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CONTINUOUS ON-LINE MONITORING OF PARTIAL DICHARGES IN HV DISTRIBUTION CABLES

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ABSTRACT

The most effective method of monitoring insulation condition in high voltage distribution cables is by continuous on-line partial discharge monitoring. However, on-site partial discharge measurement sensitivity can be limited by high levels of interference which can make it difficult to obtain and interpret adequate PD data for insulation assessment purposes. Differential circuit methods can be used to reject common mode interference but for high frequency non-conventional PD methods the standard balanced circuit will not produce satisfactory noise-free results, especially for medium or longer length power cables. A software based differential technique has been developed and has proved effective for on-line PD monitoring of power cables. The method gives good interference rejection and the sensitivity is suitable for assessment of both extruded and paper insulated cables. The monitor has been applied successfully to a number of various on-site cable systems in Australia.

KEYWORDS

Cables, Monitoring, On-line partial discharges, Insulation assessment.

INTRODUCTION

The high voltage cable distribution infrastructure in a power system is arguably the most important part of the power infrastructure. Because of the time and cost required for repairs of cable failures it is a necessary requirement that cables be reliable. The reliability is significantly determined by the presence of any defects in the insulation. Thus insulation assessment is a key factor, as in almost all high voltage plant. In most insulation materials the dielectric deterioration is normally accompanied by partial discharge (PD) activity and thus PD monitoring is the most effective and sensitive assessment method available. PD measurement is thus now very widely used for insulation condition monitoring in all items of high voltage equipment.

However in the case of XLPE cables the application of partial discharge methods for insulation assessment is not as apparently useful as in impregnated paper insulated cables. While paper insulation is relatively tolerant of some PD activity, XLPE (and EPR) insulated cables are not able to tolerate any significant PD activity for prolonged periods.

Different classes of HV equipment and their insulation systems can differ greatly in their capability to withstand PD activities [1]. Typically, paper insulated cables are able to withstand PD levels of several hundred or more pico-coulombs without significant effect on insulation life. However for XLPE cables the permissible (withstandable) PD levels are only some tens of pC.

In many substation environments the equivalent background electrical noise level may be one or two thousand pC. Thus the measured PD signals have to be extracted from this high level noise. For paper insulated cables it is possible to monitor PD levels with a sensitivity that is adequate for detecting PD levels that will cause damage to the paper (thousands of pC). However in the case of XLPE, damaging levels of PD activity fall some orders of magnitude below the typical PD sensitivity detection levels with such background noise levels. Even low levels of PD activity can cause breakdown in XLPE [2]. It is thus necessary to use noise reduction techniques for application with extruded cable PD monitoring. As XLPE is almost the universal choice of new distribution cable the assessment requirements for such cable necessitate the development of new and more sensitive PD monitors.

The problem is further compounded by the fact that although water tree growth in XLPE insulation, which is the most common form of degradation in XLPE, takes a very long time to develop, once the water tree changes to the electrical tree phase, the time taken for the dielectric to progress to full breakdown is quite short. Electrical trees will generate PDs, while water trees will not. As a result, while regular routine monitoring of PD activity may be adequate to provide sufficient forewarning of potential failure in paper insulated cables, in XLPE cables the water tree - electrical tree transition may progress to full breakdown in a time shorter than the intervals between regular routine PD testing. This rapid development to breakdown of electrical tree degradation requires the new PD monitors to be continuous and on-line.

As a result of this rapid deterioration of the XLPE and the general resistance of asset managers to providing more facilities for more frequent offline monitoring, the only option available is to use continuous online PD monitoring of cables. The additional constraint of the low PD tolerance of XLPE means that PD detection sensitivities have to be improved to allow detection of levels of at least 100 pC against possible background levels of the equivalent of some thousands of pC.

There have, in recent years, been a number of approaches used to improve PD coupler sensitivities, using a variety of filtering techniques, including hardware based methods and a number of software based methods including adaptive filtering, digital filtering, wavelet transform methods and software based differential methods. [2].

The ultimate goal of any PD monitoring is to provide information for the insulation assessment procedure, including determination of the current dielectric condition and also to provide some indication of any degradation trend over time. To achieve such goals, the characteristics of the insulation and of the partial discharge activity in the dielectric must be investigated fully in order to make an accurate insulation assessment and prognosis of the dielectric condition.

In modern partial discharge applications, such an attempt at a global analysis means that the PD activity must be detected, recorded and analysed fully in both the time and frequency domains using high frequency sensors that are capable of measuring PDs up to hundreds of MHz in frequency [3,4,5]. It is generally agreed that such non-conventional PD methods offer a much better indication and prognosis of insulation condition than the standard conventional PD monitoring approach as described in IEC 60270 [6].

Thus, the filtering techniques used to provide PD data to achieve such detailed analysis of insulation condition must be able to cover the full frequency range utilized by such methods and should also be able to retain the individual PD current pulse waveforms for frequency domain analysis after filtering. This requirement places some constraint on the interference rejection methods able to be used. Hardware-based methods such as differential monitoring using simple signal subtraction by a balanced circuit are limited because the very high frequencies used mean that even minor physical variations between the two sensing circuits will not allow the necessary subtraction to be achieved. For example Figure 1 shows a simple hardware based differential approach for two high frequency current transformer PD sensors which are ostensibly monitoring the same high frequency interference signal in a cable system. It can be seen that the subtraction of the two signals does not yield the required null result.

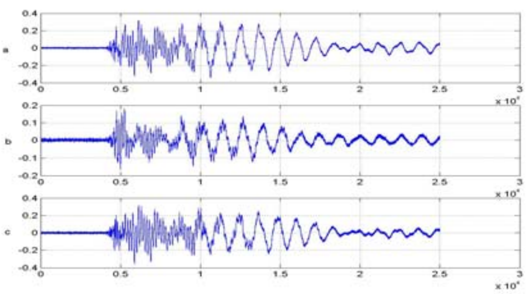

Figure 1. Differential monitoring with hardware
Figure 1a is interference captured from HFCT#1; Fig1b is the interference captured from HFCT#2 on the same cable; Fig. 1c is the simple subtraction of the signals shown in Figs. 1a & 1b.

However the application and achievement of the general principle of differential or balanced circuit monitoring is able to be realized at high frequencies by the use of software based techniques. These can analyse the monitored signals, taking any slight temporal differences due to slight variations in cable circuit characteristics into account and performing signal correlations to achieve true differential removal of interference.

This paper presents an application of a software-based differential technique for PD detection in an environment where there is a high level of electromagnetic interference. The method is particularly aimed at medium or long length cables. Conventional balanced differential circuits have been widely used and proved to be very effective for equipment with small dimensions such as CTs, power capacitors and short cables. However satisfactory results are very difficult for on site PD measurements on longer cables [7]. A comparison between the conventional balanced circuit and the proposed software method reveals the advantage of the software based differential technique to on-line PD detection. On-line PD detection is more desirable than conventional off-line PD measurement because of the potentially rapid deterioration of XLPE with PD activity. With on-line monitoring there is also no interruption to the normal service, no separate source is needed and it is non-destructive as it is conducted under the normal operating voltage and not at elevated voltage as in separate source testing. It also allows monitoring the PD behaviour trend and hence the trend of condition. The only disadvantage is the difficulty in performing calibration of the monitor.

The monitoring system described here has been used in a number of high voltage distribution substations in Australia and in Hobart and has achieved good sensitivity and results in cable systems at voltages ranging from 11 kV to 132 kV.

MEASUREMENT SYSTEM

The development and application of a software-based differential technique began with the investigation of PD activity in power cables in a major 33kV substation supplying a large industrial load. The typical 33kV feeder configuration is shown in Figure 2. Each phase comprises two 33kV XLPE power cables with duplication because of reliability concerns for a large steelworks supplied by the substation.

Figure 2. 33kV Feeder cable terminations

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The continuous on-line PD measurement system used for the software-based differential technique comprised two PD sensors with the same frequency response (to within design and manufacture limitations), a fast digital oscilloscope, a fast digitiser with large storage and a computer for recording and subsequent post-processing of PD data. The PD sensors are clip-on type high frequency current transformers (HFCT), which were clamped around the cable metallic screen - earth connection [8], as shown in Figure 3. The HFCTs are OEM type with measured frequency response up to 100 MHz.

Figure 3: HFCT PD signal couplers on 33kV cables

BALANCED CIRCUIT

The principle of the balanced differential circuit is well known. It has been widely accepted as a noise rejection tool for off-line testing using conventional (IEC 60270) PD techniques for many years. Theoretically the balanced circuit is a noise immune system. When two identical detection circuits are available, the differential method will facilitate PD testing with good noise immunity [9].

Six 33kV single core power cables in one three phase feeder were tested using a high voltage separate source supply. The length of the cables was about 170 metres. First, a single cable was tested at the system operating voltage with the conventional PD method. This showed that 500 pC level PD activity could be discriminated against the 200 pC background noise level at the site. In order to obtain higher sensitivity, two cables within the same phase were connected into a balanced circuit together with the PD input unit. The 200 pC background noise should have been eliminated by this hardware differential connection. However at the same voltage, the noise jumped to 1000 pC as may be expected from Figure 1. The measurement was repeated and gave the same result. Thus, using a balanced hardware circuit, instead of rejection of common mode noise, the noise increased to a higher level. The reasons for this are:

- Absolute balance over a large frequency range is very difficult, if not impossible;
- Exactly identical equipment, sensor or dielectric characteristics are impossible to achieve;
- At the higher frequencies, the external disturbances coupled into the circuit between the two cables are added in the bridge measurement circuit [9]
- A slight shift in time domain of the signals (signal travel times) means the common mode interference cannot be counteracted in two separate cables by simple subtraction of signals.

One of, or a combination of, the above reasons caused unbalance between the signals from the cables and thus did not allow true cancellation of the common mode noise. In addition to the above the long length of monitored power cable may act as an antenna to pick up more on-site EMI. The common mode interference coupled into the two separate power cables may have a slight time difference at the sensors because of different travel times. Thus they cannot cancel each other if they do not arrive at the balanced circuit simultaneously.

SOFTWARE - BASED DIFFERENTIAL TECHNIQUES

Figure 4 illustrates the principle of PD discrimination and noise cancellation by the software-based differential PD system used.

The two identical HFCTs are clamped around the cable screen – earth conductor [8]. They have been placed specifically with the same polarity as shown in Figure 3. Thus when any external interference (shown as signal #1) is coupled into the two separate power cables, this interference signal will be picked up by both HFCTs. The signal output from each of the two HFCTs should consist of a similar waveform with the same polarity.

An internal signal generated by a partial discharge in one cable only (signal #2 generated in cable C_B) then propagates to cable C_A. This PD (internal) signal will be detected by the two HFCTs with a similar amplitude but opposite polarities, if slight signal attenuation over the intervening circuit length is ignored. However, at the high frequencies used, the limitations of the balanced hardware circuit make it almost impossible to acquire two identical power cables or exactly identical sensors and connections with the same properties over the very wide PD frequency range used in modern non-standard PD monitoring systems. Thus it is not possible to totally suppress on-site noise by subtracting two such signals with the simple balanced hardware circuit approach.

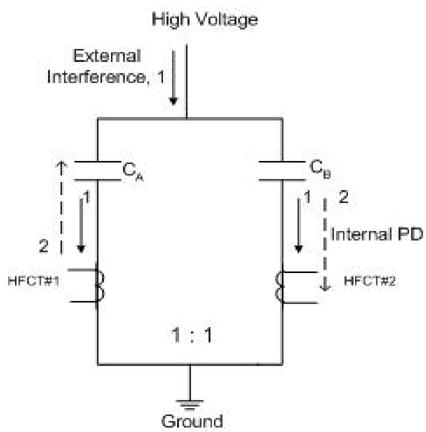

Figure 4. Principle of the balanced differential system.

The software based differential technique overcomes this problem. By using the concept and application of the correlation coefficient, a normalized measure of the linear relationship strength between the variables, the PD signals and the interference, can be discriminated.

The correlation coefficient γ_{xy} between two variables (signals) X and Y is defined as the covariance of signal X with signal Y divided by the product of the standard deviations of signals X and of Y, as shown in equation [1].

$$r_{xy} = \frac{\text{cov}_{xy}}{s_x s_y} = \frac{\sum_{i=1}^{n}(x_i - \overline{X})(y_i - \overline{Y})}{(\sum_{i=1}^{n}(x_i - \overline{X})^2)^{1/2}(\sum_{i=1}^{n}(y_i - \overline{Y})^2)^{1/2}} \quad [1]$$

The interference signals captured by the HFCTs should be similar with the same polarities. Thus the normalized correlation coefficient should be a positive number close to 1 for balanced interference and a negative number close to a magnitude of –1 for an unbalanced internal PD signal.

The absolute value of the normalized correlation coefficient γ_{xy} depends on the similarity of the two measured waveforms. The more similar the two waveforms are, the higher is the correlation coefficient magnitude. Even if the signals from two separate cables are not identical, or not balanced at all frequencies, which is required by the balanced hardware circuit method, they can still be discriminated with the correlation coefficient method. The slight time shift that occurs at these high frequencies can also be handled by the software based differential technique.

In general, any PD activity can be grouped into one of three possible discharge classifications: [3].

- corona discharge
- surface discharge
- internal discharge

To provide optimal usefulness, the PD measurement information obtained should not only provide the PD magnitude and phase angle details but also information about its potential severity with regard to its interaction with insulation material. A small but very concentrated discharge in a high field region may be very detrimental while relatively large discharges along a low-stressed surface can be relatively harmless [10].

For XLPE power cables, the internal PD is regarded as the most harmful process since it will develop rapidly and break down the insulation very quickly. Asset managers in industry may tolerate PDs of hundreds of pC in terminations of XLPE cables, but not for internal PDs in the main cable body where effectively no PDs are tolerated. This means that more sensitive differential techniques are needed.

OFF-LINE PD MEASUREMENT

Off-line PD measurements were conducted first in the 33kV substation using the separate source to confirm the validity of the proposed software method. First, sensors on two 33kV XLPE power cables were connected into the balanced circuit. The output of the balanced circuit was then connected to an oscilloscope. At 10kV, much lower than the PD inception voltage, there was no PD activity. The noise level was about 1000pc. The signal recording was triggered manually and is shown in the upper trace of Figure 5.

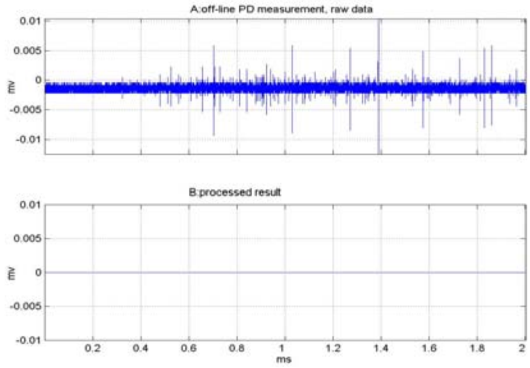

Figure 5. Recorded signal (upper trace) and differentially processed signal (lower trace).

Then the software based differential method was applied to analyse the data obtained from the oscilloscope. The PD monitors and circuit were as shown in Figures 3 and 4. The triggering level was set at 100pC. All signals whose magnitude was greater than 100pC were then captured and their waveform recorded. The captured waveform correlation coefficients were then calculated. The results for the major voltage transients in Figure 5 are shown in Table 1 below.

Table 1: Correlation coefficient of recorded off-line PD measurements for Figure 5

0.9197	0.9068	0.9107	0.9179	0.8849
0.8773	0.8856	0.9042		

Table 1 shows that all the correlation coefficients are all positive and close to 1 in magnitude, which means the waveforms compared are all simple common mode interference. This conclusion agrees with the measurement set-up, where the voltage was 10kV, too low to initiate cable internal PD activity. Thus any waveform captured would not come from cable itself, as in Figure 5, lower trace.

ON-LINE PD MEASUREMENT

The software based differential technique was also implemented for on-site on-line PD measurement. The measurements were carried on the feeder cable immediately next to that one used in the off-line PD measurement described above. The aim of the test was to reject the external interference and to investigate any possible internal cable partial discharge activity. The PD measurements were able to be conducted on-line without any interruption to service, using the clip-on HFCTs.

On line calibration still remains a challenge to the application of such on-line PD measurements. In these tests on-line calibration was performed by comparing the signal magnitudes with the off-line calibration results. In the tests described for medium or long length cables, or large capacitance items, the load has very little effect on the PD magnitude when the signal is captured by the HFCT [11]. In this case with on-line application, maximum signal levels were detected at around the 1000pC level as shown in the upper trace of Figure 6. The total signal comprised a high level of background interference coupled through any of: radiation, the earthing conductor, possible termination discharges and internal cable PDs.

The software based differential method was then applied to the data. The signal recording was adjusted to be triggered at the 200pC level and the typical results obtained are shown in Figure 6 below. The upper trace record is the total unprocessed signal as monitored and the lower trace is the differential signal obtained after processing. As before, correlation coefficients were calculated for the pulse signals detected.

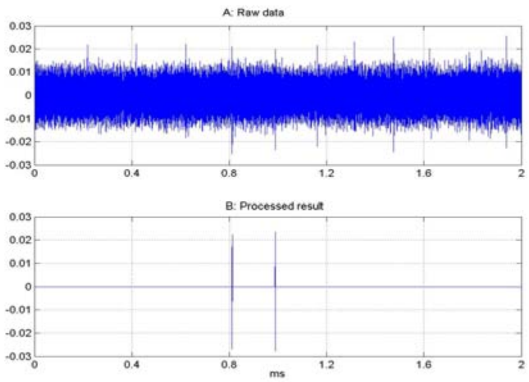

Figure 6. Differential on-line PD tests on 33kV cable.
Upper trace is recorded signal with noise. Lower trace is signal after differential processing

The correlation results are shown in Table 2 below and show correlation coefficients of all signals with magnitude greater than 200pC. The common mode interference signals were removed and true PD signals were retained in the lower trace of Figure 6. As can be seen from the correlation coefficients only two instances of PDs were detected.

Table 2: correlation coefficient of on-line PD measurement for Figure 6

0.6214	-0.5190	-0.4633	0.6135	0.5400
0.2500				

Figure 7 shows another result with the intervening stage shown. The upper trace is the recorded signal and the middle trace shows the potential PD signals after initial processing. The lower trace shows the final correlation result with only a small number of confirmed PDs.

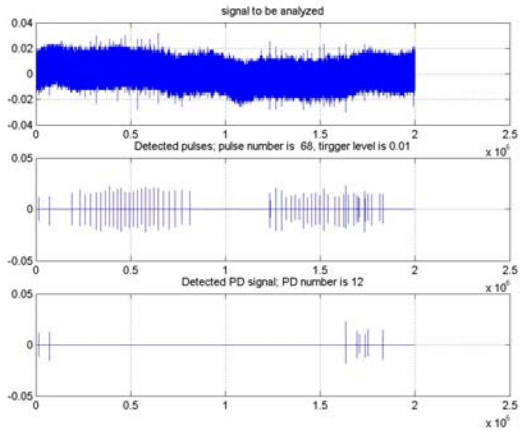

Figure 7, Extraction of PD signals

Triggering of the system at a level less than 200pC was also been attempted. However, due to the high interference (and consequent poor SNR below 200 pC), signal oscillation and overlapping, the coefficients calculated gave very small values close to zero, which makes it not reliable to use as a criterion to distinguish internal PD and common mode interference. Because of excessive interference, threshold setting by less than 200 pC also caused triggering and capture difficulties. Thus 200 pC remained the de facto minimum sensitivity level for these tests.

HYDROGENERATOR CABLE PD TESTS

The differential system was used on a number of different applications and proved to be able to achieve best results in detection of PDs from background noise. Figure 8 shows the results of tests performed on the stator output cables of an 11 kV hydrogenerator in Tasmania. The hydrogenerator had IRIS stator slot coils installed and these were able to be used to gate the PD activity so as to assist the cable PD sensors to determine when there was PD activity in the stator. This allowed detection of PD activity in the cables.

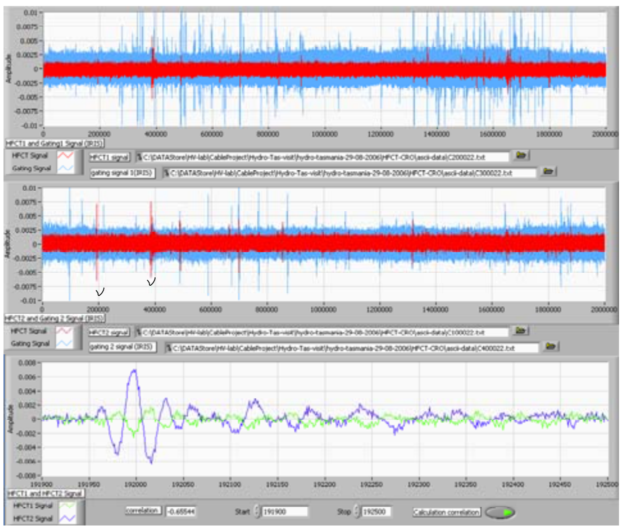

Figure 8, PD activity in a hydrogenerator stator.

In Figure 8, the top trace is the HFCT #1 signal (red or lower noise amplitude signal) buried in the IRIS signal (blue) which is used to gate the HFCT from the stator PDs. The middle trace is the signal from HFCT#2 with also a gating signal. The two CT signals are processed differentially to get the third (bottom) trace which shows a correlation coefficient of – 0.66, indicating a probable PD signal.

CONCLUSION

The software based differential technique described here achieved good results for rejection of common mode interference. It has a great advantage over the conventional balanced circuit, especially in PD measurements on medium or long power cables.

The proposed method can also be implemented in on-site and continuous on-line PD measurement. This capability makes it more desirable than off-line PD measurement techniques as it does not require interruption to the normal service. This method could also be used for monitoring the insulation long-term deterioration trend if the sensor system is installed permanently.

Apart from the difficult on-line calibration issue, there were problems with the triggering process, which limited the sensitivities to about 200 pC. In poor SNR situations, excessive interference causes unwanted triggering. A smarter triggering system and better post-data processing by the software based differential technique is currently being developed by the authors to improve this method.

The sensitivity level of 200 pc achieved is however a reasonable level to provide useful PD information on degradation even in the case of XLPE and EPR cables.

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