New Methods in On-Line PD Detection for HV Plant

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INTRODUCTION

Partial discharge (PD) is becoming increasingly viewed as the best diagnostic for insulation, particularly for on-line measurements. Clearly this applies to insulation which exhibits and is degraded by PD activity. However, even for insulation which is designed to be PD free, the knowledge that the system is actually PD free is still a vital part of the diagnostic process. Hence PD measurements which are accurate and reliable, always contain important information about the high voltage (HV) plant to which they apply.

With the development of on-line PD methods, several problems still exist to be solved to yield the optimum diagnostic for insulation. These are:-

- *Noise interference from RF radio broadcasts*
- *Noise interference from pulses other than PD pulses*
- *Location of PD pulses on cables and static plant (e.g. switchgear, transformers etc)*
- *Estimation of remaining service life for the PD activity measured in the HV plant under test*

The remaining service life of plant exhibiting PD activity is briefly dealt with for restricted types of plant, otherwise this is left for a future paper. This paper addresses the main issue of making reliable PD measurements, namely the identification and removal of noise sources, and the location of PD events. To be able to do this allows the identification of discharging plant, and hence the assessment of the risk to reliable service performance.

This paper describes the development of methods to distinguish between noise and PD activity, and to distinguish between several different types of PD. The recognition is done using simple algorithms which use the waveform shape of the PD (and noise) pulses, to discriminate between the different types.

Partial discharges (PD) in voids and cavities in general produce very similar pulse shapes with very fast pulse widths. Values of a few tens or hundreds of picoseconds are typical. The pulse times are closely related to the breakdown time across the cavity. However, at the terminals of the high voltage equipment (or using an electromagnetic pickup if these are used) the pulse shape is dependant on the parameters of the detection circuit. Often these are determined by the equivalent circuit of the power plant at the detection point. The observer may not have much control over the detection circuit in these cases. Hence it might appear that using the waveshapes of the pulses to distinguish between noise and PD (and between different types of PD) does not have a bright future.

However, there are two classes of PD pulses which do retain a reasonable consistency of behaviour, for both on-line and off-line testing. These are cable PD's and PD's from local equipment (switchgear etc). In this case, local equipment means plant within a few metres of the measurement point. The algorithm used in the development described in this paper, essentially makes three categories of pulsed signals. These are cable PD's, local equipment PD's, and all others are regarded as noise. This simple algorithm gives remarkably good results in a wide variety of circumstances, and has now been successfully incorporated into several commercial products.

PD EVENTS FROM HIGH VOLTAGE CABLES

In the special case of partial discharge in cables, the cavity responsible for the PD discharges into a real impedance. This is the surge impedance of the cable and is purely resistive at the point of launch. The resulting pulse is virtually monopolar with fast risetimes and very short pulse width. This pulse travels outward from the originating site, and arrives at the detection point wider and smaller due to attenuation and dispersion on its travel down the cable. The pulse is in general well defined by the time it is detected, and in practice retains much of the same characteristics as a consequence of originating in the cable. Figure 1 shows a typical cable pulse, with the computer generated cursors to measure the risetimes and pulse properties.

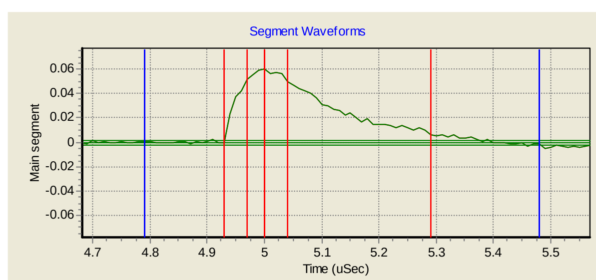

Fig 1 Pulse from a partial discharge in a cable (showing computer generated cursors)

Providing the risetimes and widths fit into sensible values for a PD pulse, then the event is categorized as a cable event. The risetimes are typically between 50nSec and 1mSec, with pulse widths in general being less than 2mSec. Actually for XLPE cables these values are generally shorter than this, as the loss and dispersion are considerably less for XLPE cables. The pulse risetime and width are dependent on both the pulse shape at the cable end, and the detection circuit. Hence the neat method of using the risetime (or pulse width) as a measure of the location of the pulse, cannot be rigorously used, as the detection circuit is not known, and for example, may contain a large inductance and always then give slow risetimes and longer pulses. However, the risetime is nevertheless a valuable tool in the initial localisation of the pulses, as for on-line PD detection using high frequency current transformers (CT's) the detection circuits generally have large bandwidth (>20MHz) and simple localisation works reasonably well.

Fig 2 High frequency current transformers (CT's) around cores of 33kV cable for PD measurement (CT's are arrowed)

Figure 2 shows the current transformer arrangements for a 33kV XLPE cable, where the CT's can be placed around each of the single cores, above the earth strap take off point.

Normally the current transformers are placed around the earth strap. The PD pulses travelling down the cable to the termination, have an equal and opposite polarity on the conductor and screen respectively. Hence it does not matter whether the CT's are placed in the earth strap, or the conductor. The important criterion is that only one of the earth or conductor currents is intercepted. In practice the two signals are very similar, but often the noise content can vary between the two detection points.

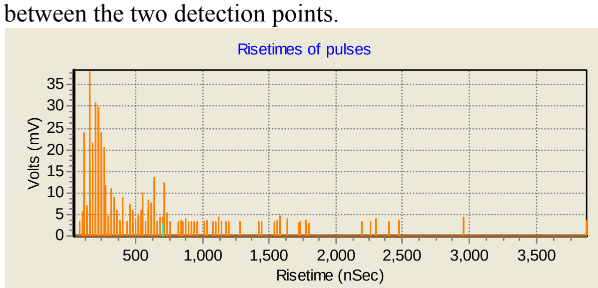

Fig 3 Distribution of pulse risetimes from a cable

Figure 3 shows a cable with a spread of risetime events, where there are clear bands to the risetimes recorded. In principle, a graph could be constructed from figure 3, with the ordinate calibrated in metres. This would assume a relationship between the risetime and the distance travelled for PD pulses in cables. This is actually reasonably well established (depending on the cable type), but the main problem is the unknown detection impedance at the termination. For example, if the detecting impedance contained a large inductance, then the risetimes of the pulses would be dominated by the detection impedance, and not the distance travelled by the PD pulses. In cases like this, a relationship between risetime and distance cannot be made. The response of the detection circuit could be measured, and if possible, the relationship could be correctly established. This will be the subject of a future paper.

The results in figure 3 were taken from a 33kV paper insulated cable tested on-line. Notice that the risetime of the PD events for this cable are around 200nSec. The cable was around 2km in length, and the locations were all from a single joint located at 1600m.

The huge advantage of carrying out PD detection using the waveforms of the PD pulses, is that it allows for correction of the magnitude of the discharge almost irrespective of the distance down the cable the pulse has travelled. Particularly for paper insulated cables where the attenuation is large, making magnitude only measurements of PD pulses leads to poor conclusions about the peak magnitudes. A PD of the same size can easily look a factor of 10 or 20 smaller when seen at some distance down the cable. Hence a very severe event remote to the measurement site can be observed as quite a modest PD if the attenuation has reduced the peak magnitude by a factor of say 20 or so. Using the waveform to measure the area under the curve of the PD current, a measure of magnitude can be made which is much less sensitive to attenuation. The measurement of charge is made by simply integrating the charge under the current curve:-

$$Charge = \int_{start\_of\_pulse}^{end\_of\_pulse} I * dt = \int_{start\_of\_pulse}^{end\_of\_pulse} const * V * dt$$

where 'const' is the multiplier which converts the current to voltage. This will include the transfer impedance of the current transformer and such factors as the cable impedance and amplifier gain. Hence using this method for calculating charge, the values of PD magnitudes can be measured in Pico Coulombs, provided that the detection impedance may be assumed to be the cable surge impedance, or a correction factor used. In practice the variation in the change of surge impedance at the ends tends to be less than 20% or so, when compared to measurements made in the earth straps of joints in the middle of the cable, where the surge impedance will be close to the surge impedance.

As an example of measuring the charge in this way, at 3km on an 11kV paper insulated mass impregnated non draining (MIND) cable, the area measure had only reduced by a factor 3. The amplitude measurement had reduced by factor of 15.

This means that for on-line PD tests, without the need for any calibration, the cable events can all be expressed in pico coulombs.

LOCALISATION OF PD EVENTS ON CABLES USING A TRANSPONDER

In the special case of testing high voltage cables, the usefulness of measuring PD activity is vastly increased if a localisation of the PD origin can be made. For short cables, a double ended method of timing the arrival of the PD pulses is the most effective. This requires a sensor at both ends of the cable, and a calibration of the cable travel time for both legs. For longer cables, getting a radio frequency cable to the far end sensor is not usually possible. Several methods have been attempted to overcome this problem. GPS sensors can be used to tie two PD recorders to the same absolute time. This method takes a lot of care is setting up, and requires a great deal of marrying up signals after the data is recorded.

Figure 4 The trigger unit and large pulse generator of the transponder unit

Alternatively, the timing information from the remote end of the cable, can be directed back down the cable cores themselves. A simple method has been adopted to achieve this. A transponder consists of a detector and trigger level for PD pulses, linked to a large voltage pulse generator, which launches pulses back onto the cable under test. Figure 4 show a photograph of the two battery operated devices. The trigger levels for the input device spans the range 1mV – 1V. The linked pulse generator is capable of generating 1mSec pulses at 200V into open circuit.

If high frequency current transformers are used as the detection and launching sensors, the system can be used successfully with cables of 2 or 3 km or more. The accuracy of the device is dependant on the risetime of the PD pulses, as the trigger must occur somewhere on the rising edge.

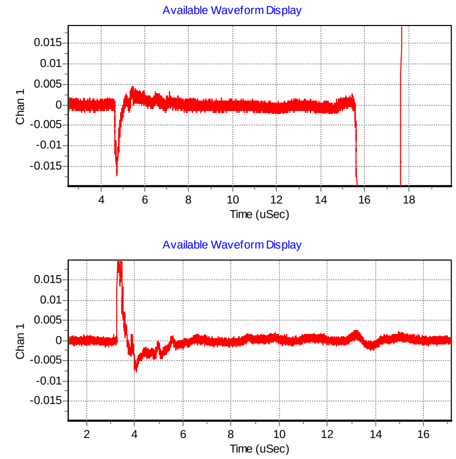

Fig 5 Location of PD pulses with and without transponder location pulses

Figure 5 shows the results of carrying out the locations of a cable PD with and without the help of a transponder. In this case the location of the PD event is very close to the measurement substation, and the very large transponded pulse is clear. In this case the cable length was around 750m.

The transponder developed for localisation of cable PD's was battery powered, allowing remote substation locations to be made possible, even with no local mains power. (a circumstance which is actually quite common)
This method for localisation has proved very successful largely as a result of its simple and direct application. If the PD pulses are clear, then the transponder method is very robust, and locations are always clear and unambiguous.

PD EVENTS FROM LOCAL EQUIPMENT

For on-line testing local equipment (switchgear, transformers, bushings etc) for PD activity, the most effective sensor is an electromagnetic pickup, placed on the outside of the earthed metalclad surface. Figure 6 shows a typical TEV probe.

Figure 6 transient earth voltage probes (TEV's or capacitive pickups)

These so called transient earth voltage (TEV) pickups detect the electromagnetic pulses from inside the local plant. They are essentially a capacitive coupling with the metal surface.

This type of sensor is only suitable for local PD pickup, as the sensors do not pass low frequencies. Typical cutoff frequencies are in the region of 2MHz -5MHz, and signals must be above this frequency to be detected.

Hence for local PD, if the frequency content is typically above this cutoff value, the chances are extremely high that the pulses are from PD's originating in local equipment. The argument also applies to testing plant with a high frequency current transformer as the pickup, as long as the upper frequency cutoff is above say 20MHz, so that the larger frequency content of the local PD pulses is observable. Figure 7 shows a typical resonant response from a local PD event. Notice the fast oscillations denoting the large frequency content.

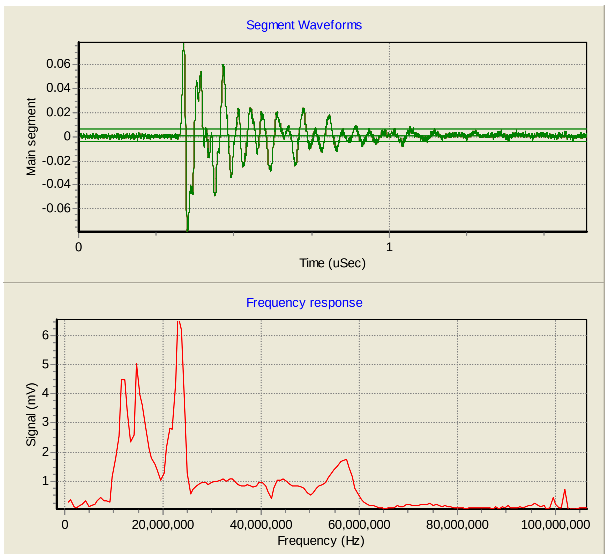

Fig 7 Waveform of local equipment event using a capacitive sensor

The algorithm for recognising a local PD event, is therefore very simple. If the frequency content of the event is above a critical cutoff, (somewhere in the region of 2MHz to 5MHz) then the event can be counted as a local event. This method cannot apply to ultrasonic signals and sensors, all of which have much smaller frequency content. Other methods apply for the ultrasonic case.

It is reasonably surprising that such a simple algorithm for recognising local PD events is effective. However, pulses with larger frequency content which are not PD related, are in practice quite rare. The authors have seen some local processing equipment (intelligent switchgear monitors) which produced similar high frequency pulses, but with this exception, the vast majority of pulses with larger frequency content tend to originate from PD's within switchgear or similar plant.

NOISE REDUCTION FROM CONTINUOUS WAVE INTERFERENCE

A large problem in PD detection comes in the form of radio broadcast interference. This is particularly the case for on-line measurements made on cables attached to switchgear which is not metalclad, although it can sometimes be a problem for metalclad switchgear.

To overcome this major problem, a spectral subtraction method was developed. Again the ideas for this were simple, and are shown schematically in figure 8.

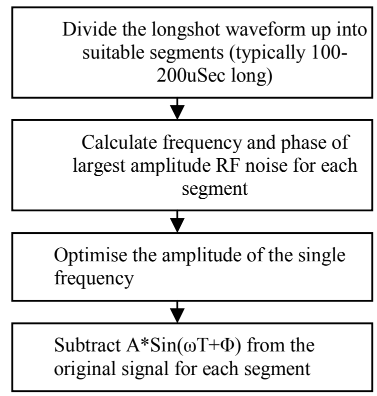

Fig 8 Method for reduction of RF interference from waveforms

Essentially the largest frequency in the waveform is calculated, and this frequency is subtracted from the waveform, leaving all the pulse data unchanged, but without the interfering RF noise. As the RF radio broadcast noise is in general in the medium or short waveband, the carrier is in general amplitude modulated. Hence the best results are achieved if the length of the waveform is made over a time in which the modulation does not change much.

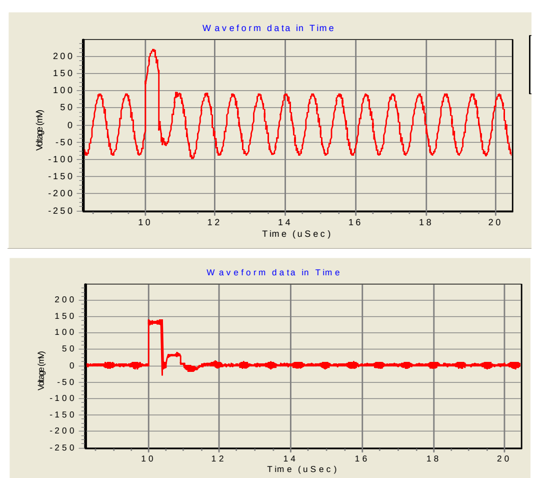

Fig 9 Waveforms from before and after the application of the noise reduction process

In practice for noise reduction for a waveform spanning whole power cycle, the length of the segments which are noise reduced are typically 100mSec - 200mSec. Figure 4 shows the method for noise reduction for RF interference. Figure 9 shows waveforms before and after the noise reduction process.

In figure 9 the reduction in the standard deviation is around 7.6 between the two cases. The waveform interference is reasonably sinusoidal, and the results would be expected to good in this case, but similar practical cases also yield similar reduction ratios. The double pulse in figure 9 is now clear and can be used for location purposes, whereas before the noise reduction, the second pulse is not evident.

OPERATION OF EVENT RECOGNISER METHOD

The implementation of the event recogniser algorithms starts with recording the complete waveform of a single power cycle of data. This is recorded at full sample rate (normally at least 100MSamples/sec). This 'longshot' recording is now RF noise reduced if required.

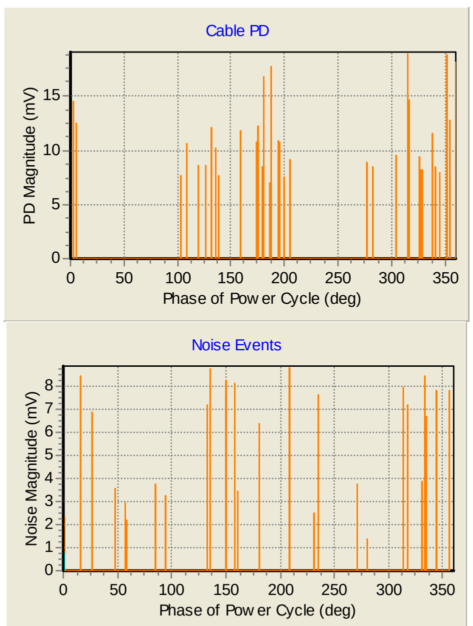

Fig 10 PD distributions across the power cycle in separate categories of cable PD and noise

The resulting waveform is then analysed for all the pulse data, and separated into populations of cable, local equipment and noise events. These categories can now be treated separately if required. The pulsed data is now really a list of PD events with properties such as position in the cycle, channel number (if this applies), category of pulse, and all the pulse data from the curve fitting and frequency analysis. This per-cycle analysis provides for very powerful techniques for monitoring and spot testing. The traditional data resulting from PD measurements was a record of the peak and count values. In the new method, the peak and count data can be carried out for each category of pulses, and hence in essence for each type of high voltage plant.
Figure 10 shows the results of 2 minutes of data recording, which recorded around 6 power cycles of complete waveform data. In this case, the PD pulses were mixed with a large number of different noise sources. The event recogniser has separated out the good data from the PD recordings, so that all the cable PD events are correctly identified. This was verified by manual inspection of the individual waveforms. Figure 11 shows two typical waveforms representing noise and cable PD respectively. If only peak and count methods had been used, all of these pulses would count as valid data. Using the event recogniser technique, noise can now be distinguished from the cable PD events. The recordings were made on an oscilloscope with an open PC, so the event recogniser software can be run internally on the device which records the data.

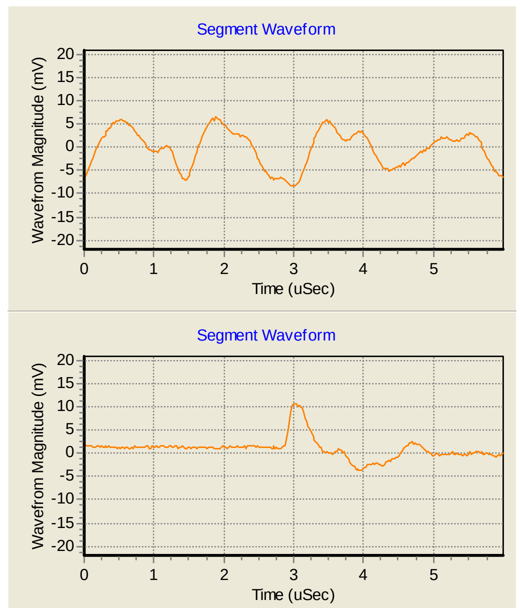

Figure 11 Waveforms of noise and cable PD respectively from the data in figure 10

This improves data transfer rate between waveform recorder and the PC by a factor of between 2 and 5 times.

CONCLUSIONS

The paper has described several new tools which can help to make PD (partial discharge) detection for high voltage plant much more robust and reliable, by removing two of the largest obstacles to making good PD measurements on high voltage plant, namely:-

- Noise reduction of radio Interference from broadcasts and power line carrier signals
- Separation of noise pulses from cable PD pulses and local equipment PD pulses

The methods described follow simple algorithms, and produce reliable results in practice. All the older traditional methods of measuring peak, counts and distributions for PD activity have all been retained. The new event recogniser tools essentially sit as an add-on to the original data. However, the clarity and discrimination given by the new event recogniser methods will allow huge improvements in the quality of the PD data recorded. This especially applies to on-line PD measurements.

For the case of high voltage power cables, a location method based on a transponder placed at the remote end of the cable is described, which allows localisation of PD events on cables to be made. This is particularly useful for on-line PD measurements where it is notoriously difficult to interpret waveforms to give good location data.

The tools have been developed into several commercial products, where the results from the users (not the authors) have been very encouraging.