a level of attenuation and a certain time delay that are reasonably consistent provided that the geometry is fixed. As long as we can detect the signal at each sensor simultaneously (that is, apart from the inherent time delay we are interested in), we can calculate two important parameters. The first is the difference in arrival time of the signal at a pair of sensors, Δt, which we will later use to locate the signal source. The second is the ratio of signal energies, R, often more usefully expressed as a logarithmic value, $log_{10}(R)$.

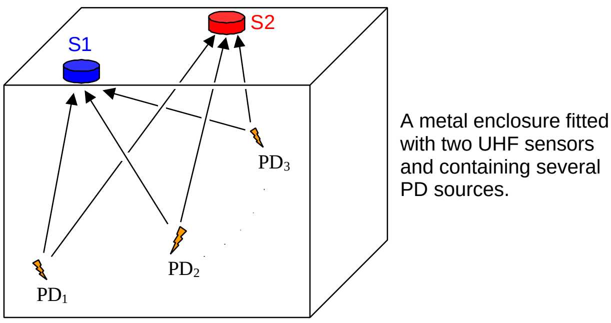

Figure 6: Recognizing Multiple Signal Sources Using Two or More UHF Sensors

A typical pair of UHF signals is shown in Figure 7. These can be acquired using a digital sampling oscilloscope or a high speed sampling card. A bandwidth of 500 MHz is necessary to obtain the sub-nanosecond resolution required to locate PD sources to within 20 cm. Typically, the sampling rate of the digitizer will be 2 GHz or more. The number of raw data samples acquired for each PD pulse is consequently very high, but all of the important information can be condensed into two parameters, *time of arrival* and *signal energy*. Figure 8 shows how these values are obtained by working with the integral of the voltage waveform, which maps the accumulation of UHF energy during the burst of signal.

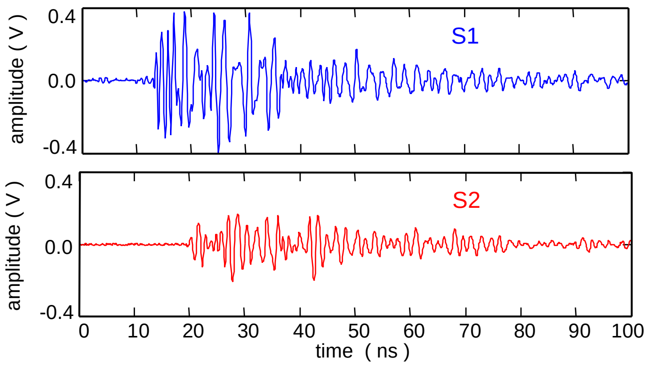

Figure 7: Time-Domain UHF Signals Recorded Simultaneously at Two Sensors

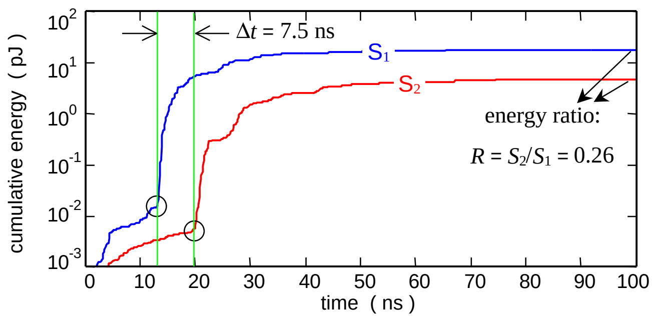

Figure 8: Cumulative Energy Plots Illustrating Parameter Extraction for a UHF Signal Pair

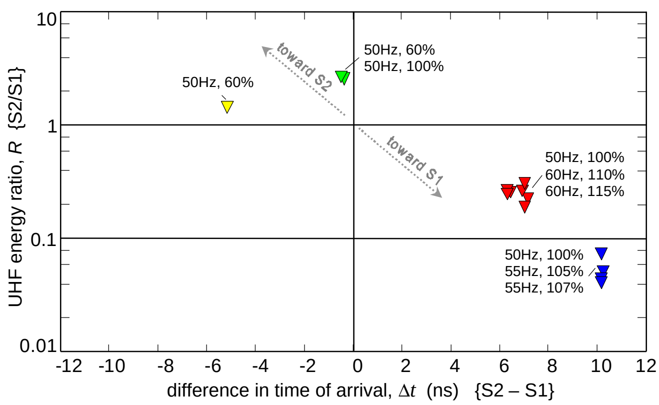

Figure 9: Map of Time-Domain UHF Signal Parameters Showing Multiple Discharge Sources (*Specific test frequency and operating voltages* [%] *are indicated beside each data cluster*)

Each incoming PD pulse can then be mapped onto a two-dimensional plane by means of its $\{\Delta t, R\}$ co-ordinates, as shown in Figure 9. This plot shows real site data from the grid transformer, which had two main discharge sources represented by the clusters at the lower right of the graph. The disadvantage of the 2D plot is that it conveys no sense of the discharge intensity. This can be rectified by using a 3D plot in which the vertical scale represents UHF signal energy. To illustrate this, the data from Figure 9 has been plotted as an energy-cluster map in Figure 10.

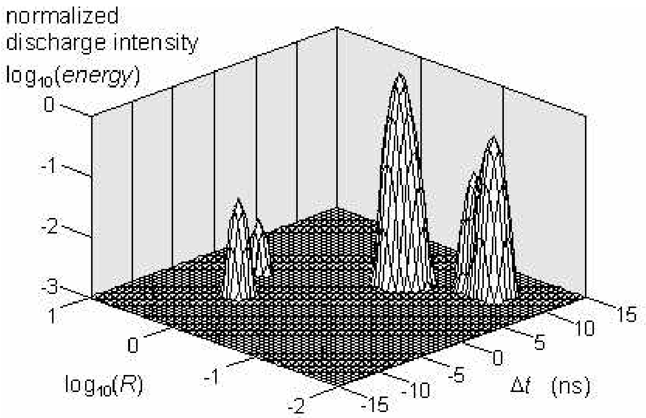

Figure 10: Three-Dimensional Energy-Cluster Map of PD Activity
(*Vertical scale shows the signal energy relative to the cluster with the highest energy*)

4.2 Acceptance Testing

The purpose of this investigation was generally to measure any UHF signal present in a transformer in good condition during factory acceptance tests and particularly to see how these relate to the apparent charge (IEC60270) levels recorded using conventional equipment. The unit under test was a generator transformer for step-up to 275 kV. Four windows for UHF sensors were fabricated from PTFE sheet 20 mm thick, clamped over apertures in the tank wall of diameter 130 mm. PTFE was used because it is both chemically inert and impervious to moisture.

Highest PD levels occurred during the induced overpotential tests, performed at 200 Hz and reaching twice the rated operating voltage for 10 seconds. The unit passed the specification limits with ease, showing PD levels of only 28 pC and 9 pC on two windings respectively. However, clear UHF signals were detected in both cases, demonstrating good sensitivity in relation to standard factory tests.

4.3 Traction Transformer

This 18 MVA single phase 132 – 25 kV unit had shown an increased rate of production of Hydrogen and Acetylene. Thorough internal inspection did not reveal any signs of discharge activity. Replacements were made for three inspection hatches located on the top of the tank. Each of these incorporated a dielectric window for mounting a UHF sensor. Figure 11 shows the transformer and UHF sensors. Coaxial cable assemblies 24 m long were prepared and their electrical length was checked using a UHF network analyzer. Cable delays were matched to within ± 0.1 ns around an average value 115.8 ns.

When the transformer was energized, quite large UHF signals were recorded using a digital sampling oscilloscope running at 10 G sample s^{-1} (analog bandwidth 3 GHz). Unusually, no preamplifier was required, as signals were in the range 50 – 100 mV peak-to-peak. Order of arrival of signals at the sensors was: S1, S3, S2. Differences in time of arrival were noted for use in locating the discharge source.

A portable UHF PD monitor (GIS type) was used to record the phase-resolved characteristics of these signals. A typical pattern is shown in Figure 12, revealing strong 180° phase symmetry. Identical patterns appeared at all three sensors, but the amplitude was consistently greater at S1. To establish whether the discharge was affected by changing operating conditions, the portable UHF monitor was left on site to record data continuously for 6 days. Over this period the PD pattern and amplitude remained remarkably stable despite loading variations from 2 to 17 MVA.

When the measured time differences were analyzed, the source was identified as being just under one of the tap changer mechanisms, as highlighted on the model at the left of Figure 13.

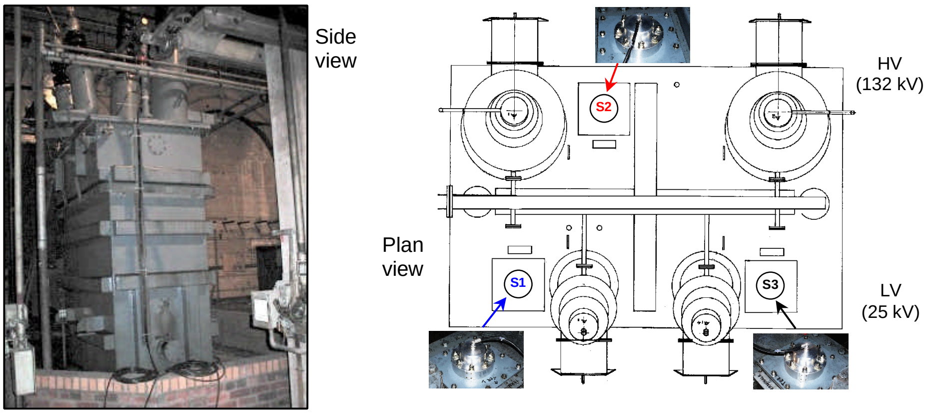

Figure 11: An 18 MVA Single Phase Traction Transformer Equipped for UHF Monitoring

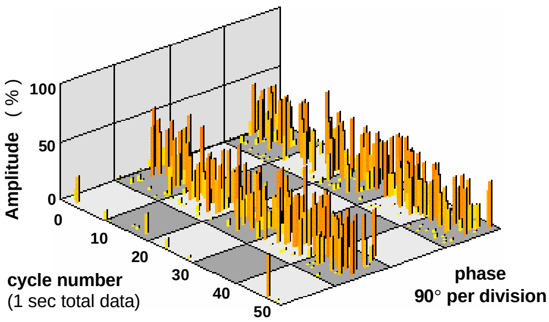

Figure 12: UHF PD Signals from Sensor S1, Phase-Resolved to the 50 Hz Power Frequency

Before an outage could be arranged to inspect this region, a through fault on the load side of the transformer was followed by rapid gas accumulation that tripped the Buchholz relay. Some weeks later, the transformer was detanked for forensic inspection. Considerable evidence of physical damage was apparent, including failure of the winding clamp.

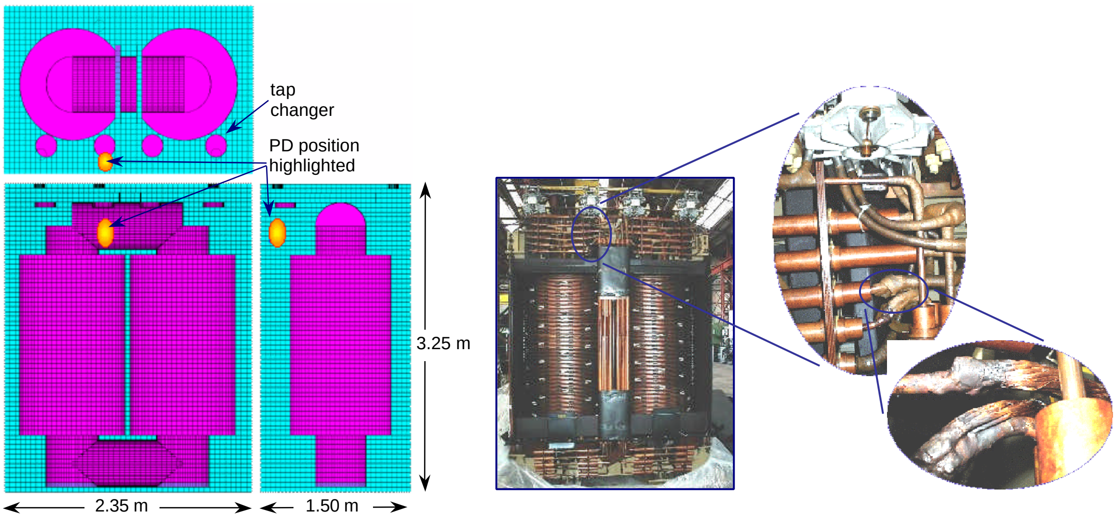

Figure 13: Predicted PD Location (left) and Photographs from the Forensic Investigation (right)

In the region where the electrical discharge activity was predicted, paper on the tap changer leads was burnt. Sludge from this discharge had accumulated nearby. No other signs of heating could be seen. Underneath the area of blackened paper were bulky joints between solid conductors and flexible leads. Different views of the area in question are shown at the right of Figure 13. The location of this discharge site was about 15 cm from the center of the suspect region highlighted in the computer model. The fact that neither of the tap leads involved was load-bearing during PD monitoring accords with the observation that the PD signals did not vary with load. Onset of this PD was probably brought about by cumulative mechanical distortion of the assembly.

4.4 Industrial Transformer

This 120 MVA, three phase 275 – 33 kV transformer supplied a large industrial complex and therefore operated under quite variable conditions. Gas production was abnormal but the cause could not be identified. Modified hatch plates were manufactured and fitted to the transformer at the locations shown in Figure 14. In this instance, the GIS-type UHF monitor was left running continuously on-site for 17 days. PD data collected was very different from the previous case. Discharge activity tended to occur in distinct blocks of several hours duration, but there was no apparent correlation with load. The UHF signals were much smaller than in the previous investigation, so preamplifiers (26 dB gain) were used throughout the monitoring period. The phase-resolved pattern of the PD signals was also quite variable, as can be seen from the examples in Figure 15, providing strong evidence of more than one PD source.

Whenever we visited the site with the high-speed oscilloscope, the discharge was inactive. Consequently, we were not able to record the Δt values that would have allowed us to locate the signal source(s). Further testing was prevented by the timetable for replacing the unit. A gradual disassembly procedure was followed, during which a severely damaged joint between the LV winding and a solid T-piece busbar to the LV bushings was found. Heating had been so severe that several strands of the flexible lead had burnt through, as can be seen in Figure 16. Tests on this transformer highlighted the need for a continuous monitoring device that can automatically measure Δt values for defect location, rather than simply PD data in phase-resolved form. This will be essential if intermittent PD sources are to be located, especially when activity is infrequent.

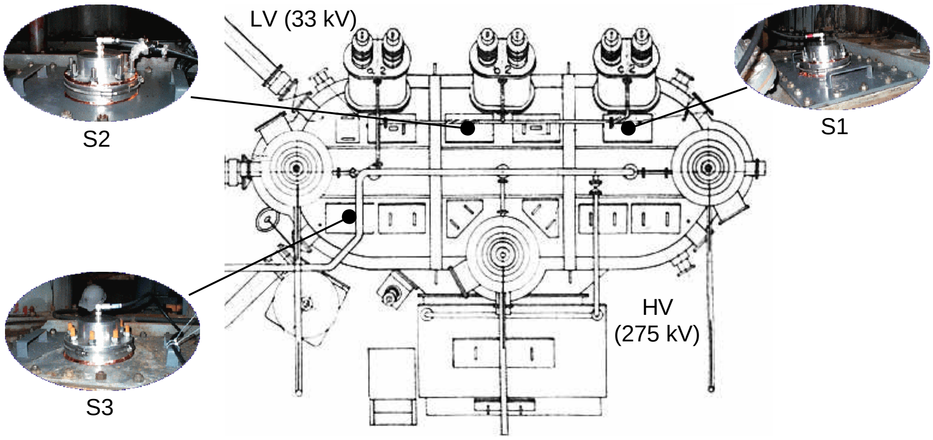

Figure 14: Top View of the 120 MVA 3-Phase Transformer Equipped for UHF Monitoring

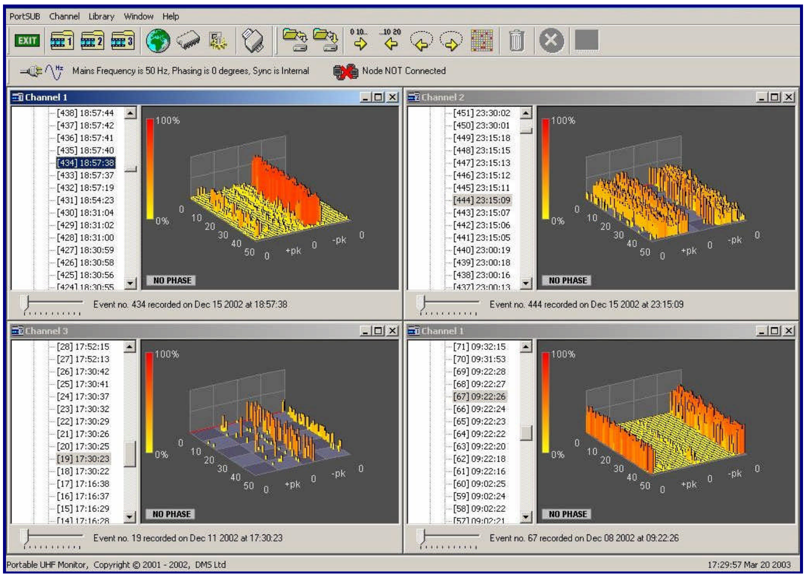

Figure 15: Examples of PD Patterns Recorded at Different Stages During the Monitoring Period

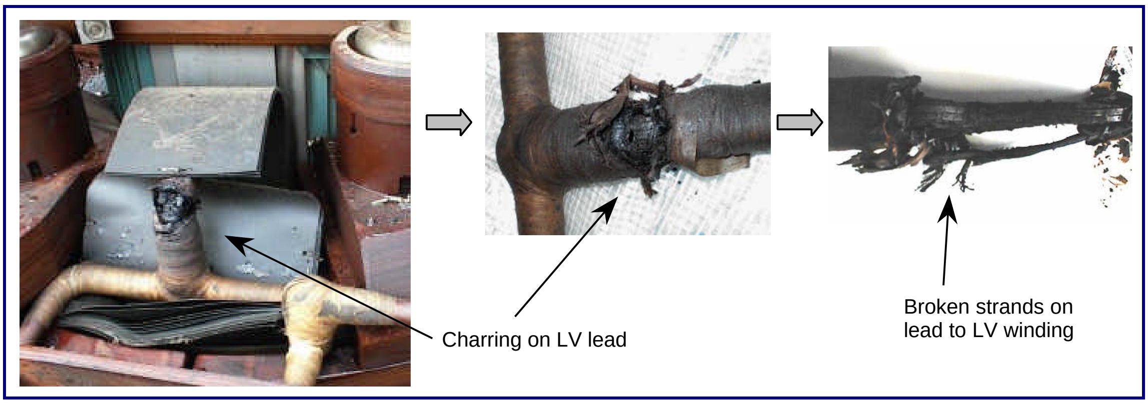

Figure 16: Damaged Joint on 33 kV Lead

5. Development of a Power Transformer Monitoring Unit

5.1 Strategies for Monitoring

The development of UHF transformer monitoring to its present stage has been supported by SP Power Systems, part of the utility company responsible for the transmission network in southern Scotland and parts of northern England. A number of transformers have been identified as requiring further investigation on the basis of DGA results, production of free gases (Buchholz relay) or the track record of sister units. The trials reported above have been part of this process. Results have been sufficiently promising for SP Power Systems to require dielectric windows to be fitted to all new transformers at manufacture.

A portable UHF monitor (probably comparable with an FRA test set in size and cost) could service a large fleet of transformers, given that most will be trouble-free. A scenario potentially of interest to utilities would be to have sensors supplied with new transformers, their cables terminating at a bulkhead or in the signal marshalling kiosk. A portable monitor could be used to check for PD at the same time as oil samples were taken for DGA. Alternatively, the equipment could be left on site for a number of days or weeks to check for any internal discharge activity, record its temporal variations, analyze its phase-resolved pulse patterns and establish its point of origin. This would provide an opportunity to identify relationships between discharge activity and factors such as loading, temperature, LTC settings and switching operations. Quality of the data produced would be enhanced by the inherent ability of the UHF system to distinguish between multiple sources of PD/arcing/interference that are simultaneously present [21]. All of this functionality could be accessed remotely (over modem, LAN, internet, etc.,) and viewed almost in real time if routed through a broadband data network.

Manufacturers may have reservations about fitting additional monitoring that allows the user to detect internal PD activity. This was certainly the case initially with GIS, but has been overcome as manufacturers have found that they are able to produce higher quality products because they can locate and rectify insulation defects before any damage results. Another difficulty that UHF monitoring can help to overcome is establishing whether a signal appearing on the conventional PD test set is actually coming from inside the transformer or not. If any debate could immediately be resolved by referring to a “live” 3D internal image of the transformer, valuable time might be saved during the test process.

UHF diagnostic tools in their present state of development can assist in dealing with troublesome transformers in the existing population, for example, in monitoring units of a particular design that are known to experience problems. Widespread retrofitting of dielectric windows to healthy units would be difficult to justify in view of the need for an outage to lower the oil and replace inspection hatches. The appropriate stage for UHF windows and sensors to be fitted is during manufacture. While we all hope that units currently in production will give many decades of trouble-free service, we could be doing the next generation of engineers a favor by incorporating features that could make their transformer fault investigations somewhat less oily.

5.2 Development of a Portable Monitor

The case studies covered in this paper confirmed to us that the full potential of the UHF technique cannot be established in relation to power transformers without an automated, fully functional system that can be left on-site for periods of continuous monitoring. To this end, a PC-based system (Figure 17) is being constructed that will function as a development platform. A typical data processing display from this equipment is shown in Figure 18. The main graphs show the detected leading edges of incoming signals, the $\{\Delta t, log_{10}R\}$ plot for three sensor pairs, the distribution of pulse count against Δt and the energy timeline for each sensor. Not yet functioning is the plot of pulse energy against power frequency phase angle, which is in the process of changeover from an analogue to a digital input stream.

To link the data acquisition stage with the location mapping display, software is being developed that recognizes clusters in the incoming data and passes the relevant parameters to the 3D display. At present, the centers of the clusters must be transferred manually to a separate program that calculates and display the point of origin (as shown in Figure 5 earlier).

Figure 17: Portable UHF Transformer Monitoring Unit in Development

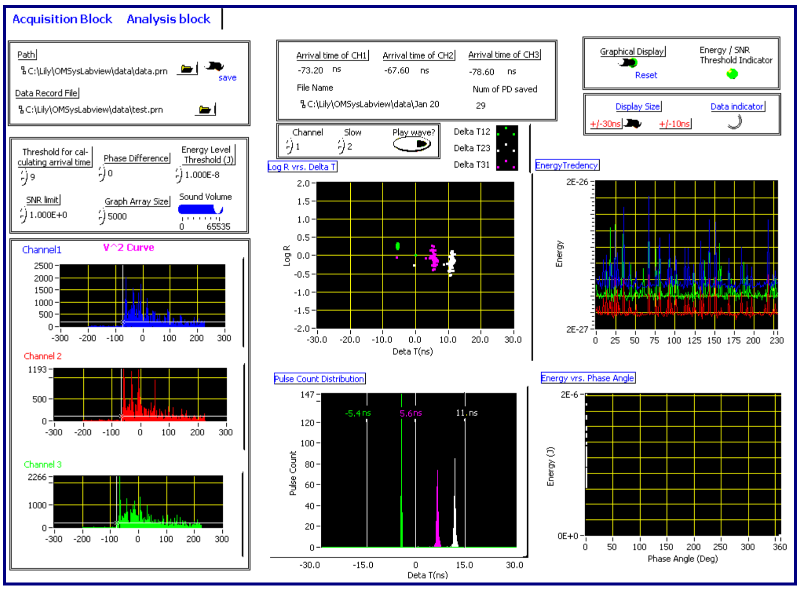

Figure 18: Screenshot of the Data Acquisition Display

6. Future Work

6.1 Application to Complete Substations

The principles of locating discharge sources based on shortest path calculations and triangulation between three sensors could also be applied to a complete substation. Any discharge activity would be mapped onto points in a mesh large enough to contain all plant and components of interest. On a very large scale, the basic principle is the same as that of a lightning detection and tracking system. We hope to report on substation trials later this year.

6.2 Monitoring of Mechanical Displacement in Metalclad Plant

A new research topic in UHF monitoring has arisen as a result of the observation that mechanical damage to transformers caused by through faults or harsh loading conditions may not give rise to PD and would therefore not be detected by a system that only listens for PD (what we might call passive mode: no PD = no information). Initial tests have shown that active interrogation of the mechanical structure could be carried out using the UHF sensors that are simultaneously monitoring for PD. Figure 19 shows a network analyzer trace sweeping at a constant frequency, displaying variations in signal power caused by a gently swinging nut in a metal tank fitted with UHF sensors. Our view is that this technique will allow engineers to interrogate the transformer monitor after a potentially damaging event to ask the following question: *Has the internal structure of the transformer been permanently altered, or has it reverted to its previous shape*? Since the timescales of interest for mechanical deformation are much longer than for UHF signals, the data sampling rate required would be very low, resulting in a much lower hardware cost. If it proves to be effective, this technique would therefore be applicable to quite small transformers, with trackside units being an obvious area of application.

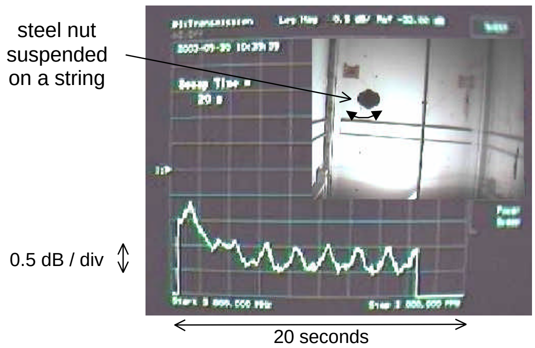

Figure 19: Using UHF PD Sensors to Detect Mechanical Displacement Inside a Tank

6.3 Devolving Intelligence and Systems Integration

Integration of plant monitoring data within a wider condition monitoring information architecture is a goal that many utilities are pursuing. A recent research project has defined the structure of an integrated approach to condition monitoring and plant lifetime modeling [22]. Condition monitoring intelligence can increasingly be devolved to lower levels, with the aim of meeting the asset manager’s requirement for monitoring systems to give a simple “traffic light” status indication of plant health. An indicator of this type will be more reliable and more readily implemented if the front-end monitoring hardware delivers data of the highest quality.

A major issue to consider with all new monitoring strategies is, *How many times will the monitoring system have to be replaced/upgraded during the lifetime of the transformer*? If the monitoring system is PC based, obsolescence is almost guaranteed within a few years. However, once the monitoring hardware matures and becomes very small and very cheap, the question itself will become far less important. What remains is to ensure that the sensors installed are capable of providing high quality data and will last as long as the transformer. Our view is that UHF sensors can meet this reliability requirement, opening up opportunities for new and effective monitoring techniques throughout the life of the transformer as new, low cost electronic hardware becomes available.

7. Conclusions

Compared with its application to GIS, UHF PD detection and monitoring for power transformers is in its infancy. However, results are sufficiently promising to warrant serious attention in view of the following advantages:

- Good immunity to interference from extraneous air corona
- Data is readily acquired in phase-resolved form for automatic interpretation
- There is clear discrimination between internal PD and external noise signals
- Location of PD sources can be automated and therefore displayed remotely
- Multiple PD sources can be handled simultaneously, for example, allowing a small but dangerous PD to be tracked in the presence of a large, benign signal source
- Once a standard sensor mounting arrangement has been defined, the cost of including UHF sensors at manufacture will be negligible
- Hardware with the necessary high bandwidth and sampling rate will become increasingly widespread with time and its cost will fall, driven by the consumer market for mobile communications devices

Considerable confidence can be placed in the likely success of the UHF method for monitoring power transformers because it builds on the foundation of experience and technological developments that have taken place over many years for GIS. The advances made during our investigations have opened up a new realm for interpreting UHF PD data, based on the use of multiple sensors “looking” into a single volume of insulation. These will be applicable to other plant and equipment in addition to power transformers.

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Craig Bennoch is a Research Student in the High Frequency Diagnostics Group at the University of Strathclyde. He is currently working towards a PhD in condition monitoring of high voltage apparatus using UHF techniques. Craig has been a postgraduate student at Strathclyde since 1997. His research activities have focused on a number of modern high voltage plant condition monitoring technologies. Projects have included techniques to monitor the level of surface pollution on solid insulators based on PD measurements and the use of modern wireless local area networking technology in PD monitoring. These skills are being utilized in his PhD project where a new technique for interpreting UHF signals from PD is being developed to accurately locate the sources of multiple insulation defects.

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