LIMITATIONS IN THE APPLICATION OF ON-LINE AND OFF-LINE PD MEASUREMENT SYSTEMS

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INTRODUCTION

The first underground cables to be installed in the UK were paper-insulated cables and their installation dates back as early as the 1920’s. Although the manufacturing technology was primitive compared to that available today, there are still 50-60 year old cables that remain in working condition. In the modern power system, these cables are both an asset and a liability. Failure can lead to interruptions in supply and customer minutes lost, indices used by the regulator to reward distribution network operators. Companies are therefore under pressure to somehow improve the performance of cable assets. However, the economic costs relating to the replacement of all cable assets at the end of their life are prohibitive and large. Very-low frequency (VLF) allows the cable to be energised at 0.1Hz therefore preventing any large capacitive current from being drawn and minimising the size of the test set. While off-line testing is a valuable resource, it is costly in terms of manpower, results in a loss of power system security while a circuit is taken off-line and can only take a snapshot of the cable health.

In contrast, on-line detection can monitor the health of a cable for prolonged periods and can be achieved by fitting current transformers or other transducers around earth straps connected to the sheath of a cable. There is no system security risk associated with on-line testing but it can be susceptible to noise and location is more difficult.

Whatever the method of testing, the way in which PD pulses propagate through a power cable play an important role in the accuracy of the measurements. Attenuation or distortion of pulses as they propagate along the cable will alter the signal received at the measuring equipment. Amongst other issues, this can lead to the apparent presence of high levels of partial discharge close to the measurement site and lower levels further away while in reality the original magnitudes may be reversed. Further problems result from the consideration of the influence of joints, ring-main units and cable tee-sections.

OFF-LINE / ON-LINE TECHNIQUES

Methods of PD testing can be split into two main types, off-line and on-line. Off-line testing has traditionally been used to provide information about partial discharge location along a cable using time domain reflectometry (TDR). Off-line testing can be carried out using 50Hz generators although these have to supply considerable capacitive current to the cable and are therefore extremely large. Very-low frequency (VLF) allows the cable to be energised at 0.1Hz therefore preventing any large capacitive current from being drawn and minimising the size of the test set. While off-line testing is a valuable resource, it is costly in terms of manpower, results in a loss of power system security while a circuit is taken off-line and can only take a snapshot of the cable health.

Basic Principles

A PD occurring between phase and earth in a power cable results in a flow of current on both the phase conductor and the power cable sheath. The maximum duration of the PD current resulting from the breakdown of small voids is at most a few nanoseconds [1]. This type of pulse contains significant high frequency components. When the current pulse is formed, it splits and travels in two opposite types of transducers to measure the partial discharge signals is also discussed.

PROPAGATION OF HIGH FREQUENCY SIGNALS THROUGH A CABLE SYSTEM

Basic Principles

A PD occurring between phase and earth in a power cable results in a flow of current on both the phase conductor and the power cable sheath. The maximum duration of the PD current resulting from the breakdown of small voids is at most a few nanoseconds [1]. This type of pulse contains significant high frequency components. When the current pulse is formed, it splits and travels in two opposite
directions towards each end of the cable (used as an advantage in off-line TDR techniques). An equal and opposite PD current will be found on any location of the power cable sheath and conductor at any moment in time. The magnitude and shape of the current at any location varies due to the behaviour of the cable as a low pass filter.

A simplistic high frequency model of the cable illustrates why this behaviour takes place. Both the conductor and the sheath consist of resistance and inductance. At high frequencies, the series impedance of this path is high. The insulation between the conductor and the sheath can be modelled as capacitance and resistance and therefore has low impedance at high frequencies. The high frequency components of the discharge do not propagate great distances down the power cable but flow between the conductor and the sheath close to the discharge site.

Using the Telegrapher’s equations, a relationship between the current and the voltage entering and leaving a cable section of length ‘d’ can be given by equation 1 [2] where \( \gamma \) is the propagation constant and \( Z_c \) is the characteristic impedance. Through the use of Fourier transforms, the voltage and current at any point along a cable system owing to the input of a specific pulse can therefore be calculated.

\[
\begin{bmatrix}
V_c(0) \\
I_c(0)
\end{bmatrix} = \begin{bmatrix}
cosh(\gamma d) & Z_c \sinh(\gamma d) \\
\sinh(\gamma d)/Z_c & \cosh(\gamma d)
\end{bmatrix} \begin{bmatrix}
V_c(d) \\
I_c(d)
\end{bmatrix}
\]

(1)

**Attenuation Of PD Pulses Along A Uniform Cable**

A fast partial discharge pulse is rich in both high and low frequency content when it is represented in the frequency domain. However, the high frequency content cannot propagate through the cable for reasons already described and is increasingly attenuated as a function of cable length.

Both the magnitude and the shape of the pulses therefore change as they propagate with a finite velocity along a cable.

Figure 1 shows the results of a simulation in terms of the peak voltage produced by a current transducer placed at a substation when a 20000pC PD pulse originates at a PD site in a cable (i.e. 10000pC propagates to the substation and 10000pC proceeds in the opposite direction down a semi-infinite cable length). As is expected, the magnitude of the voltage measured at the CT decreases as the distance the PD must propagate to the substation increases. The most important consequence of this decrease in partial discharge magnitude is the ultimate reduction in the output of the CT to below the noise level present within the measuring environment.

The figure clearly shows the need to correct measured partial discharge pulse levels as a function of cable length. A large PD a long distance away could produce a smaller signal at the substation in comparison to a small PD a short distance away. If partial discharge maps such as those produced in VLF testing are to be interpreted accurately, correct modification of the plots is important. The result is significant for both on-line and off-line testing.

![Figure 1 – Measured signal versus distance](image1)

**Attenuation Of Pulses Through A Mixed Cable Network**

A common and necessary practice in distribution circuits is to join cables of different size and type. Different sizes are found where repairs have been carried out or where cable sizes are simply tapered along a radial length containing tees. With most utility companies now preferring XLPE to
paper cables, it is also very common to find paper and XLPE cables connected together.

With the surge impedance of cables varying according to size and insulation type, discontinuities in PD propagation due to impedance mismatch are expected. Travelling wave theory can be used to calculate the transmission and reflection coefficients that indicate the relative proportions of the pulses transmitted or reflected at an interface made up of two different size cables. The change in pulse magnitude due to a cable interface and the attenuation along the cable length must be known to be able to find the original magnitude of a PD pulse.

Equation (2) calculates the current transmission coefficient for a 240 to 95mm$^2$ cable interface. In terms of pulse current, it shows that only about 80% of the pulse magnitude entering the interface will be transmitted to the remaining 95mm$^2$. For an interface made up of 95mm$^2$ to 240mm$^2$ cable, 120% of the pulse would be transmitted to the 95mm$^2$ cable as shown in (3).

$$\beta_{240\rightarrow95} = \frac{2Z_{240mm^2}}{Z_{240mm^2} + Z_{95mm^2}} = \frac{2*21}{21+33} = 0.778$$ (2)

$$\beta_{95\rightarrow240} = \frac{2Z_{95mm^2}}{Z_{240mm^2} + Z_{95mm^2}} = \frac{2*33}{21+33} = 1.222$$ (3)

**Attenuation Of Pulses Due To A Teed Connection (Cable Or Transformer)**

When a partial discharge pulse propagates past a teed connection, the pulse will change in magnitude and propagate down both paths. Two specific situations can be considered, one where the tee consists of a cable of significant length and one where the tee consists of a transformer connected by a short cable (the case found in a typical UK urban system using ring main units).

Taking the simple situation of one cable splitting into two, for a current of 1pu magnitude flowing into the junction, a current of 0.67pu will flow into each of the two cables. The significant attenuation of the pulse therefore further restricts the distance that a specific sensor can ‘see’ down a cable circuit when the noise level is accounted for. If the teed-cable is short in length (and therefore has a low travel time), there is also a possibility that a reflection from the end of the cable will cause distortion in the magnitude and shape of the pulse attempting to be measured.

Where a cable circuit is connected through a ring main unit and there is a short piece of cable terminated with a transformer, there is not likely to be a significant effect since for most frequencies the transformer will appear as an open-circuit. The impedance of an 11kV/415V transformer measured phase-to-earth is shown in Figure 3. The impedance does not reduce below that of typical cables (20 to 30O) until a frequency of some 300kHz. For a ring main unit consisting of a long cable and a transformer, the cable alone will dominate the effect on the partial discharge pulse.

![Figure 3 – Transformer open circuit impedance](image)

**IMPLICATIONS FOR ON-LINE AND OFF-LINE MEASURING SYSTEMS**

**Off-Line Systems**

In the typical off-line measurement of partial discharge using the time domain reflectometry technique, it is usual to plot a graph of pulse magnitude versus distance. The information presented above implies the following limitations in this technique:

- An error in the absolute magnitude of the partial discharges will result from attenuation of the pulses. Where multiple partial discharge sites are present in the cable circuit, it would not be possible to judge relative severities unless a suitable correction was made.

- When long cable circuits are tested, small partial discharge pulses may not be detected. Testing from both ends would help eliminate this problem. With an off-line system this implies the circuit will be disconnected from the power system for a longer period meaning more risk to the system security and higher man-hours of labour.

- For long cables, the use of time domain reflectometry would be difficult even if partial discharges can be measured. This is because of the increased attenuation of the reflected pulse that has, as a minimum, got to travel the full length of the cable circuit and sometimes almost double the length before it is detected.

**On-Line Systems**

For on-line systems utilising current transducers placed onto the earthed sheath of cables, the ambient noise level is likely to be significantly higher than the off-line case. There is also more likely to be an impact of power electronic / switching noise, transient in nature but high in magnitude, on the measurement system. The limitations
are, however, similar to those identified for the off-line system:

- An error in the absolute magnitude of the partial discharges will result from attenuation of the pulses. Where multiple partial discharge sites are present in the cable circuit, it would not be possible to judge relative severities unless a suitable correction was made (as before).

- When long cable circuits are tested, small partial discharge pulses may not be detected. Testing from both ends would help eliminate this problem. With an on-line system, the only real impact of this is on the initial installation and regular maintenance costs of the measurement system. It is unlikely that such a system would be applicable to XLPE cables as typical detection levels would not be low enough.

- If localisation of the partial discharge pulses is being attempted by examining the shape of the pulse, shape distortion due to reflections or noise will be problematic.

POSSIBLE SOLUTIONS

Matched Filtering

Detection of PD and location of the source under noisy on-line conditions has previously been shown to be improved by matched filtering [3]. A single filter is considered matched to a particular waveform if its impulse response is that waveform reversed in time. A bank of filters matched to different waveforms can be used to optimally detect which specific waveforms are present in a noisy signal. Using models of PD pulse propagation through different lengths of distribution cables [4], a matched filter bank can be constructed with different waveforms for different PD source locations covering the full length of a cable. Some sample model pulses are shown in Figure 4. Clearly received propagated PD become more alike the further along the cable they have travelled and in the presence of noise, the filter bank will select a variety of possible locations with the trend indicating the most persistent PD source.

A typical scatter plot combining matched filter detected PD pulse-shapes from successive measurements is shown in Figure 6. This shows a range of pulse shapes and relative amplitudes are present on the circuit.

A typical detected pulse is shown in Figure 7 along with the best matching propagated model PD waveform scaled to show best, the similarity.

The matched filter output can be conveniently shaped as a sequence of detected PD pulses. The basic elements of such a sequence are pulse locations (i.e., indexes for the best matching pulse shapes, e.g., 250m), pulse arrival times.
(i.e., arrival samples relative to start of longshot, e.g., sample 35,343), pulse ‘magnitudes’ (i.e., with some calibration, the estimate of the pulse magnitude scalings).

Other useful information could be bundled into the matched filter output. For example, actual noisy samples of each detected pulse (for further analysis, noise rejection etc.) or other measurements derived from these (e.g., time and frequency standard deviations [5]).

Matched filter output PD sequences can be used for investigations into separating multi-source PD, classifying incident and reflected pulses (with TDR), fault location by pulse shape, fault type vs PD phase (of power frequency), relative distribution of positive and negative pulses, pulse magnitudes, correlation to cable temperature, pulse repetition rates, eliminating PD-like disturbances and so on, tracking the various features over time. In this way, the matched filter output can support the basic efforts to relate PD measurements to assessment of condition of cable and accessories.

CONCLUSIONS

This paper has described how on-line and off-line methods used to detect partial discharge signals in paper cables can be affected by the circuit characteristics and the presence of electrical noise. The effect of attenuation down a length of cable, the impact of transformers and of teed cable sections has been described.

It is important to correct partial discharge activity measured at a substation to account for attenuation and to therefore give a truer picture of the real problems the cable may have. The use of matched filters to detect partial discharge signals within noisy environments has also been described.

REFERENCES


