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Citation for published version (APA):
Clark, D., Mackinley, R., Seltzer-Grant, M., Goodfellow, S., Renforth, L., McWilliam, J., & Shuttleworth, R. (2013). On-line partial discharge testing of some of the worst performing circuits on a utility distribution system. In *host publication* Electrical Insulation Association.

Published in:
host publication

ON-LINE PARTIAL DISCHARGE TESTING OF SOME OF THE WORST PERFORMING CIRCUITS ON A UTILITY DISTRIBUTION SYSTEM

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INTRODUCTION

The service performance of power cables depends on a number of factors, and as yet the quantitative dependence on the obvious factors has not yet been established. This is a clear failure of the research, but in the defence of the researchers, the dependence of the cable service life on the various factors, is not a simple cumulative outcome to establish. The other large difficulty is that the timescales for degradation and failure in cables tend to be very long. The cables often live longer than the researchers. In this paper we are looking at the relationship between failures in service, and partial discharge (PD) activity in power cables. In addition, we report progress in making locations of PD pulses using pulse shape methods. This allows simple measurements to reveal locations of PD events, and whilst this turns out to be not as accurate as the double ended methods (e.g. transponders etc), they are nevertheless a worthy addition to the armoury of diagnostics for high voltage cables.

In making comparisons of service performance of power cables, and the PD activity, there are several things which must be taken into account. Firstly, PD activity (especially in paper insulated cables), is the main reason for long term degradation of the insulation in power cables. Chemical changes of course exist, but these are generally associated with ingress of moisture or oxidizing agents, and are normally put down to mechanical failure [1]. Cracking of the outer lead sheath in paper cables is not normally regarded as an insulation failure (although clearly it must be in the end), and is really a mechanical failure of the cable components. In such a way, the very large majority of insulation failures in paper insulated cables (and to a lesser extent, polymer insulated cables) is due to degradation from partial discharge action [2].

Looking at the PD activity essentially looks forward to the death of the parts of the cable responsible for the PD activity. However, the service record looks back at the past performance of the cables, and only in a statistical way, will this be related to the future failure rates. Manufacturing defects distributed along the cables would be a case where the failure performance may also act as a predictor of future performance. In general, there is no such link, and this makes this study a bit like economics, where we know almost everything about the past, and are prepared to say almost nothing about the future. This paper is an attempt at reconciling the two views of cable performance, with the possibility of edging ahead of the economists in the prediction stakes.

PARTIAL DISCHARGE AND WORST PERFORMING CIRCUITS

One of our authors has helped to produce figures for the worst performing paper insulated lead covered (PILC) cable circuits. These are failure records for a consecutive number of years. They refer to both 11 kV and 33 kV cables. In this programme, some of the worst performing circuits were tested using the on-line PD methods from HVPD. From any given substation, testing all circuits on-line, allows for both the worst performing cables (i.e. our target cables), and the 'non worst' cables to be investigated. This has provided a mix of both of these cable types which is the subject of the present study.

TABLE 1 Failure Statistics for 113 circuits over 7 years

Total Circuit (km)	Average Circuit Length	Average No of Faults/Year	Average Faults/100km/Year
791	7.0	90.7	11.47

Table 1 shows the failure statistics for a set of 113 circuits over a period of seven years. Note the Average fault rate is over 11 faults/100km/year. For 'normal' circuits the failure rates would likely be 10 times smaller than this, but these cables represent the worst performing circuits.

We have introduced the more statistical idea of the chance of failure of a circuit, say P_i for any circuit i. This is simply related to the failure rate per 100 km/year as per Equation ii.

$$P_i = \frac{F_i L_i}{100} \qquad \text{(i)}$$

Where F_i and L_i are the circuit failure rates/100km/year, and circuit length (in km) respectively. From the failure statistics, i.e. the number of failures occurring in any particular year, we may draw out the chances of a circuit failing zero, one, two, three times etc. These are all directly related to P_i.

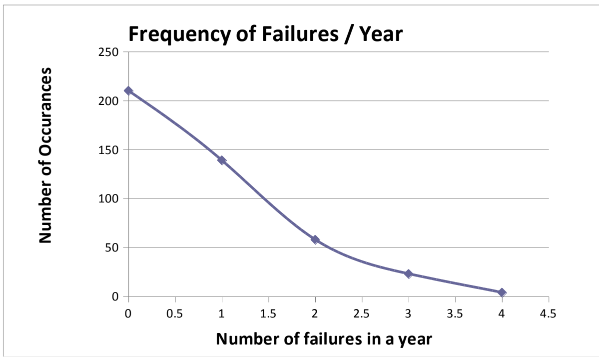

Figure 1 Cable failure occurrences, for 61 of the worst performing circuits over seven years

Figure 1 shows such a picture for 61 circuits taken over seven continuous years. The ratio of no failures to one failure is given by Equation ii.

$$P(F,1) = \frac{1 - P_i}{P_i} \qquad \text{(ii)}$$

From this the failure probability can be calculated, and hence the failures/100km/year. For the data in Figure 1, the probability $P_i = 0.398$. Using an average circuit length of 7.0 km, gives $F_i = 5.7$ failures/100km/year. Note that the data in Figure 1 is different to the data averages in Table 1, and the average circuit length for the data in Figure 1 is not known.

The interesting part about Figure 1 is that even in the case of the worst performing circuits, the most likely outcome is that in any particular year, the circuits do not fail. This may not be expected for the worst circuits in a distribution network.

In making a link between the failure records of circuits, and the PD measurements made on-line, some link must be made between the past failure data, and the future performance as measured by the on-line PD results. In this work, some 56 circuits were tested for on-line PD, 13 circuits of which were in the 'worst performing' list, and 43 circuits which were not.

Figure 2 High frequency current transformer sensor attachment

The on-line PD measurements were made using high frequency current transformers (HFCT's) on the cable earth straps, or the cables themselves, above the earth strap take off point. Figure 2 shows the typical arrangement for the HFCT's on an 11 kV installation. Note the requirement for an insulated gland to get good quality PD data.

The data of the PD testing is summarised in Figure 3, where the peak PD levels are shown for various PD magnitude bands.

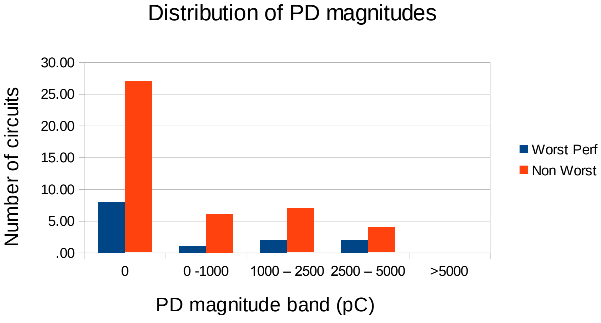

Figure 3 Distribution of PD sizes for 56 on-line 11 kV and 33 kV cable measurements

The cables cited in the worst performing circuits are clear, but those not in this class, are simply a random selection of circuits. In no sense are they 'best performing'.

To make some sense of the data of Figure 3, it should be established if there exists any statistical difference between the two classes of circuits (i.e. worst performing or not). To do this, one may use the ratio of the number of circuits with discharges to the number of circuits without discharges, and compare these between the two classes. HVPD has some rules of thumb about PILC cables, which states that any cable with less than 2500 pC of partial discharge activity is deemed to be within acceptable limits of PD activity. For our purposes, we have used a figure less than this, i.e. 1000 pC, on the basis that this should provide more sensitive results. Hence if we compare the number of circuits with PD less than 1000 pC with the number of circuits with PD over 1000 pC, the two classes of circuits should be directly comparable.

TABLE 2 Comparison of the worst performing circuits to the non-worst performing circuits

Circuit designation	Ratio = (No circuits < 1000 pC) /(No circuits > 1000 pC)
Worst performing circuits	1.8
Non-worst performing circuits	5.14

Table 2 shows the two ratios. Hence it is clear that the meaning of the worst performing circuits is clearly demonstrated in the on-line PD results. In making some simple deductions about the on-line PD data, the ideas of time to failure and PD initiation must be made.

It has long been argued that PD is the only long term deterioration mechanism for cable insulation. (this does not include sheath deterioration, and water ingress which are separate causes and only weakly related to long term deterioration of the insulation). If we make an assumption about an initiation rate say M_k, (k is a sort of cable position index) the rate of introduction of failure sites in a cable. If the time to failure of these sites are T_k, and of course we make no mention of the rates or gradients of T_k with time, then simple thought experiments leads one to the conclusion that the introduction of a T_k merely delays the appearance of a failure to a later date. If all the T_k's were short, or instant, then the failures would be distributed according to the initiation rate M_k. Looking at the PD data, for the non worst performing circuits (and actually to some extent the worst performing as well), the huge majority of circuits do not show any PD activity. This has the instant implication that if the long term deterioration and failure is PD related, the times to failure T_k must be short. If $T_k = 10$ years say, then the worst performing circuits would all show PD activity throughout their seven year failure data, and they clearly do not as over half show no PD at all. This implies that the time to failures must be short, and statistically less than two years to give the large majority of 'low or zero PD' results which are observed. This will only really be confirmed if the cables are followed up and future PD measurements made, confirming this behaviour. Anecdotally, there is some evidence that low level deterioration happens over a long time in PILC cables, followed by a much more rapid growth to failure. Confirmation of this (or not) would be a large advance in the understanding of circuit performance.

The next section is the important area of PD location using only a single on-line sensor.

PULSE PROPAGATION IN POWER CABLES

Power system transients such as PD pulses are often made up of a broad frequency spectrum, typically ranging from DC to MHz. Discharge processes produce fast-fronted, short duration pulses which propagate, with some frequency-dependent velocity along the cable conductor, and earth. Understanding how PD pulses propagate from the discharge site to the measurement position is important for locating defective areas of cable insulation, and also to assess the severity of the insulation breakdown process at work. Pulse amplitude attenuation and broadening ensure that as the PD pulse travels along the cable to the measurement point it becomes distorted from its original shape. Changes in the PD waveform are frequency dependent and are predominately due to skin-effect losses due to the presence of semi-conductive layers within the cable, which severely attenuate the high-frequency components of the PD pulses.

To describe the changes experienced by an individual PD pulse it is possible to use a form of the frequency-dependent propagation constant, given in Equation iii.

$$\gamma(\omega) = \sqrt{(R + j\omega L)(G + j\omega C)} \qquad \text{(iii)}$$

$$= \alpha(\omega) + j\beta(\omega) \qquad \text{(iv)}$$

Equation iv is another form of expressing the frequency-dependent attenuation (α) and phase constant (β). Incorporation of the basic cable elements, i.e. resistance (R), inductance (L), conductance (G) and the capacitance (C) into the formula allows the pulse attenuation, and broadening to be computed, if such parameters were all known. For many cables these parameters can be determined by measurement, but are generally not quoted by manufacturers. Instead the method adopted was to use the frequency-dependent transfer function given in Equation v to describe the distortion of the pulse.

$$H(\omega) = e^{-\gamma(\omega)l} \qquad \text{(v)}$$

$$= \frac{v(\omega)_l}{v(\omega)_0} \qquad \text{(vi)}$$

Equation vi represents the ratio of the pulses at some distance l and 0 (at source), both expressed in the frequency-domain. Pulse attenuation and broadening is determined by the behaviour of the real and imaginary parts of the transfer function given in Equation ii, which are directly related to the geometry of the cable and the dielectric properties of the insulation [3]. Splitting the transfer function into its real and imaginary parts is an application of Levy’s method, and can help to understand the behaviour of the parameters with frequency. As a PD pulse travels along a cable parameters such as the pulse rise time, fall time, width, amplitude and energy all alter due to the dispersive effects of the transmission line; a power cable in this case [4]. Exactly how these pulse parameters alter as a function of distance propagated is fundamental to making single-ended PD locations based on pulse shape analysis.

Applying the propagation constant in the frequency-domain allows estimations of PD pulse shape, and characteristics at various distances along the power cable to be approximated. Such pulse propagation modelling can assist in single-ended discharge site locations, and also help to understand the severity of the discharge location at source. Pulse injection experiments were initially carried out on RG223 co-axial type cable to establish the reliability of the pulse propagation modelling technique. Using the input pulse it was possible to replicate the pulse at 200 metres as shown in Figure 4.

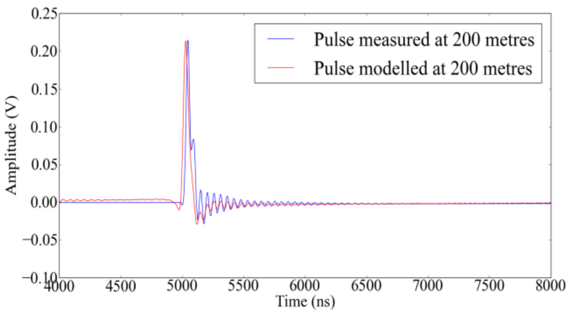

Figure 4 Measured and predicted pulses at 200 m

Given the co-axial structure of medium voltage power cables, it was possible to extend the pulse propagation modelling technique to actual power cables. The next section goes on to present two case studies from on-line PD testing on UK 33 kV distribution networks, where the discharge sites were located using time-domain reflectometry (TDR) techniques and also confirmed with the theoretical approach described above.

CASE STUDIES

Case Study 1 Partial discharge activity testing and locating on a UK 33 kV distribution network

On-line PD measurements were carried out on two 33 kV cables; cable A and cable B that supply step-down transformers, Tx A. Cable A is approximately 1762 metres long. Failures of the cables over the years has meant that sections of the PILC-type cables have been replaced with 25 metre sections of XLPE cable. Measured PD pulses from cable A are shown in Figure 5.

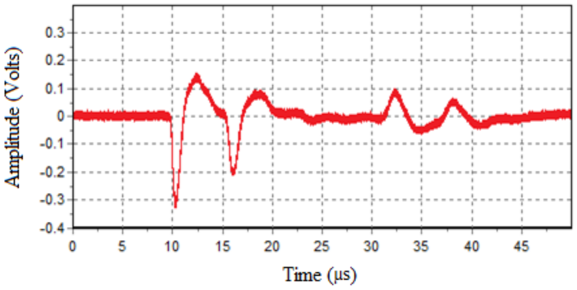

Figure 5 Partial Discharge Pulses measured on a 33 kV feeder - Cable A

Using a combination of the PD mapping software, and wave-shape analysis described in it was possible to determine the parameters of the individual direct, and reflected PD pulses shown in Figure 5, as well as an approximate location for the discharge site, and hence knowledge of approximate pulse propagation distances. From Figure 5 and it was possible to compute the parameters of each of the four pulses, thus allowing calculations of pulse parameters against distance propagated to be made. Although the reflection and transmission coefficients (Γ and T respectively) can distort the PD pulse shape, and parameters, the significant impedance of the transformer ensures that at the transformer end of the circuit, the pulse encounters what may be considered to be a virtual open circuit condition, and hence reflects and retains much of its energy. To illustrate the change in PD pulse shape with distance propagated, the increase in measured and simulated PD pulse rise time is shown in Figure 6.

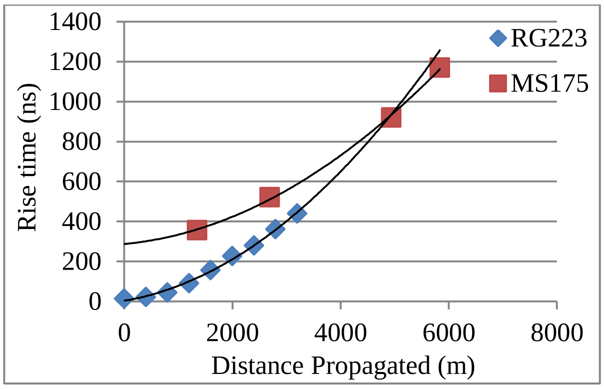

Figure 6 Simulated Pulse and PD Pulse Rise Time plotted against distance propagated

Polynomial curves shown in Figure 6 were fitted to plots of the simulated (carried out on RG223 co-axial cable) and measured PD pulse pulses. An increase in the pulse rise time with distance occurs due to attenuation of the high-frequency components of the pulse, which constitute the fast fronted edge of the pulse.

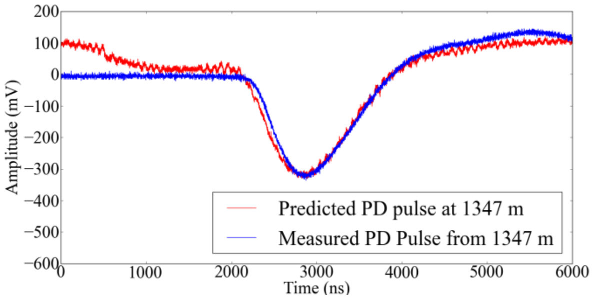

Figure 7 Partial discharge pulses measured and predicted at 1347 m from a 33 kV feeder cable

Figure 7 above shows the direct and reflected PD pulses as measured with a high-frequency current transformer (HFCT) sensor. Using the equations that describe pulse attenuation and broadening it was possible to reproduce the PD pulse measured at 1347 metres, based on the reflection from the far end of the cable.

Case Study 2 33kV Mixed Cable type circuits

Two 33/6.6 kV, 14 MVA distribution transformers; T1 and T2 are fed from a tee-cable circuit. Circuit 1 is

2677 metres long with 28 joints, and made up of a combination of 185 mm² PILC, XLPE and EPR cable lengths of between 150 and 3 meters in length, some dating back to 1930. Circuit 2 is 926 metres, 240 mm² Copper, XLPE cable with five joints and has been operational since 2001. High levels of discharge activity were detected by a pre-installed PD monitoring unit, which initiated a PD location project, the results of which are presented here.

Discharge location work shows that there were two active PD sites upon Circuit 1 at the following approximate locations, the first site was at 1564 m from the primary substation, and the second site at 1681 m. The locations may correspond to a trifurcating joints at positions 1575 m (SJ8699/27) from primary substation, and a further trifurcating joint at 1695 m (SJ8699/18). Figure 8 shows the PD location map indicating the two different sites of PD activity.

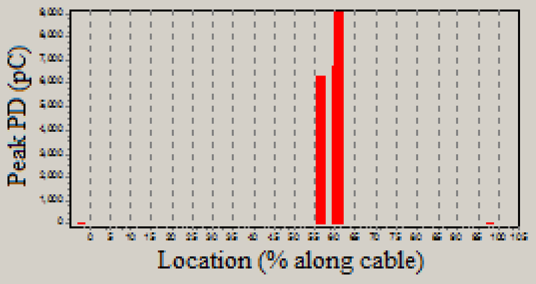

Figure 8 Partial discharge locations for Circuit 1

Location work revealed that the discharge sites upon the cable corresponded well to joints positions. Waveforms from the PD sites are shown in Figure 9

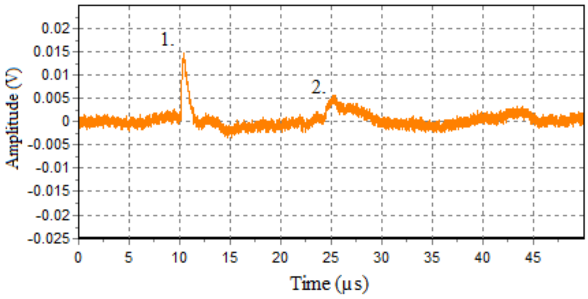

Figure 9 Partial discharge pulses from two different locations on Circuit 1

With reference to Figure 9, pulse 1 was determined to be from joint 27 at 1575 m, and pulse 2 from joint 18 at 1695 m. This case study shows the applicability of on-line PD location work.

CONCLUSIONS

A study of some of the worst performing circuits in a distribution has been made. On-line PD methods were used to characterise the circuits, and a comparison and analysis of the statistics and the PD data has been made. On-line TDR methods of PD activity locations have also been made, can be supported by single-ended pulse shape analysis.

The conclusions are as follows:-

- Statistics of failure of the worst performing circuits are presented which show that even for this class of circuit, the most likely outcome in any given year is no failures.
- The relationship between the probability of failure and the number of failures/100km/year is shown. The probability of failure is sometimes more useful in a statistical analysis.
- The difference between on-line PD results in the worst performing circuits, and the non worst performing circuits is shown. These show remarkable differences, implying that the PD results really do distinguish between the worst performing cables and not.
- From the number of PD measurements which were zero, or less than 1000 pC, it is clear that the time to failure of PD circuits must be relatively short, and typically less than two years from the initiation of a large PD site which eventually fails.
- The waveshape of PD events on PILC cables can be calculated from cable parameters, and used to calculate the locations of the PD events. These are not as accurate as transponder methods, but can be achieved with a single ended measurement.

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