CABLE DIAGNOSIS USING VARIABLE FREQUENCY AND PARTIAL DISCHARGE DIAGNOSIS WITH DEFECT LOCATION AND CHARACTERIZATION

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Abstract

A new approach to cable diagnostics is discussed in the present paper. It combines the advantages of testing with variable frequency over non standard wave shapes for commissioning and diagnosis on cable systems with a partial discharge measuring system based on the apparently well assessed measurement and location of partial discharges activity in cables, but with innovative and substantial diagnostic value added.

The different methods for condition assessment on power cables based on different wave shapes are compared to testing with line frequency, and a variable frequency system for testing medium voltage cable is described.

The working principle of this new diagnostic system is described and its potential on the example of a paper-oil insulated cable, where artificial defects have been previously introduced, discussed.

1. Introduction

The on-site testing of cables has to check the insulation condition after-laying and assembly of cable systems, as well as ageing of cables and accessories, since the performance of the cable and accessories was tested during the type and routine tests in the factory [1]. The after laying test of new cables fills the “quality assurance gap” between the type and routine tests of the cable at the manufacturers site and the commissioning of the complete cable system on-site [2].

During the assembly or repair of a cable system, defects of the cable sheath and misassembly of joints and terminations can occur. Installed cables are, moreover, subjected to aging, either natural or forced, due to temporary extreme circumstances (overload, overvoltage...), degradation under design stresses (particularly electrical and thermal) or other factors of influence (digging, water...). In order to increase the reliability and reduce costs due to condition based maintenance, the insulation condition and the future serviceability of old cables has to be assessed either on-line or off-line.

First attempts using DC voltage, which shows good results for mass impregnated cables, were not successful for AC cables due to the different electric stress distribution for AC and DC. Under DC, electrical field is controlled by the electrical resistivity, contrary to the situation under AC, where mainly the permitivity is relevant [4].

To combine the advantage of testing near the power frequency and a low necessary testing power, on-site test systems with variable frequency have been developed, for both medium and high voltage cables.

The system is further enhanced by adding a partial discharge measuring system suitable for on-site use, since partial discharges (PD) measurements constitute one of the most promising tools for the evaluation of localized defects and damages. The PD system uses most advanced statistical elaboration tools and fuzzy logic techniques to obtain an efficient noise rejection and a high performance diagnostic value.

At present, the diagnostic procedures mostly adopted for cable evaluation are based on an off-line approach to the condition assessment process: the cable being checked has to be de-energized and disconnected from any source or load from all terminals and energized with a separate voltage source.

The condition assessment of the power cable using the system object of the present paper consists in energizing the cable with a voltage stress having a value in the range of U_0 to $2U_0$ and in performing the measurement of the PD activity. The PD signal acquired is subjected to a preliminary elaboration, called *classification*, in which the complex patterns acquired are classified in homogeneous subassemblies, having in common the same kind of PD source; successively the complex pattern is subjected to a *separation* process, allowing the original pattern to be split into different sub patterns; each one of them is relevant to one class characterized by homogeneous pulses; the further step is the *identification* of the defect generating PD belonging to each class. An advanced tool for the *location* of the defects along the cable route is also integral part of the system, thus allowing to point out the presence and position of weak points and to give guidance to the cable repair working teams.

The features and the characteristics of the diagnostic system based on advanced PD analysis and variable frequency excitation source will be analyzed and discussed in the following sections.

2. Comparison between different voltage shapes

To compare the effectiveness of the different solutions, developed since the late 80’s to overcome the necessary size of 50/60 Hz test systems, a lot of research work has been done [4,6,7,9,10,11,12].

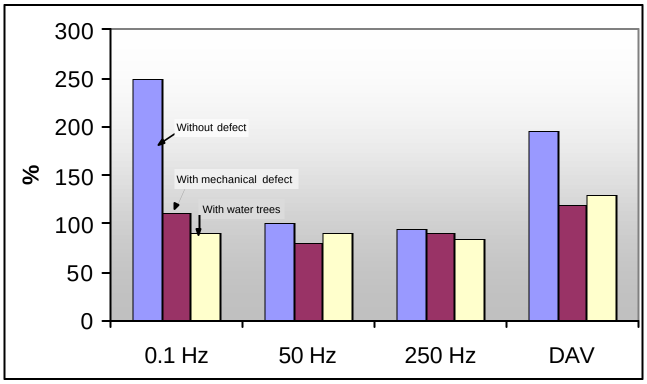

Fig. 1: *Related breakdown voltage at different wave forms [9]*

Figure 1 shows the results of breakdown tests with sinusoidal voltages from 0.1 Hz to 250 Hz and Damped Alternating Voltages (DAV) with different type of defects on model cables. It shows that the breakdown voltage for the different defects between 50/60 Hz and 250 Hz are very close and the breakdown mechanism should be the same.

The sensitivity for defects is higher for 0.1 Hz and Damped Alternating Voltages (DAV) but the absolute test value is higher and the breakdown mechanism is different compared to voltages of power frequencies[9].

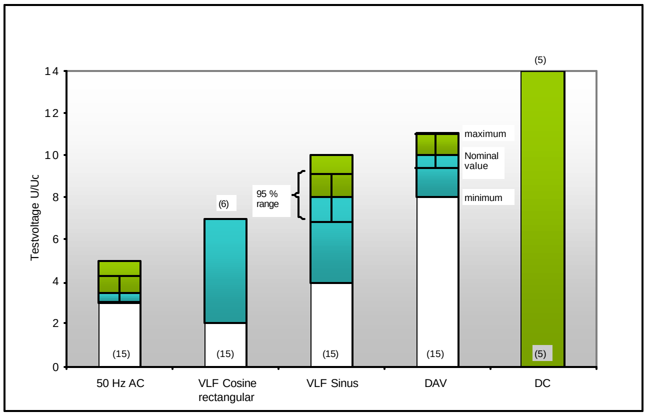

Fig.2: *Residual breakdown strength of service aged 10 kV cables (11years, 6m), vented trees at outer semiconducting layer, 85% bridged insulation [8]*

Figure 2 shows the residual breakdown strength of service aged cables with vented trees at the inner semiconducting layer and 85% bridged insulation achieved with the FGH step test.

The breakdown strength is still quite high even after 85% of the insulation is already bridged and that the values for 0.1Hz (VLF) and oscillating voltage are between 1.4 to 2.5 times higher compared to 50/60 Hz.

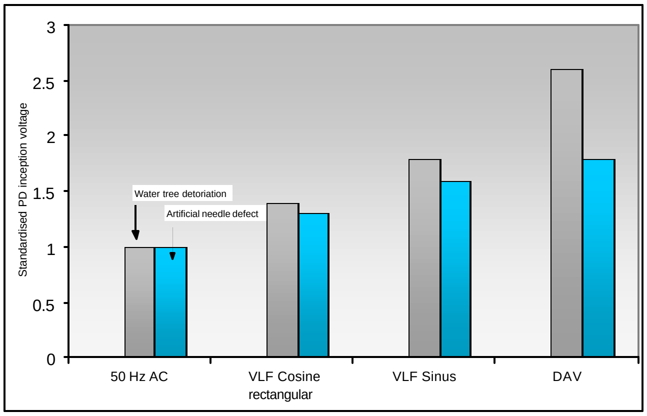

Fig.3: *PD inception voltage of service aged 10 kV XLPE veins with artificial needle fault or water trees [8]*

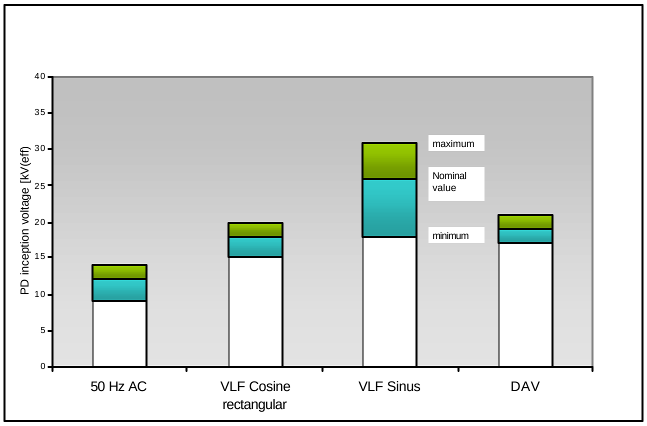

Fig. 4: *PD inception voltage of new, dry 10 kV XLPE veins with artificial needle fault (tip radius 5 µm, distance 1.4 mm) [8]*

Figure 3 and 4 show the PD inception voltage of service aged 10 kV XLPE cable veins with water tree deterioration and artificial needle faults (Fig. 3), as well as new, dry 10 kV cable veins with an artificial needle defect (Fig. 4).

These values are achieved with a step withstand time test during which after a 60 min test a PD test at 1 U_0/50 Hz is performed. As long as the PD value is still <1pC the voltage will be increased by 1 U_0 for another 60 min.

The PD inception voltage is, depending on the type of defect, between 1.4 to 2.5 times higher for 0.1 Hz and oscillating voltage compared to 50/60 Hz.

When testing with 50 impulses of oscillating voltage a risk of an unwanted pre-damage of the cable may exist [8].

Figures 5 and 6 show the channel growing rate of a needle fault, with PD measured at the different voltage shapes, as a function of the applied test voltage. It is shown that a medium voltage cable test without a PD measurement should be done for the shortest possible time, depending on applied field and shape and location of the defect, to avoid a later failure of the cable due to an electrical tree initiated during the test, but not grown through the insulation because of insufficient testing time It can also be seen from the different behaviors that the breakdown mechanism is different which complies with findings in [9].

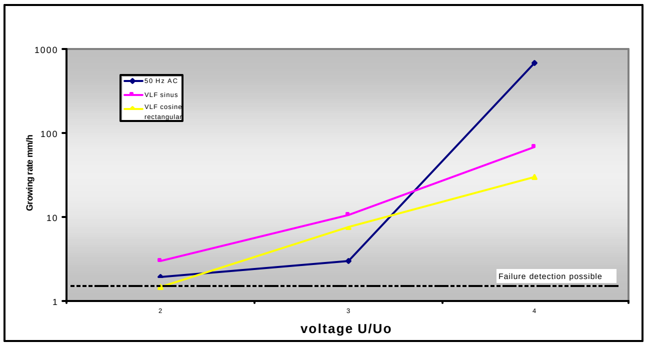

Fig. 5: *Channel growing rate of needle fault with PD on new, dry 10 kV XLPE cable veins with different voltages [8]*

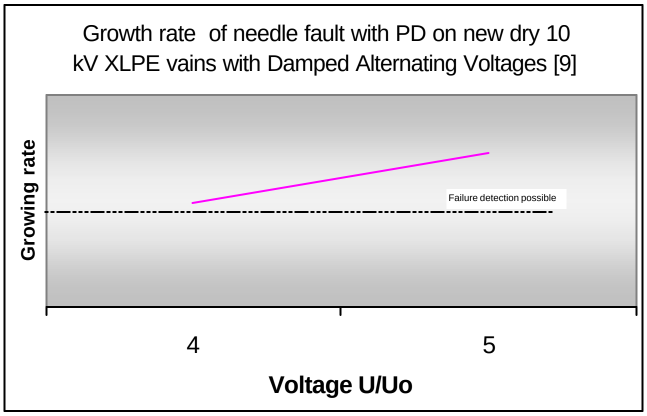

Fig. 6: *Growth rate of needle fault with PD on new, dry 10 kV XLPE cable veins with oscillating voltage [8]*

3. Test systems with variable frequency

3.1. Principle design

Due to shortcomings of the alternative and DC voltage sources discussed above and to be close to the line frequency, resonant test sets with variable frequency have been developed.

The test system mainly consists of the frequency converter, the exciting transformer, the coupling capacitor and one or more high voltage reactors with fixed inductance. Figure 7 shows an example of a high voltage system with one reactor.

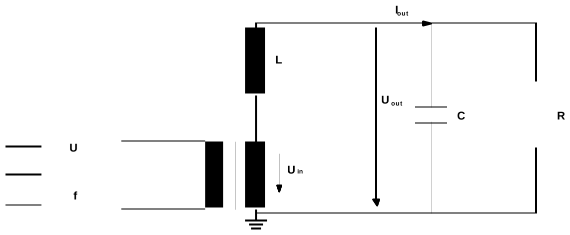

Fig. 7: *Schematic diagram of a resonant test circuit with variable frequency*

The 3-phase loading reduces the necessary supply capacity compared to a single phase load of the same size. The frequency converter, supplied with 3-phases, generates a 1-phase output with variable voltage and frequency which is applied to the exciter transformer. The exciter transformer excites the series resonant circuit consisting of the reactor inductance L and the cable capacitance C. The resonance is adjusted by tuning the frequency of the frequency converter according to the usual expression for series resonance:

$$f = \frac{1}{2\pi\sqrt{(L \times C)}}$$

The frequency range of the test system is, hence, determined by the expected capacitance range.

$$\frac{C\max}{C\min} = \left(\frac{f\max}{f\min}\right)^2$$

The quality factor "Q" of the resonance test system determines the relation between testing power and the required power supply. For XLPE cable testing a system quality factor in the range of 100 – 150 and for paper insulated cables in the range of 50 – 90 can be achieved [3]. The high quality factor of the high voltage reactors leads therefore to a compact and lightweight system design.

3.2.1 Examples for system layouts

Medium Voltage Cable Testing equipment still fit in a standard light truck depending on the length of cable to be tested.

	1 reactor
Nominal voltage	60 kV with taps @ 24kV and 18kV
Nominal power	300 kVA
Max. test load	442 nF @ 60kV, 2.76uF @ 24kV
Frequency range	30 Hz – 300 Hz
Tuning – range	1 : 100
Load duty cycle	60 min ON/60 min OFF. 6 x a day
Weight Reactor	1,550kg
Weight Excitation X-FMR	385kg
Weight Control / PS	275kg
Total Weight with Truck	< 5,000kg

Table 1: *Technical data of a medium voltage resonant test system.*

A system for testing medium voltage cables, designed to test about 2.5 km of cable together with partial discharge measurement and to fit in a standard van is described in table 1. This cable length has been chosen because of the reduction in measuring and locating sensitivity with increasing cable length [5].

4. PD measurement

The results of the current test practice show that with the usual test levels, e.g. 2 Uo /10 min, only extremely damaged cables can be found with a voltage test only, but a further increase of the voltage level will also unnecessarily increase the stress in the termination [3]. Therefore a voltage test should be accompanied by a sensitive PD measurement to keep the necessary voltage levels low and to find weak points that may develop in failures with time under service stresses. With PD measurements, local defects, like voids or weak points at the interface between cable insulation and accessories, can be detected.

Due to the disturbances generated by the network itself (e.g. corona discharges), radio transmitters and the frequency converter disturbances, on-site partial discharge measurement and detection requires a different solution than laboratory PD measurements.

4.1 Measurement system and diagnostic tools

In the following the features of the new diagnostic system based on PD detection, in terms of noise rejection, PD source location and diagnostic effectiveness, are described.

4.2 Classification

The classification consists of separating the contribution of the different sources generating the recorded PD (generally summarized in a pattern reporting PD height vs. acquisition phase). The solution employed in the new diagnostic system is to implement a fuzzy classifier in order to separate different PD phenomena according to the pulse shape of the discharges, under the assumption that discharge signals due to different sources are, generally, characterized by different pulse shape. Noise rejection, too, can be achieved thanks to this classification process, since it occurs, in general, that signals generated by background noise or external disturbances are significantly different in shape from PD signals generated within the equipment under test. This result allows homogeneous classes of data to be treated separately through advanced statistical and artificial intelligence tools, so that an identification process can provide the recognition of background noise, disturbance or whatever PD phenomenon [13]. The following example will explain more in detail the classification procedure. Data are acquired and processed by a specific software that enables the visualization of the usual 3D PRPD pattern, as reported in Fig. 8. Each acquired pulse (corresponding to a single dot in the pattern) is processed in order to extract its most salient information. For this purpose, two conventional pulse parameters, that is, T "equivalent time length" and W "equivalent bandwidth", are calculated and reported in a 2D map, the "classification map" [14].

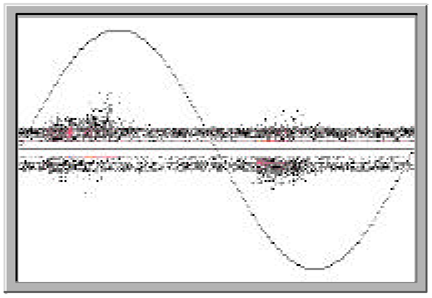

Fig. 8: *Example of PRPD pattern of an entire acquisition.*

Fig. 9 shows the classification map that results from the feature extraction procedure applied to the data whose pattern is reported in Fig.8.

The classification map is then processed by a fuzzy algorithm that generates different clusters of data (feature classification).

This procedure allows the original PRPD pattern to be split into different sub patterns; each one of them is relevant to one class characterized by homogeneous pulses (separation).

An example of the results of the separation process is reported in Fig. 10 (referring, again, to the pulses collected in Fig. 8).

As illustrated in Fig. 10, the classification map singles out the presence of different discharge distributions corresponding to groups of pulses characterized by different waveform shapes; therefore a single "cloud" in the classification map is associated to its characteristic pulse shape and identifies a sub-pattern composed by shape-homogeneous pulses. The final result is the separation of the original pattern into different pulse-homogeneous classes (sub-patterns), which can be treated separately for effective processing and diagnostic purposes (Fig. 10) [14].

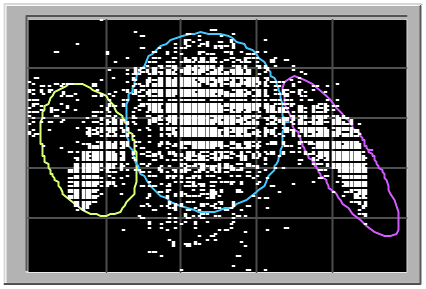

Fig. 9: *Classification map. Each point corresponds to a single pulse. The three clusters are relevant to pulses having different T,W features.*

4.3 Identification

The further step is the identification of the defect generating PD belonging to each class, which is the basis for noise rejection and enhanced diagnostics. Statistical processing of PD pulse phase and amplitude distributions is carried out in order to achieve identification and, possibly, derive diagnostic markers.

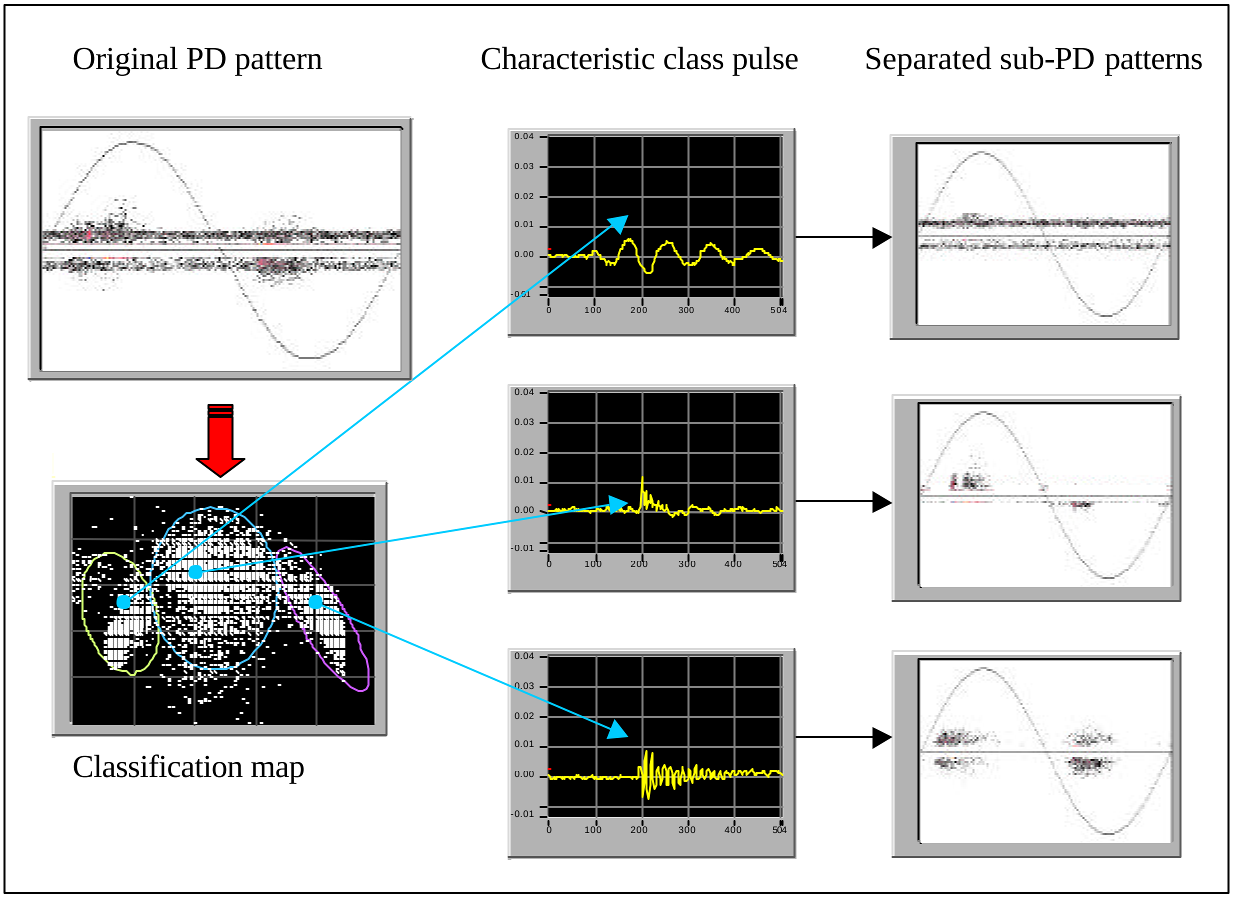

Fig. 10: The separation process: starting from the original PD pattern, the classification map is derived and classified in different clusters corresponding to different sub patterns, each one characterized by homogeneous pulse shape discharges

One of the statistical tools available derives from the application of the two parameter Weibull function to the whole set of PD height values, as well as to each single class provided by the fuzzy classifier. The two parameter Weibull distribution of PD pulse height is given by the following expression:

$$F(q) = 1 - \exp\left[-\left(\frac{q}{a}\right)^{b}\right] \qquad (1)$$

where q is the pulse charge height, α and β are the Weibull function scale and shape parameters.

The estimation of β (eq. (1)) is particularly significant for PD identification purpose, since β is associated with the physics of PD phenomena [13].

Other identification and diagnostic markers come from the evaluation of parameters such as: the rate of PD occurrence, the phase distribution range, the maximum and minimum discharge amplitude, NQN (area under the curve of pulse repetition rate as a function of pulse magnitude) [15] and other indexes calculated on the basis of the histogram of the time elapsing between consecutive discharges [16].

All these parameters are processed through fuzzy logic tools, in order to achieve identification associated with a likelihood estimation ranging between 0 and 1 (which fits human brain evaluation processes).

Special routines have been also arranged in the innovative PD system in order to identify background noise, as well as peculiar external disturbances. Noise recognition has not a unique solution, so that it must be approached by devising various techniques, each one tailored for a specific kind of noise. At present, experimental evidences suggest that random noise and noise due to AC/DC rectifiers are the most common disturbances that need to be rejected during on-field measurements (e.g., in substations, industrial environments, etc.). Background random noise is treated by investigating the lack of correlation of its phase distribution with the supply voltage wave, while the noise due to AC/DC converter units is recognized by means of special routines that identify the peculiar correlation of its phase distribution with the supply voltage waveform [17].

A scheme of the complete identification procedure is shown in Fig. 11

4.4 Location

The acquisition procedure (“location mode”) allows a PRPD pattern to be built, which is then processed, classified and identified. However there are some fundamental differences with respect to the “pattern mode”. The two modes differ for the timebase used to capture PD signals: large timebase in location mode, in order to capture the signal and its reflections, short timebase in pattern mode, in order to

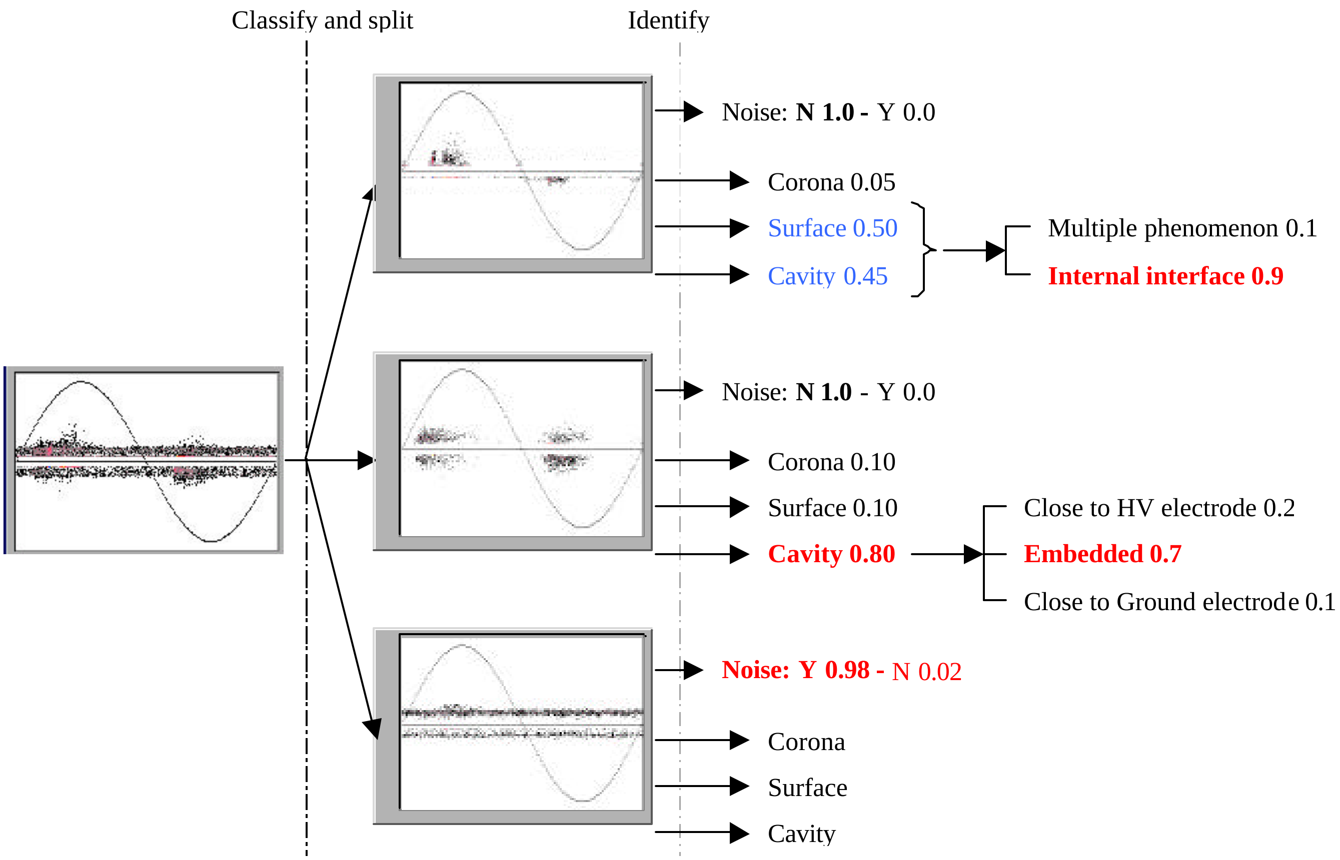

Fig. 11: *Example of the complete identification scheme. In bold (red) the PD source identified as most likely by the diagnostic system. In italic an uncertain identification. The numbers from 0 to 1 correspond to the attribution rank given to a class by the fuzzy algorithm*

record the details of a single pulse waveform. This distinction permits different source identification procedures to be applied.

Experimental results show that when pulses are acquired in sequences (due to a large time base), the fuzzy classification tool mainly distinguishes groups of sequences on the basis of the position of the intermediate pulse. This means that the classification tool is able to separate the data relevant to different discharge sites. As a result, homogeneous clusters of data are obtained, each one containing all the pulse sequences coming from the same discharge site. Once the first separation procedure has been carried out, a further analysis is required before proceeding to the identification phase. In fact, more than one PD phenomenon could be active in the same cable section. In order to distinguish among PD activities taking place in the same cable section, the shape of the first pulse of each sequence is taken into account for each location cluster; thus, data are reduced as if acquired in “pattern mode” (see Figs. 9,10) and a further classification procedure can be carried out on the basis of these pulse shapes. In such a way a complete separation of all PD phenomena active in the cable may be carried out, and for each one of them the identification is provided by appropriate routines of the system.

Limitations to this approach are, of course, related to cable length. In fact, above a given length (varying as a function of type of insulation, cable and rated voltage) defects are hardly inferred due to signal attenuation and dispersion, which may not allow to carry out separation within a located pattern.

5. Experimental Result of a paper-oil cable

Partial discharges incepted at 7 kV; the location tool indicated the presence of a defect at 130 m from the measuring point (the cable length was 194 m). At higher voltage values (over 18 kV) other pulses were detected at 65 m from the measuring site.

Hence, two different cable sections resulted as affected by PD, in correspondence to the artificial defects, positioned 65 and 130 meters away from the cable termination, respectively. The location result is shown in Fig. 10, while the PD pattern including discharges from both defective sections is reported in Fig. 11.

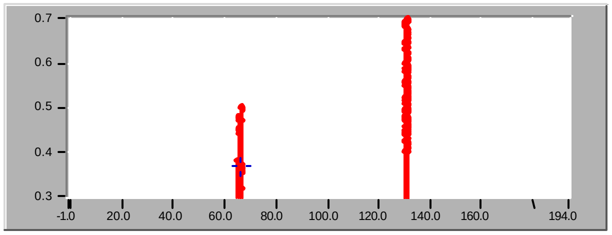

Fig. 10: *Location map (acquisition carried out at 24 kV).*

The fuzzy classification tool applied to pulse sequences (“location mode”) singled out the presence of two phenomena occurring in different cable sections, that correspond to the two located discharge sites.

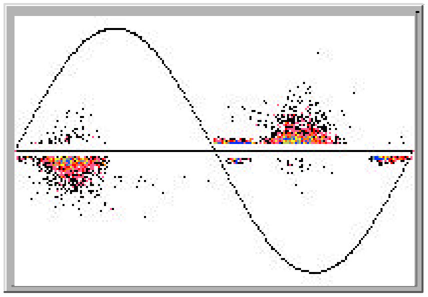

Fig. 11: *Pattern relevant to the acquisition performed at 24 kV on paper-oil cable*

Thus, the whole data set (Fig. 11) can be separated into two sub patterns, Figs. 12 and 13, relevant to the defect located at 65 m and to that at 130 m, respectively. The separated sub patterns can be processed one by one, in order to get the identification of the defect generating PD. Of course, indications could be also obtained by processing separately the patterns achieved between 7 and 18 kV, when only one PD source is active.

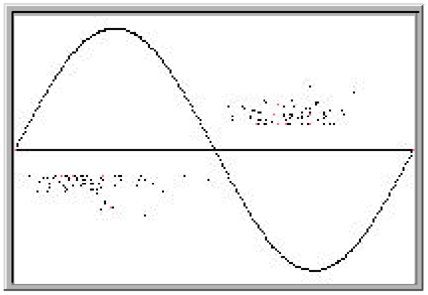

Fig. 12: *Sub-pattern acquired at 24 kV and relevant to the PD phenomenon located at 65 m.*

The analysis of the pattern reported in Fig. 12 (regarding the defect located at 65 m), as well as other patterns relevant to the same phenomenon acquired at higher voltage values, indicates the presence of internal discharges. This indication matched the nature of the artificial defect inserted in the joint (a metallic nail inserted and, then, slightly retracted in the joint). However, it must be noticed that a reliable inference about the nature of the source generating PD was very difficult because of the high inception voltage and the consequent small number of recorded discharges.

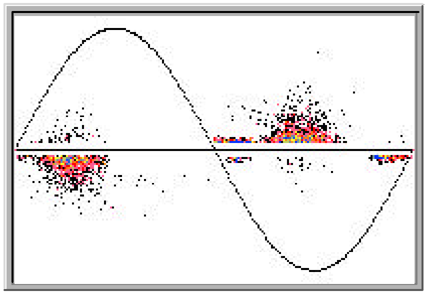

Fig. 13: *Sub-pattern acquired at 24 kV and relevant to the PD phenomenon located at 130 m.*

6. Conclusion

The experience of testing with variable frequency, and several other laboratory tests on aged cables shows the advantage of testing new and old cables with frequencies in the range of 30 – 200 Hz.

A sensitive PD measurement performed simultaneously with the voltage test increases the significance of an on site test of laid cables. If a sensitive partial discharge locating system is used a reduction of the test levels can be expected.

The purpose of this paper is to show how an effective and complete diagnostic evaluation can be carried out on medium and high voltage cables by means of an innovative approach, consisting in the integration of reflectometric technique and advanced diagnostic procedures in the same system. In favorable conditions, i.e. when PD pulses are not excessively damaged and distorted, a double goal can be achieved: location from one side, separation and identification from another side.

It is worthwhile to recall that one of the major concerns regarding the reliability of diagnosis made through PD measurements is the lack of identification of the kind of source generating PD (not only of the source location). The approach here proposed constitutes a considerable step forward in making available reliable diagnostic indicators and rules to allow effective maintenance programs to be planned.

Integration of the resonant system with the innovative PD tool and experimental validation are in course, since it is thought that the complete system thus resulting may enhance significantly diagnostic and maintenance processes in paper-oil and polymeric cables.

References

[1] K. H. Weck, „Prüfung von Kabelanlagen vor Ort“, Elektrizitätswirtschaft Jg 92 (1993). Heft 11

[2] J. Rickmann, P. Schikarski, „On-Site Cable Testing with Variable Frequency”, Haefely, IEE, National Grid Seminar “New Measurement Techniques for Electricity System Diagnostics”, April 29, 1999, Leatherhead, UK

[3] P. Schikarski, M. Gamlin, J. Rickmann P. Peters, P. v. d. Nieuwendijk, R. Koning, “Two years of experience with a mobile resonant test system for testing of installed medium- and high voltage power cables”, 11th ISH, London 1999

[4] C. Aucourt, W. Boone, W. Kalkner, R.D. Naybour, F. Ombello, “Recommendations for a new after laying test method for high voltage extruded cable systems”, Paper 21 – 105. 1990 Cigre Session

[5] W. Kalkner, M. Kuschel, T. Strehl, „Ubersicht über die Vor-Ort-Prüfung und-Diagnostik an Kabelanlagen“, Highvolt Kolloquium 97

[6] CIGRE WG 21.09, “After laying tests on high voltage extruded insulation cable systems”

[7] E. Gockenbach, G. Schiller, “The Breakdown Behaviour of XLPE- Samples at Voltages of Different Shapes”, 9th ISH, Graz 1995

[8] R. Bach, P. Kraatz, W. Kalkner, K. H. Krefter, H. Oldehoff, G. Ritter, “Spannungsprüfung zur Beurteilung von Mittelspannungskabelanlagen“
Elekrizitätswirtschaft. Jg 92 (1993). Heft 17/18

[9] E. Gockenbach, “Breakdown Behaviour of Polymer Insulating Material at Different Frequencies“, Haefely, IEE, National Grid Seminar “New Measurement Techniques for Electricity System Diagnostics”, April 29, 1999, Leatherhead, UK

[10] Th. Aschwanden, „Vor-Ort-Prufung von Hochspannungs-Kabelanlagen“, Bulletin SEV/VSE 83(1992)15.31.Juli

[11] Z. Wei, W. Kalkner, „Testing of Polymeric Insulation with VLF (Very Low Frequency) Voltages of Different Shapes“, 7th ISH, Dresden 1991

[12] J.T. Holbøll, H. Edin, “PD-Detection vs. Loss Measurement at High Voltages with Variable Frequencies”, 10th ISH, Montréal 1997

[13] A. Cavallini, A. Contin, G. C. Montanari, G. Pasini, F. Puletti, “Digital Detection and Fuzzy Classification of Partial Discharge Signals”, IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 9, n.3, pp. 335-348, June 2002.

[14] A. Contin, A. Cavallini, G.C. Montanari, G. Pasini, F. Puletti, "Artificial Intelligence Methodology for Separation and Classification of Partial Discharge Signals", IEEE - Conference on Electrical Insulation and Dielectric Phenomena, Victoria, Canada, Oct. 2000, pp. 522-526.

[15] J. F. Lyles., G. C. Stone, M. Kurtz, “Experience with PDA diagnostic testing on hydraulic generators”, IEEE Trans. Energy Conversion, Vol. 3, n. 4, pp. 824-830, Dec. 1988.

[16] M. Hoof, R. Patsch, “Detection of Multiple Discharge Sites Using Pulse/Pulse Correlation”, IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 7, n. 1, pp. 12-20, Feb. 2000.

[17] A. Cavallini, M. Conti, A. Contin, G.C. Montanari, “Automatic Noise Rejection Tools in On-Field PD Measurements”, 2001 Volta Colloquium, Como, Italy, Sept. 2001.