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Subject Procedure for Partial Discharges measurements with Pry-Cam

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0	30.09.2013	B4014069	First emission. The present report represents the translation of the original document B3025642 written in Italian

1 INTRODUCTION

This document describes the procedure to be followed to perform Partial Discharges (PD) measurements with Pry-Cam Portable instrument during the commissioning tests of high voltage cable circuits.
The document consists of a first part of a general nature in which the problem of the PD detection in electrical components is explained and of a second part dedicated to the field measurement on HVAC cable systems.

2 IEC 60270 STANDARD

Currently, the partial discharges measurement in an industrial environment is generally regulated by the IEC 60270 [1] and the relevant product standards that, for particular objects, define the limits of intensity and the test criteria. IEC 60270 describes the principles and general criteria for partial discharges measurement and aims at harmonizing the various product standards that require partial discharge measurements. In cases where, for certain types of objects, the relevant product standards are not available, the general requirements provided by the said standard may be used as a general basis for the agreement between the parties. IEC 60270 provides general criteria for the measurement of partial discharges that occur in equipment, components and systems designed for DC or AC up to a maximum frequency of 400 Hz. In particular, detailed information on the technical terms to be used, the quantities to be measured, the main test circuits that can be used, methods of measurement, the instruments that can be used, calibration procedures and test procedures to be followed are provided; there are also some suggestions for the discrimination of partial discharges with respect to external interference. In addition, given the general nature of the standard, non-electric methods for measurement of partial discharge are analyzed in order to localize the impulsive phenomena.
IEC 60270 is aimed at the definition of partial discharge measurements in a reproducible manner but it excludes the aspects related to the use of the measuring technique for diagnostic purposes.

3 DEFINITIONS

The main definitions are:

Partial Discharge (PD)
A Partial Discharge (PD) is defined as a localized electrical discharge that only partially bridges the insulation between conductors and which can or can not occur adjacent to a conductor. The partial discharge is therefore a physical phenomenon in a localized point of the insulation system where the gradient of electric potential is higher than the dielectric strength of the insulating medium itself.
Often, the partial discharges are localized in regions of the insulation system difficult to access and consequently the direct PD measurement is impossible.

Partial discharge pulse (PD pulse)

The partial discharge pulse is the pulse (PD pulse) of current that occurs within the object under test as a result of a partial discharge.
The pulses of partial discharge can be detected by instrumentation as pulses of current or voltage, originated in the system by introducing a suitable measuring circuit and a measurement impedance.

The quantities related to partial discharge pulses are:

Apparent charge q

The apparent charge 'q' of a partial discharge pulse is the charge that, injected in a very short time between the terminals of the test object in the test circuit , would give rise to the same reading on the measuring instrument of the partial discharge current pulse itself. The apparent charge, usually expressed in picoCoulomb (pC) , is then defined by comparison with a sample injected charge across the test circuit defined as calibration charge.
The apparent charge is not the real charge of the partial discharge, but the charge that would be applied to the terminals of the test object in the measuring instrument for the same indication. With this definition, the standard provides two basic indications: the first concerns the impossibility of direct measurement of the partial discharge charge, the second that the measure is relative, i.e. it is necessary to process a comparison with a known charge, called calibration charge.
The standard recommends to product technical committees to use the apparent charge as the variable to be measured wherever possible.

Pulse repetition rate n

The pulse repetition rate n is defined as the ratio between the total number of partial discharge pulses recorded in a time interval and the duration of this time interval.
The standard, considering the partial discharge pulses repetition, with this definition introduces a measurement criterion, such as that the pulses should not be judged only on the base of the apparent charge but also for their relative numerousness in the time range.

Pulse repetition frequency N

The pulse repetition frequency is the number of partial discharge pulses per second, in the case of equally spaced pulses. In common situations, partial discharge pulses are seldom temporally equidistant therefore such a definition can only be applied during calibration or verification.

Phase angle Φ_i and time t_i of occurrence of a PD pulse

The relationship between the instant of measurement of a pulse with respect to the phase angle (expressed in degrees °) of the alternating supply voltage is given by expressing the phase angle:

$$\Phi = 360\,(t_i / T)$$

where t_i is the measured time between the instant of zero crossing of the rising test voltage wave, before the discharge, and the partial discharge pulse. T is the period of the test voltage.
This definition allows the construction of the partial discharge pulses distribution diagrams also called "Pattern" (more precisely Phase Resolved Partial Discharge Pattern, PRPD) or ϕ_i-q_n diagrams.

Average discharge current I

The Average discharge current I is the derived quantity and the sum of the absolute values of individual apparent charge magnitudes q_i during a chosen reference time interval T_{ref} divided by this time interval:

$$I = 1/T_{ref}\,(|q_1|+|q_2|+\ldots+|q_n|)$$

This current is generally expressed in coulomb per second (C/s) or amperes (A) and represents the continuous current whose integral on time is equivalent to the charge associated to the partial discharges.

Maximum amplitude of the repetitive partial discharge

Maximum amplitude recorded by a measurement system whose response to pulse trains complies with the standard specifications.

Specified partial discharge magnitude

Largest magnitude of any quantity related to PD pulses permitted in a test object at a specified voltage following a specified conditioning and test procedure. For alternating voltage tests, ***the apparent charge q specified magnitude is the largest repeatedly occurring PD magnitude***.

Background noise

The term background noise identifies all signals detected during PD tests, which do not originate in the test object. Background noise can be composed of either white noise in the measurement system, broadcast radio or other continuous or impulsive signals.

Antenna directivity

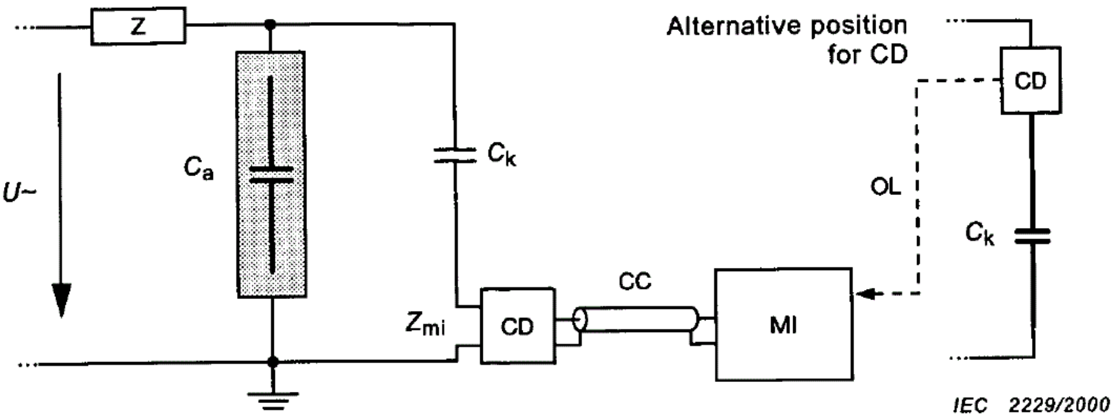
The directivity of an antenna in a certain direction is defined as the ratio between the radiation intensity emitted in this direction and the total power radiated in all directions. The directivity is defined as a function of the observation direction. The term Directivity is commonly used to identify the maximum value of this function in correspondence with the direction of the maximum.

3.1 Test circuits according to IEC 60270

Most circuits used for partial discharge measurements according to standard [1] can be derived from one of the basic circuits.

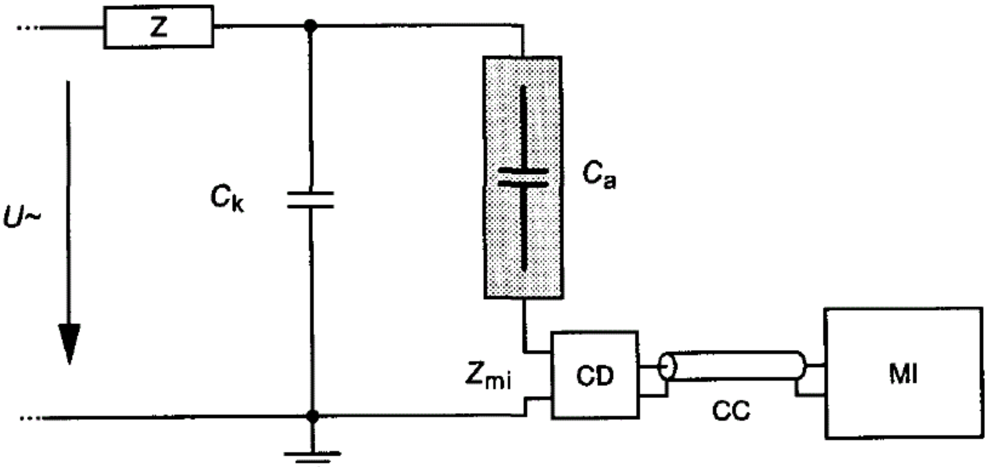
Each of these circuits consists of:

- a test object Ca;
- a coupling capacitor Ck with low inductance design and low level of partial discharges;
- a measuring system CD with its input impedance indicated by Zmi;
- a high-voltage source indicated U~, with a sufficiently low level of partial discharges;
- a series of high and low voltage connections indicated by CC, free from partial discharges at the test voltage;
- an impedance or a filter indicated by Z able to reduce the influence of background noise and interferences;
- measuring instrument for partial discharges indicated by MI.



IEC 2229/2000

Figure 1- Partial discharges classic measurement circuit. The coupling impedance Zmi is in series with the coupling capacitor Ck. Note that the impedance is either traversed by the current at the test frequency and by current pulses caused by partial discharges.



IEC 2230/2000

Figure 2 - Impedance measurement Zmi in series with the test object Ca. This circuit is not widely used although formally identical to the circuit of Figure 1, as the failure of the test object applies the supply voltage on the impedance measurement Zmi with consequent risks for the operators' safety and the measurement instrument CD.

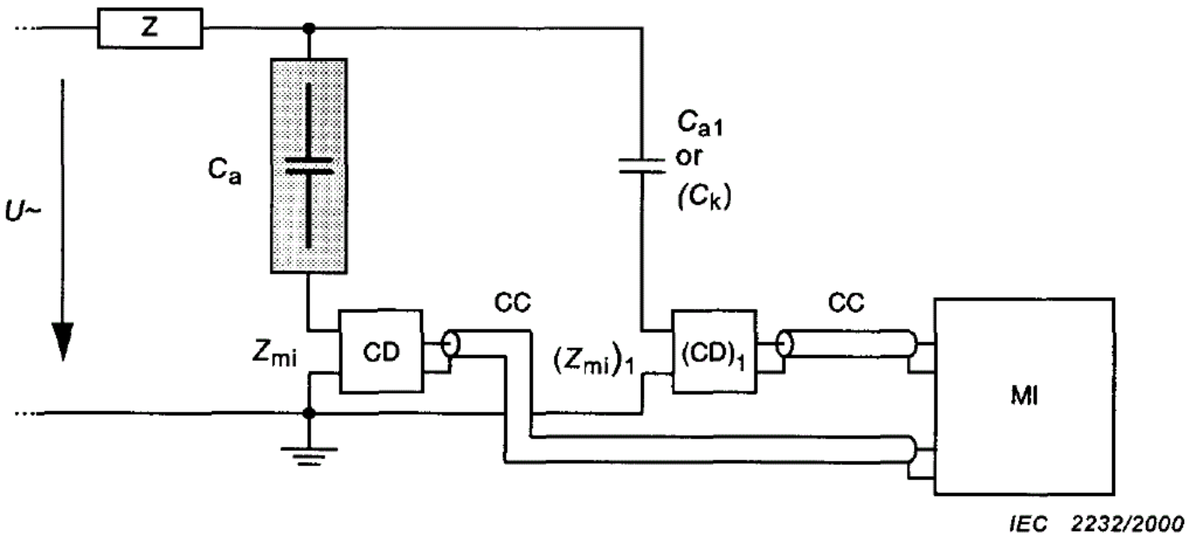


Figure 3 - Circuit for the discrimination of the pulse polarity. This circuit adopts two measurement impedances with a single measuring instrument that is able to establish the apparent current polarity from the comparison of the two signals. The circuit also allows to strongly reduce noise and interference from external sources to the measuring circuit.

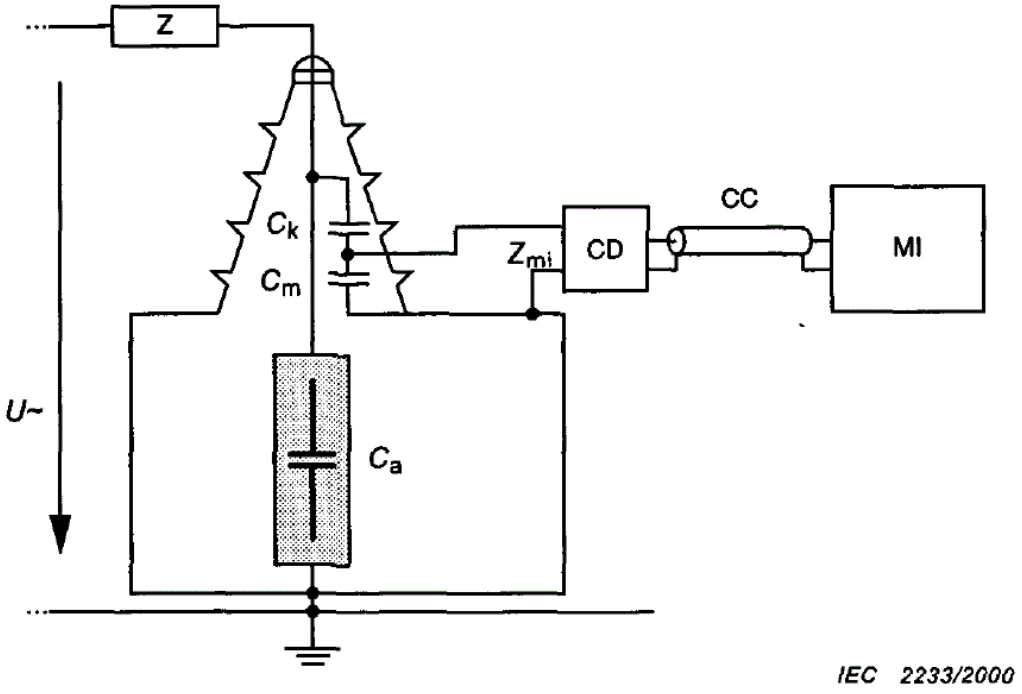


Figure 4 - Test circuit for measurement at a tapping of a bushing. This circuit is used in transformers when the coupling capacitance is not adequate or the voltage is very high. Note that capacity coupling Ck normally has a very small value (e.g hundreds of picofarad)

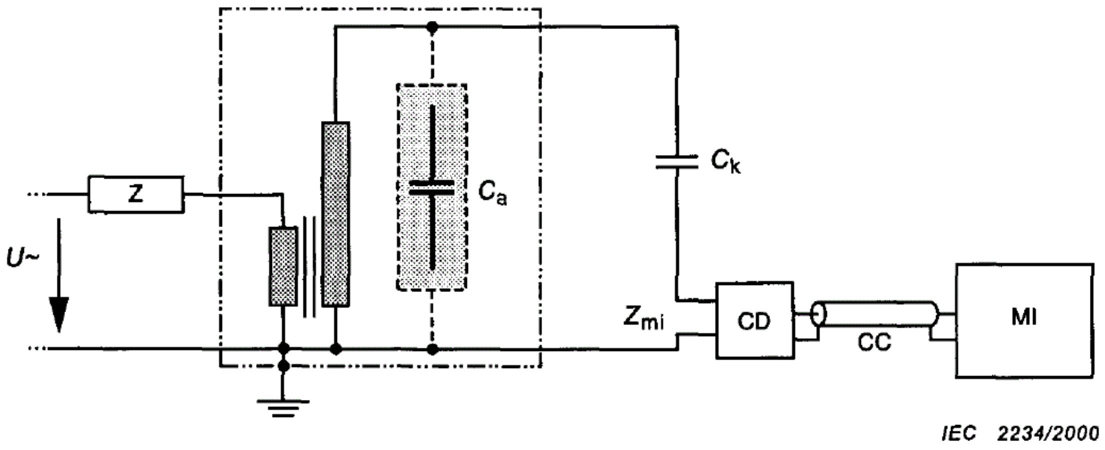


Figure 5 - Test circuit for measuring self-excited test objects. The supply voltage is provided by the test object.

According with IEC 60270 standard, partial discharges measurement should be carried out using as a reference the apparent charge wherever possible.
For each measurement the main characteristics of the measuring system shall be recorded in order to ensure greater reproducibility between different systems. The standard requires considering the measuring system including the PD measuring instrument, the coupling device and the other circuit parts that contribute to define the measuring circuit parameters.

The coupling device is particularly important in the measuring circuit, as it is designed to achieve the maximum sensitivity as a function of an appropriate test circuit and which can therefore be changed or replaced depending on the various needs leaving the measuring instrument unchanged.
The coupling circuit may be constituted by a passive or active four-terminal network to convert the input current signals into output voltage signals with an appropriately selected transfer function between input and output in order to avoid that power frequencies and its harmonics can reach the measuring instrument .
A partial discharges measuring instrument compliant with [1] generates a voltage pulse whose peak is a function of the input charge pulse, provided that pulses bandwidth is constant at least within the measuring system bandwidth Δf. Since output pulse shape, duration and peak values are determined by the impedance ***Z(f)*** transfer function, ***the output signals may have a completely different waveforms compared with input signals.***

3.2 IEC 60270 standard applicability areas

Partial discharges measurements according with IEC 60270 have some limitations.
In fact, measurement with metrological purposes has as primary goal the identification of the maximum repetitive PD magnitude, such as the apparent charge intensity of the discharge with maximum intensity in a period of the supply voltage.

This approach, which is correct from the metrological point of view, has not any correlation with insulation material degradation processes since there is no correlation with the partial discharge repetition rate.

> *In order to explain the limits of the current standard, the following example is presented. An embedded object with apparent charge intensity limit set to 10 pC is considered.*
> *During the test, two different situations are detected for two similar objects: in the first object 100 PDs per cycle with 8 pC intensity are measured, in the second object 2 PDs per cycle with 12 pC intensity are measured.*
> *According to the standard, although the average current discharge of the first object is significantly higher than the current average discharge of the second object, the second should be rejected while the first object accepted.*

From the above example, it is concluded that the current standard does not set any diagnostic requirements, which instead must be investigated with further analysis and test methods.
The partial discharges measurements performed with equipment complying with IEC 60270 are therefore measures intended for metrological quantification of the apparent charge of the test object and are not intended neither for PD discrimination nor location inside the test object.
The test result is a numerical value, which in turn must be compared with a reference value in order to determine if the test object has or has not an apparent charge level low enough to meet the requirements of acceptability required by product standard or by an agreement between the parties.
In most cases, the required limits represent a contract value, for example between supplier and purchaser and the PD metrological measure provides the evaluation criteria for acceptance according to standards.

The purpose of the metrological measures is not, therefore, to discriminate the different sources of PD phenomena within the test object but only give the most reliable and reproducible indication with minimum uncertainty.
Measurements carried out with these criteria can provide the insulation system quality assessment only if the detected partial discharges have negligible values, while a diagnosis can not be performed when the measured partial discharges level is not negligible.

With metrological measurement, in fact, neither the PD type nor the location in the test object can the defined; therefore it is impossible to establish whether the PDs will reduce the test object life time (e.g. if PDs are located or not in a self-healing insulation).

Therefore partial discharges measurements with Ultra Wide Bandwidth (as described in the following section) carried out with a metrological approach could wrongly lead to the test object rejection due to PDs in self-healing insulation with intensity higher than the contractual value although these PDs are harmless with respect to the insulation quality and life time.

On the contrary, partial discharge measurements for diagnostic purposes are aimed to identify the partial discharge type and location in the test object. This approach is useful to evaluate the risk associated to the partial discharge activity intensity measured, for instance, according to the recommended procedure of the standard.

Based on a diagnostic PD measurement, the internal or external location of the degradation phenomenon can be identified, which allows to know whether this will or will not reduce the test object life time.
Concluding, with partial discharge measurements for diagnostic purposes, the goal is not only to measure the PD intensity but also to identify the PD type in order to evaluate the insulation status.

Partial discharges measurements for diagnostic purposes are a valuation process including three main steps: the first step is the measurement, the second is the PD phenomena recognition and localization and the third step is the results interpretation.

As in all other diagnostic techniques, due to the fact that the result is an estimation of the degradation level of the test object, qualitative factors such as the deep knowledge of the test object and the experience, meant as both a deductive ability and a phenomenon relevance assessment and statistics, derived from a data-set from previous experiences are very important aspects. For this latter task, some recent database with data relevant to the most common phenomena can be of great support.

4 DEVELOPMENT OF PARTIAL DISCHARGES MEASUREMENT TECHNIQUES

The studies carried out since the seventies on the partial discharges phenomenon and on the physical mechanisms involved in the dielectrics degradation in electric industry, have led to a greater understanding of these phenomena and their characteristics. In particular it was found the dependence of the partial discharge waveform on the applied voltage, on the specific dielectric type and on the geometry of the system. For this reason, the last decade has led to the idea of detecting not only the partial discharges intensity but also the temporal evolution of the current.

For this purpose, the traditional measuring instruments (designed in accordance with the standard [1]) based on the principle of pseudo-integration, have been further developed to become new instrumentation also able to acquire the PD current waveform. In order to distinguish from traditional broadband instruments based on the principle of pseudo-integration described in the standard, these new UWB (Ultra Wide Band) instruments have enough bandwidth to accurately acquire the current waveform associated to the partial discharge.

Generally, ultra-wideband PD acquisition devices are composed by a sampler (digital recorder / acquisition board / oscilloscope) equipped with an electronic part able to optimize the recording and to perform a first signal processing on the acquired signals. In addition to the acquisition of the current pulse waveform, the UWB instruments provide, compared to the traditional instrumentation, additional advantages such as:

1. **Overlap error reduction:** the overlap error is reduced as the instrument response to the pulse is the pulse itself;
2. **Reduction of the resolution time between pulses:** in principle the resolution time of ultra wide-band systems are much shorter that wideband systems as in order to discriminate two impulsive phenomena it is sufficient the exhaustion, even partial, of the first phenomenon compared to the next. This time is typically hundreds of nanoseconds. In the case of signal acquisition with memory segmentation based techniques, there is a second time factor, related to the minimum time between a

trigger reset between a frame acquisition and the next. The trigger reset time is usually dependent on the length of the acquisition window and can be of a few microseconds;

3. **Integration error reduction:** the integration error is due to the inability of the broadband system to perform a proper pseudo-integration due to the input pulse dynamics. In the case of ultra-wideband systems, where the integration is done numerically after acquiring the exact waveform, the problem does not arise;
4. **Better noise rejection:** the possibility of a better control of the acquisition enables the use of more sophisticated techniques for noise rejection or for its elimination through processing algorithms applied to the data;
5. **More information are acquired:** the acquisition of the pulses waveform allows extracting a significant amount of additional information on the phenomenon with respect to the amplitude measurement of traditional techniques (e.g., polarity, duration, frequency, etc.);
6. **Better time resolution:** the high-speed acquisition of the waveforms allows obtaining a high time resolution useful in PD localization applications.

The Pry-Cam can be fully considered a UWB measuring instrument.

5 GENERAL INSTRUMENTATION FEATURES

Pry-Cam is an integrated instrument for detection of Partial Discharges (PDs) in high voltage or medium voltage (HV/MV) electric components such as cables, joints, terminations, transformers, GIS and rotating machines. The instrument integrates a proprietary (patented) electromagnetic sensor and a high performances acquisition system able to acquire 200 million of samples per second, with a bandwidth of 100 MHz. Thanks to the specific kind of sensor, its embedded implementation and the use of wireless (WiFi) connection, the instrument (fig. 6) allows to perform on-line measurements in an easy and effective way on powered components (fig. 7), without the need of a galvanic connection, and making possible the exploiting of these kind of diagnostic technique in fields and applications previously not possible due to costs and feasibility reasons.

Figure 6 – Pry-Cam TM - Portable version.

Figure 7 – Pry-Cam™ during a field measurement.

5.1 Electric field wireless sensor

The sensor employed in the Pry-Cam consists in a special Ultra-Wide Band antenna (patent WO2009150627), designed to receive electromagnetic signals emitted from partial discharge phenomena in dielectrics. The fast charge recombination at the base of PDs generate impulsive currents that imply the irradiation of electromagnetic pulses able to propagate in the surrounding media. Impulse features are closely related to the features of the current pulse that generated it, in particular information such as the energy and frequency content are proportional to the one of the original phenomenon.

The frequency band received by the sensor is the one comprised from 0.5 MHz and 100 MHz (that is however internally cut-off to 50 MHz). This frequency bandwidth was chosen since the most frequency components of typical PDs fall within 50 MHz. A distinctive feature of the sensor is that it has a very flat response, both with regard to the frequency and the phase, and so free from whatever resonant behaviour. This allows to preserve the frequency content of the incoming signal and so its waveform. This feature allows obtaining more diagnostic information on the detected phenomena, and also allows a better separation among different phenomena and a better noise rejection capability. It is interesting to note that the most part of current commercial PD sensors have a resonant response, so they provide their harmonic response when stimulated by impulsive signals.

5.2 PD signal detection

The sensor has a directional behaviour, so during PD measurements the instrument have to be directed toward the test object, either cable, joint or termination (see below the specific paragraph about directivity). The sensor is able to detect electromagnetic pulses generated from the PDs at a distance from the source, without the need of any galvanic connection: this makes possible its use on powered components (without the need to disconnect them in order to perform the measure).

The overall sensor sensitivity, verified during measures performed in a shielded laboratory, resulted lower than 1 pC, and the transduction coefficient was about 10 mV/pC at 1 cm from the source.

Figure 8 – The patented electric field sensor.

5.3 Synchronisation signal detection

The sensor employed in the Pry-Cam is able to detect, in addition to PD pulses, also the phase of the AC voltage supplying the component under test. It is in fact able to pick up, like a capacitor the electric field of the AC voltage on the component and to provide a phase reference signal for the PD measure (especially used to build the “Phase Resolved Pattern”).

This ability is advantageous from many points of view:

- It avoids the use of additional specific sensors such as CTs, Rogowski coils, capacitive couplers, thus simplifying the measure;
- It avoids errors in the phase measurement, since it is directly sensed from the voltage (electric field) and not from the current, and also it is detected right on the component under test, so it is exactly referred to the voltage triggering the PDs in the component itself, and there is no ambiguity in multi-phase systems;
- It allows maintaining the full galvanic isolation during the measurement.

The sensitivity of the AC voltage detection is determined by the geometry of the component under test, from the AC voltage level and from the distance. As an example, it is possible to obtain a robust synchronisation signal also from a low voltage (150V) powered component, at a distance of about 10 cm.

When it is not possible to use the integrated synchronisation sensor, for example when the electric field is too low to be detected, the instrument is provided with an input channel for an external signal obtained from a traditional sensor. This possibility is relatively unlikely, and may happen in three-phase systems, when the three sources are very close. This situation may be encountered during medium voltage measurements, but never with high voltage systems.

5.4 Acquisition system

The Pry-Cam integrates, in addition to the electromagnetic sensor, also a high performance acquisition and processing system. The acquisition system allows sampling the PD pulses with a high temporal resolution in order to record the entire waveform of each pulse, not only the peak value as done by many commercial instruments. This allows, as already said, to considerably increasing the diagnostic capability and noise rejection. The input stage of the acquisition system is endowed with a programmable amplifier with a gain ranging from 0 to 40 dB. The sampling rate is 200 Msps (millions of samples per second), at 8 bit and with a bandwidth of 100 MHz. The triggering system is fully digital and allows associating an ultra-precise timestamp to each acquired pulse for localization purpose and statistical analysis. The synchronisation signal is acquired with a 16 bit resolution, allowing a phase resolution in the order of microseconds in the frequency range 10 Hz to 1 kHz.

The system is provided with an optical interface (Fast Ethernet Base-FX) and a WiFi (802.11b/g) interface for communication with a local or remote control PC. During measurements the system is powered by the internal battery (more than 4 hour of battery life), so it is completely autonomous and insulated. Thanks to these features it can be positioned close to powered (operating) components to perform the measurement, with the help of an insulating hook stick if required.

5.5 Directivity and distance from the source

The sensor employed in the Pry-Cam is an ultra-wideband antenna, and so it is characterised by a specific directivity and a sensitivity that is related to the distance from the source. The directivity is greater than 24 dBi (gain, in dB, referred to the isotropic radiator), and was specifically designed to be of a high value since it brings some advantages:

- It allows to precisely localise the PD source, either as a specific component in a plant and as the exact point within a component;
- It attenuates the effects of the environmental noise or adjacent sources, reducing the solid angle in which the instrument is more receptive.

The maximum directivity of the instrument is toward the sensor principal axis.

The dependence of the signal level from the source distance is an intrinsic characteristic of every antenna and of the electromagnetic radiation itself. This property allows a certain signal to be strongly received when near to the source and to be weaker at a greater distance. This behaviour may appear as a drawback at first, but it turns to be useful for the same reason above described for the directivity, i.e. it enhances the localisation and noise immunity capabilities of the instrument.

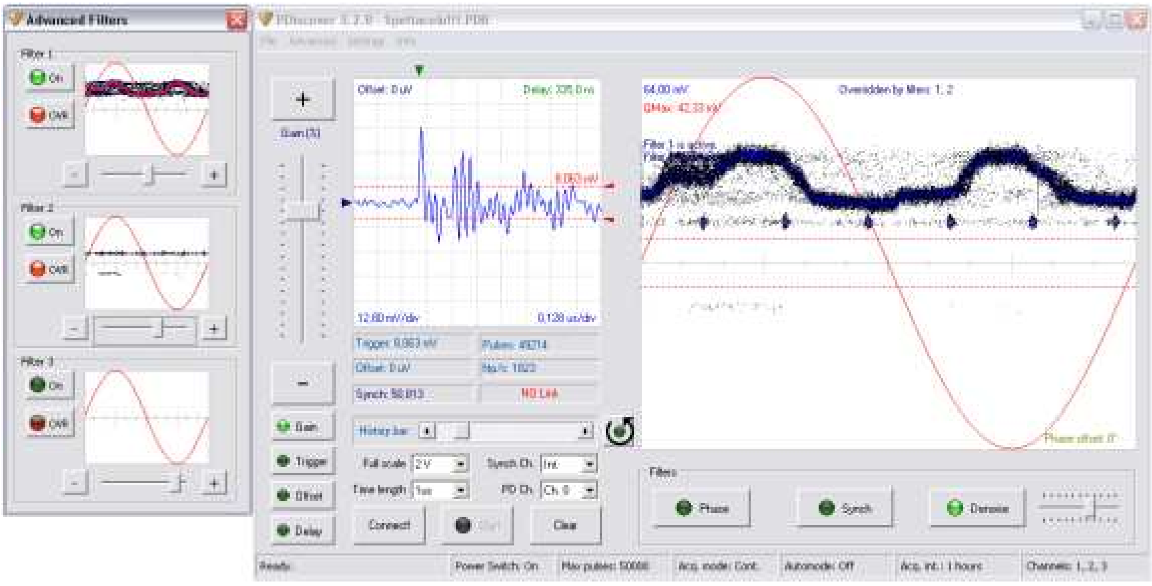
As already said, the directivity and the sensitivity to the distance allow the Pry-Cam to localise in a very accurate way the position of a PD source. This operating mode is not possible with traditional sensors and instruments, since they are set in a fixed position and cannot be moved during measurements. The Pry-Cam instead can be used in "survey mode", that is pointing it toward various components in a plant and observing in real time the amplitude (and the pattern) of the detected PDs. The maximum amplitude is obtained when the instrument is pointing or is above the actual source of PDs. Some tests performed with the instrument allowed to find (localize) defects with accuracy in the order of tens of centimetres.

The variability with distance and direction of the detected signal from the other side imposes a greater care in the execution of calibration measurements, that has to be done performing the measure (according the technical standard IEC 60270) after choosing a specific and fixed position of the Pry-Cam. This position has to be maintained for all duration of the calibration measurements on a given component. It has to be noted however that the same precaution is implicitly taken into account also when performing calibration measurements with traditional sensors that cannot be moved.

5.6 Acquired signals processing

The PD acquisition process with the Pry-Cam allows to obtain a collection of pulses each characterised by a specific waveform, a phase angle with respect the voltage supplying the component, a timestamp and other additional parameters. Pulses are processed by the Pry-Cam control software either in real time, either, more commonly, subsequently. The most common processing operation, a part from the pattern generation, consists in the separation and classification of the pulses according to their common features. The "separation" process is the operation, automatically performed by a numerical algorithm, of separating pulses coming from different discharge sources. The "classification" process instead is the automatic association of each class of pulses with a specific physical defect model.

In particular pulses featuring similar waveforms are usually generated by the same phenomenon, on the contrary incoherent pulses or non-impulsive signals can be considered noise. The software provides a number of filters based on the waveform analysis that allow to group pulses with similar features and reject the incoherent ones. This allows to separate different PD source simultaneously present in the same component and rejecting the noise as well. Once different phenomena have been separated they can be individually analysed and classified on the basis of the operator experience or also automatically (once uploaded on the centralised web server) according their defect type and so making the analysis of their severity easier.



Trigger: 9,063 mV
Pulses: 49214
Offset: 0 uV
No/s: 1023
Synch: 50,013
NO Link
Full scale: 2V
Synch Ch: Int.
Time length: 1us
PD Ch: Ch. 0
Ready
Power Switch: On
Max pulses: 50000
Acq. mode: Cont.
Automode: Off
Acq. int.: 1 hours
Channels: 1, 2, 3

Figure 9 – PDiscover acquisition and processing software.

6 MEASUREMENT PROCEDURES

6.1 The Pry-Cam measurement system and its operating modes

As previously said the Pry-Cam is an advanced PD measurement system with an ultra-wide bandwidth (0.5-100 MHz) that acts like components CD, CC and MI showed in figures 1, 2, 3, 4 and 5 as reported in the standard [1]. Even if it shares many features with similar instrumentations, it has a unique architecture integrating an electromagnetic sensor (covered by a number of patents), a high speed acquisition and processing unit capable of handling up to 200 Msps, and a communication system (optical fiber and WiFi). It is capable of sensing at a distance pulses generated by PDs as well as the electric field of the AC voltage powering the component under test. This allows detecting the electromagnetic signal generated from the PD current either from a connected conductor or from the surrounding media in the nearby space. It is also possible in the same way detecting the phase angle in which the PD occurred by detecting the phase angle of the supply voltage. Given these possibilities, the Pry-Cam can be positioned in all the configurations described by the standard, in the same positions of the CD, CC and MI blocks.

Figure 10 – Pry-Cam™ instrument.

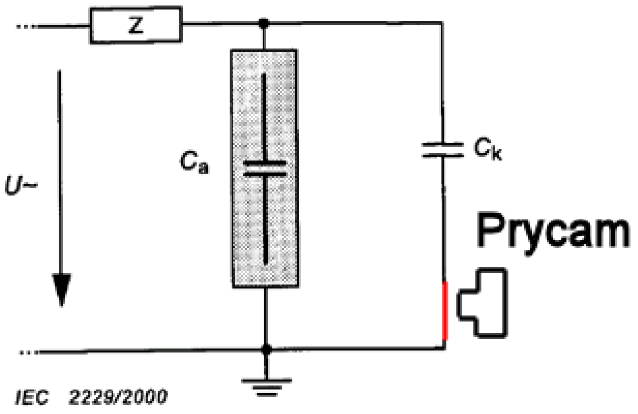


Figure 11 – Classical PD measurement circuit (see figure 1) with the Pry-Cam positioned in parallel with the test object.

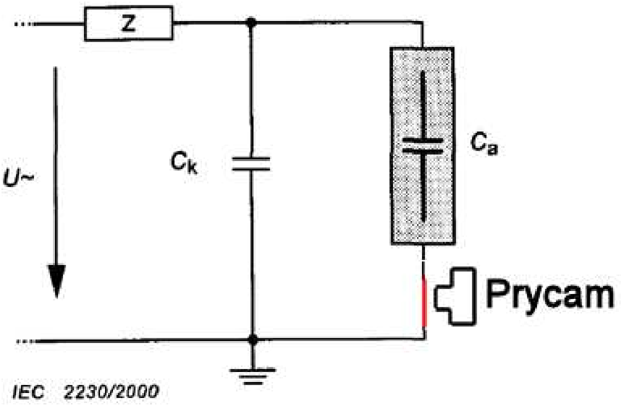


Figure 12 – Measurement impedance in series with the test object. This circuit is occasionally used in laboratory setups, but it is the most frequently used for on-line measurements on the field. Its limitations are overcome (Figure 2) thanks to the galvanic insulation allowed and obtained with Pry-Cam.

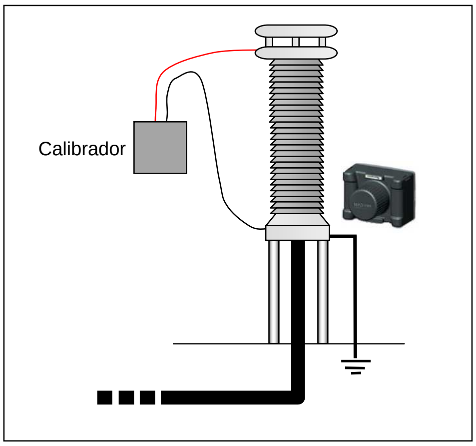


Figure 13 – Calibration procedure in a test circuit with the Pry-Cam.

Figure 11 and 12 show two insertion modes described in the standard adapted to employ the Pry-Cam. It has to be noted that, since the instrument is not physically connected to the circuit, the coupling is given by its position and orientation. The Pry-Cam should be positioned and directed so to face a conductor that carries the PD current, as shown in Fig. 12. Alternatively it can be positioned at a short distance from the PD source that guarantees an adequate safety level (Fig. 11, where the C_k capacitor represents the capacitive coupling through the surrounding media). Once the distance from the conductor or component has been established, also the ratio between the apparent charge and the detected signal is fixed, apart from nonlinearities introduced from the component itself. In order to quantify this factor a calibration procedure can be carried out; this step is very similar to the one usually performed with traditional instrumentation, and it is depicted in Fig. 13.

During the acquisition, the Pry-Cam is able to acquire about 10.000 p/s in full waveform mode when connected with optical fiber with the control PC and about 6.000 p/s when using the WiFi. When operating in "pattern only" mode, i.e. when only the ϕ_i-q_n plot is acquired, the Pry-Cam is able to acquire more than 50.000 p/s, further enhancing the noise immunity. This happen since when a heavy noise source is present, the PD pulses are relatively infrequent compared to noise pulses, so a higher repetition rate allows detecting few PD pulses. As an example, if in a second only 10 PD pulses are generated and 9990 noise pulses are present, it is required to acquire at least 10000 pulses per second in order to acquire the PDs. Otherwise the PDs cannot be completely detected in this situation.

7 PARTIAL DISCHARGE MEASUREMENTS DURING COMMISSIONING (TEST AFTER INSTALLATION) OF A CABLE LINE

Figure 13 – Online measurement on outdoor termination.

Since the Pry-Cam allows to perform partial discharge measurements without galvanic connection to the system under test, one of the most common scenarios where this feature can be very useful is during *commissioning* activities and test after HV cable installations. In these applications, technical standards require that the system under test has to be powered by an auxiliary power supply working at a frequency different from the nominal one and supplying for one hour a voltage higher than the nominal one U_0, i.e. $1.2U_0$ for 380kV systems and $1.7U_0$ for 170kV. Another possibility expected by technical standards is supplying the system under test at the nominal voltage U_0 for 24 hours continuously. In these cases the PryCam can be installed, as it was discussed above in the previous section, on the earth connections of the test objects. Some pictures showing the use of the PryCam on outdoor terminations are here reported. In particular figure 13 shows how the instrument is placed as close as possible to the earth connection to the test object, in accordance with the circuit reported in figure 11, which refers in turn to the insertion scheme of figure 2 of the technical standard IEC 60270. In the case of indoor terminations used to connect to GIS, measurements can be performed not only on the earth connection of the lower side of the terminations, but also through the epoxy spacer (see figure 14), being this transparent to electromagnetic signals generated by any possible partial discharges whose the system might be affected by. This measuring position proved to be a good spot for catching also the electromagnetic field associated to the industrial power supply voltage of the system under test.

Figure 14 –Measure on a GIS termination.

Figure 15 – Online measurement on coax cables coming from the joints.

The commissioning tests can also be performed on other components of the plant such as joints. In these cases, procedures change whenever the joint is accessible or is not. If the component is accessible, i.e. it has been installed in a tunnel, the measurement can be performed placing the PryCam on the joint itself. In particular, if the joint is sectionalized, the most effective way to perform the measure is by placing the Pry-Cam on the screen separation of the joint itself. In this condition, the electromagnetic fields generated by partial discharges are measured with high sensitivity because of the absence of the semiconductive shield and, in turn, its shielding effect. If the joint is not sectionalized the most suitable position is on the conductors that connect the shield to earth. So the measure can be performed both close to the joint or inside the hole housing the "link box" (figure 15), placing the Pry-Cam on the coaxial cables connecting the shields to earth. This configuration is adopted also with not accessible joints. In these conditions the synchronization can also be taken, but a correction to the phase must be applied (30° or 90°) and this has to be calculated every time, depending if the joint is sectionalized or not. If necessary, it is possible to use an accessory to use the current on shields as sync signal, the same way as it is usually done with other instruments. In these cases, it is obtained the same measuring sensitivity achieved with traditional coupling system i.e. HFCT.

The same measuring procedure is valid in case a test has to be performed after repairing or replacing an accessory, i.e. in case of fault.

7.1 Measure on a single accessory (termination) or on the entire line (with attenuation problems) and with many PryCam installed

When the measurement is performed during normal operating, the installation procedure of the PryCam is basically the same as discussed in the previous section, with some additional simplifications. In particular, during commissioning, the supply frequency is different from the network frequency, so in case there are other plants close to the one under test, it is necessary to check that the sync frequency captured by the PryCam is the correct one. In fact, the proximity of a circuit powered by the network voltage at its proper frequency can affect the measure being performed on another circuit powered by the auxiliary power supply at different frequency. During test on circuit at the nominal voltage, on the contrary, the sense of the correct synchronization signal is straightforward, for reasons depending by the higher amplitude of the synchronization signal and also because it is easier finding a component, powered by the same voltage of the accessory under test, from which sensing the sync signal.

When it is necessary to test many components of a line, the procedure for a single measurement has to be just repeated for every component. It can be useful to take advantage of the attenuation at which the PD signal is subjected travelling on the line in order to identify the component affected by PDs. In fact, the PDs have frequency content in the range 900 kHz – 40 MHz approximately. This signal, travelling on the power cable acting as transmission line is attenuated and loses progressively the higher harmonics, so that after some hundreds of meters the signal has smaller amplitude and a lower fundamental frequency. This effect can be exploited not only to find the joint or the termination where the amplitude of the signal is higher and in turn where the fault is located, but also, on a cable, the position of the point where PDs are actually generated. In this case even only one Pry-Cam is enough to perform two or more measurements in two or more joint holes and, comparing amplitude and frequency content of the PDs, obtain with very good approximation the location of the PDs.

If the localization by looking for the spot with the maximum signal amplitude is not precise enough, more Pry-Cam at the same time can be used. In this kind of applications, the GPS receiver integrated on the instrument enables to refer every acquired pulse to the absolute time of the GPS satellites, basically obtaining a very precise synchronization between all the Pry-Cam used during the localization test. In this way, it is possible to compare the measurements acquired by the Pry-Cam, evaluating the propagation delay of the pulses inside the cable with a very high-precision. In the end it is possible to evaluate the exact location of the faulty part within a range of 3 meters. This mode of operation is very useful when you are dealing with buried cables or when it is necessary to test a cable reel in factory.

7.2 Acquired data interpretation

After the measurements have been performed, it is possible to evaluate the existence of partial discharges in the component under test and the relative risks associated to them. This evaluation is performed relying on some statistical parameters compared to the ones collected on the Prysmian database. In this way many comparisons are automatically performed under supervision and a very accurate diagnosis is given. In many cases this activity is performed in real-time, in particular in case of “good health of the system” diagnosis. If partial discharges associated with a degrading process are found, this diagnosis must be further investigated in a post-elaboration phase. This is the most important phase because it enables to formulate the correct diagnosis about the insulating system, and its working status.

7.3 Evaluation of the measurement results

7.3.1 Introduction

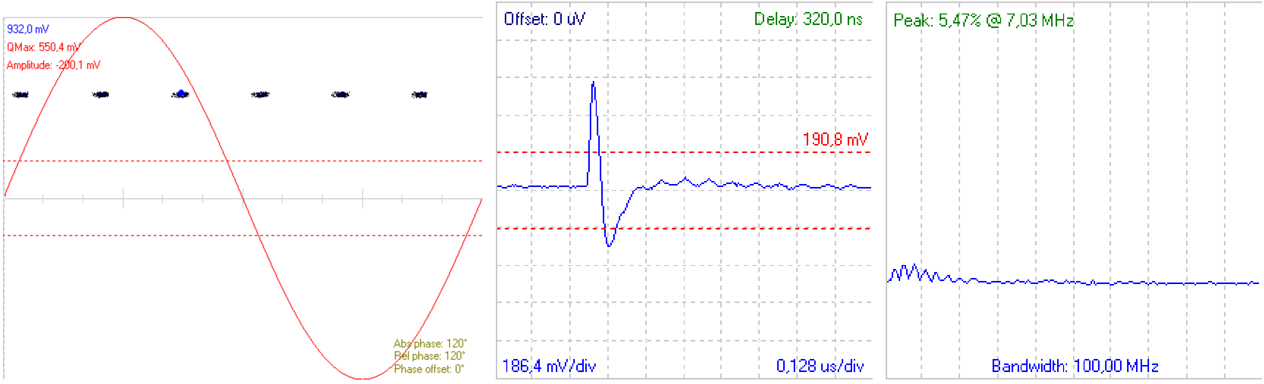
As it was previously discussed in this document, the PryCam can be used in similar way to a traditional measurement system, in terms of the positioning of the instruments. However the high-directional nature of the sensor and its high sensitivity, enable to obtain complete diagnostic data adopting some “smart tricks” while using the instrument. In order to evaluate the quality of the measurements performed with the PryCam, many measuring campaign have been performed, also comparing the results with the ones obtained using other instruments. This comparison will not be discussed in this document, proved the good correspondence of the measurements with other commercial instruments.

Now some PD patterns and the information obtained from them will be evaluated. In particular as examples three typical cases will be discussed.

7.3.2 Evaluation of PD pattern, statistical parameters and characteristics of the pulse

In order to first evaluate the acquisition quality, a PD pattern generated by a calibrator in a test circuit has been evaluated. The amplitude of the generated pulses is 20 pC and the pattern is shown in figure 16. In can be noticed how the measurement is clear and without any noise. The signal is very clean and the shape of the pulses is compliant to the ones acquired by a scope in perfect impedance matching conditions. In fact the PryCam is able to acquire the shape of the pulses with a very high fidelity. This feature has been emphasized by the constructor and represents the main innovation of the deposited patent.

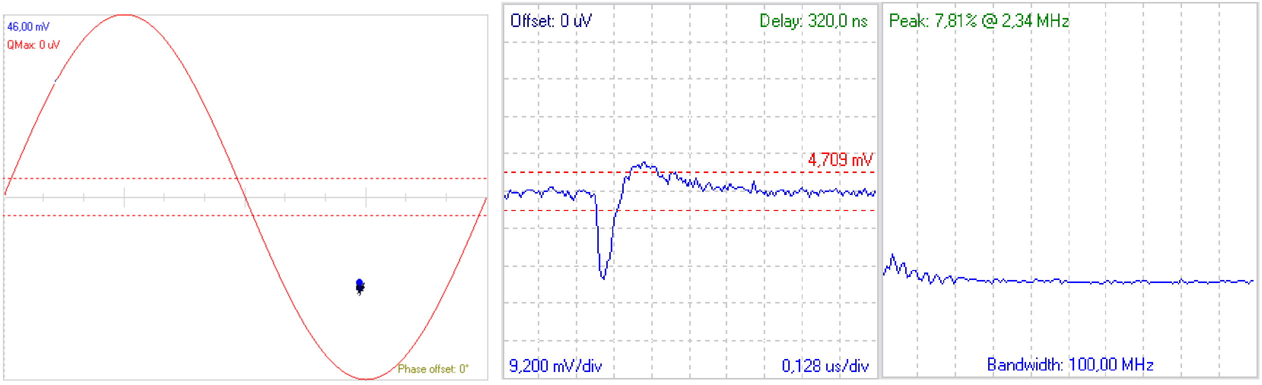
Furthermore, the number of the acquired pulses is 300 per second, being compliant with the ones generated by the calibrator. This parameter confirms the PryCam capability to capture all the pulses. The minimum time distance declared by the constructor between two pulses that can be acquired is 40µs.



a) b) c)

Figure 16 – a) Complete pattern, b) calibration pulse, c) relative frequency content for the 20pC calibration pulse.

The second measurement performed in order to evaluate the instrument performances is a corona effect measurement. A needle has been connected to a high-voltage test system and the voltage has been incremented until the triggering voltage. The relative pattern is shown in figure 17.

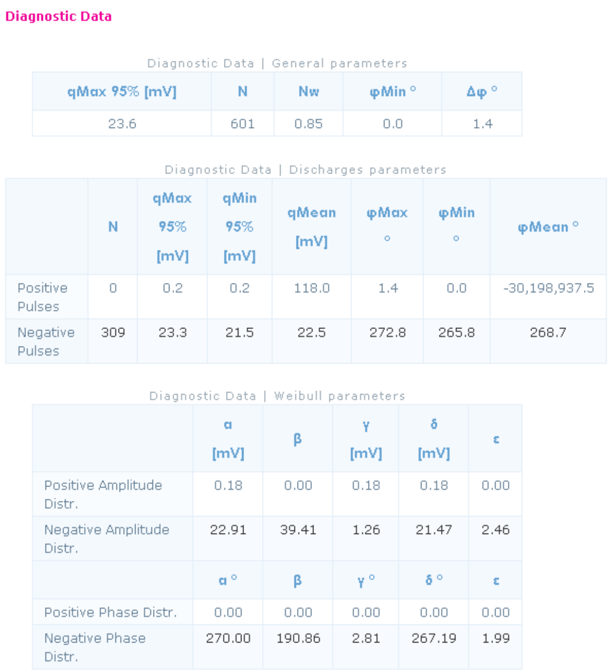


a) b) c)

Figure 17 – a) Complete pattern, b) PD pulse, c) relative frequency content of corona effect, 5.5kV

In Figure 17 it can be seen that the pattern is neat, with very low noise and the pulse shape clear and without any oscillation phenomena. The pattern is typical for the corona effect, being perfectly centered on the maximum of the negative half cycle. This demonstrates the correct evaluation of the pulse phase by the synchronization at the line frequency using the electric field sensor.

The frequency content is the one expected for this kind of partial discharge. The diagnostic parameters, together with the statistics, have been calculated automatically after the upload of the measurements on the relative Prysmian Electronics website (http://www.prysmianelectronics.com) and they are compliant with the expected ones of the corona effect (see figure 18).



Diagnostic Data

Diagnostic Data | General parameters

qMax 95% [mV]	N	Nw	φMin °	Δφ °
23.6	601	0.85	0.0	1.4

Diagnostic Data | Discharges parameters

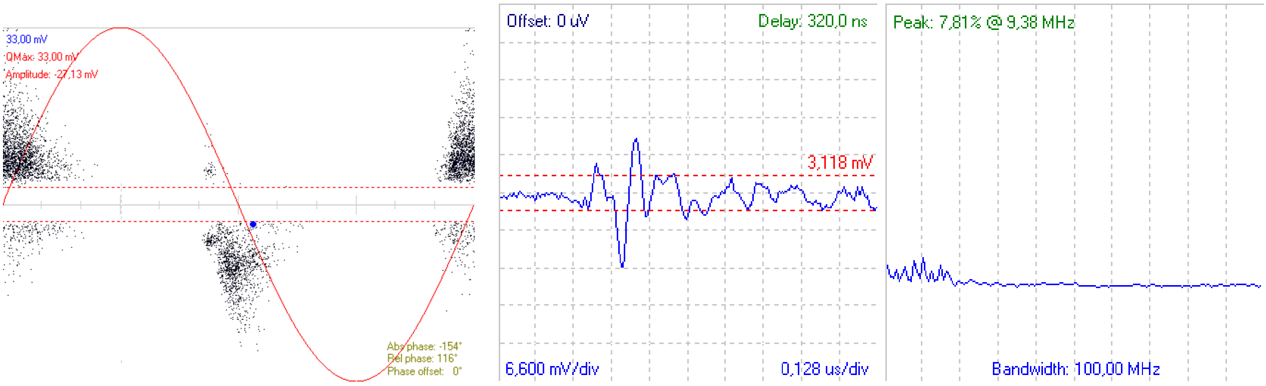
	N	qMax 95% [mV]	qMin 95% [mV]	qMean [mV]	φMax °	φMin °	φMean °
Positive Pulses	0	0.2	0.2	118.0	1.4	0.0	-30,198,937.5
Negative Pulses	309	23.3	21.5	22.5	272.8	265.8	268.7

Diagnostic Data | Weibull parameters

	α [mV]	β	γ [mV]	δ [mV]	ε
Positive Amplitude Distr.	0.18	0.00	0.18	0.18	0.00
Negative Amplitude Distr.	22.91	39.41	1.26	21.47	2.46
	α °	β	γ °	δ °	ε
Positive Phase Distr.	0.00	0.00	0.00	0.00	0.00
Negative Phase Distr.	270.00	190.86	2.81	267.19	1.99

Figure 18 – Diagnostic parameters calculated on the acquisition of figure 14 and available on the website interface.

In figure 19 the third acquired pattern is relative to surface partial discharges on a GIS termination, where a certain quantity of insulating oil has been removed. Even in this case the pattern is neat and without any noise. The pattern is typical for this kind of partial discharges and the frequency content is considerably wider than in the previous two examples. The pulse shape is such as to create the minimum polarity error on the acquired pattern. The amplitude of the acquired discharge, after the calibration measurement discussed before, shows that the maximum amplitude of this pattern is about tens of pC.



a) ***b)*** ***c)***

Figure 19 – a) Complete pattern, b) PD pulse, c) relative frequency content of an acquisition on a GIS termination, 150kV.

7.3.3 Conclusions about the evaluation of the measurements

In light of the measurements made, which of course are not limited to those described herein, we can say that the measure and the quantitative and statistical parameters calculated from them are in line with the ones expected from an instrument of this class.

The information provided by the manufacturer is in line with the findings during the use of the instrumentation.

8 MEASURE PROCEDURE

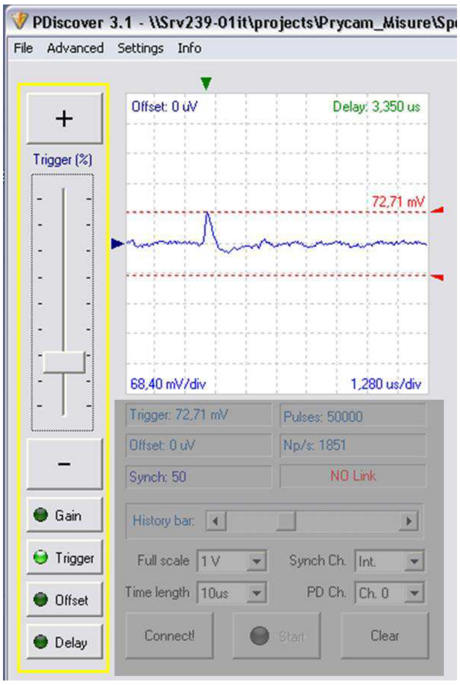
Because of the licensing policy, the Pry-Cam imposes some initial activities, before starting a measurement campaign.
The first of these is the creation of a work order, an operation that is performed via Prysmian Electronics website, which enables the system to be used for a certain number of measures. Once completed this task, the user can proceed to download the work order file, which enables the instrument as well as the communication with the PC, in order to ensure data security that in some case can be considered "sensitive data". Once the PryCam has been enabled, it is possible to start the measurements on site.

8.1 Arrival on site

After the arrival on site, all the information about the system, the characteristics of the components and in some cases the wiring diagram of the circuit under test (in case it is particularly complex), should be taken. Completed this step, the proper sequence of the measures to be performed is identified, in consideration of the power supply location of the components under test and of the circuit topology.
In case of the PD measurement has to be performed on a single component only (such as a terminal), only one PryCam will be installed.
In case it is necessary to perform the localization of the source of a previously detected PD, two or more Pry-Cam will be positioned in the most suitable locations. In consideration of the type of components, e.g. measurements on many joints, it can be necessary to open one or more link box in order to place the instruments, as discussed in the previous sections.

8.2 Preliminary environment measure

When the system under test is powered by the grid voltage, it is possible to take advantage of the mobile nature of the PryCam. In this case, it is strongly advisable to perform first an environment measurement at a safety distance. The equipment has an "autoset" function, helping the user in setting the main acquisition parameters.
This preliminary measurement enables to evaluate if any strong PD activities are in progress and the potential dangerous situations that can be sensed even from far distance. In case, it is discouraged to proceed further to a closer measure; the system should instead be put out-of-service and a safer off-line test with adjustable voltage be performed, avoiding potential risks.
If the preliminary measure does not give any significant PD, closer measurements can be performed.
This procedure is always strongly advisable and becomes mandatory when tests on components with porcelain insulator (such as outdoor terminations, CT, VT) are performed.



Offset: 0 uV
Delay: 3,350 us
72,71 mV
68,40 mV/div
1,280 us/div
Trigger: 72,71 mV
Pulses: 50000
Offset: 0 uV
Np/s: 1851
Synch: 50
NO Link
Full scale 1 V
Synch Ch. Int.
Time length 10us
PD Ch. Ch. 0

Figure 20 – Acquisition settings on the PryCam software.

This environment measure is an additional possibility compared to what is offered by other instruments. Many instruments are, in fact, coupled to the component by means of a high-frequency current transformer, it is necessary to disconnect the power to supply during the installation of the sensor and it is not possible to perform an environment measure.

8.3 Measurement on the accessory

Once the accessory is ready to be measured at a close distance and the connection to the PC has been established by means of the Wi-Fi interface, the PryCam can be positioned in the most suitable conditions, as discussed in the previous sections, and the measure can be started. First, the acquisition parameters are configured, as shown in figure 20, such as Gain, Trigger, Offset, Time scale. These parameters are usually common to other instrumentations. Whenever possible, if the system is powered by an autonomous resonant power supply, it is advisable to perform a measure with the calibrator in order to find the conversion factor between mV, PryCam main unit, and pC. This conversion factor is very useful in commissioning activities, since many installations are constrained to a maximum allowed threshold in pC for the PD test.

Whenever it is not possible to perform the calibration, an average conversion factor of 10pC=1.5 mV has been found in many tests in laboratory. This is the most frequent conversion factor found in many calibrations performed on high-voltage systems with the measurement conditions described in the previous sections.

Now, after a first automatic regulation of the parameters, these can be further manually adjusted in order to have the best picture of the signal on the application. If the pattern shows just noise, the measurement can be saved.

Figure 21 – Use of the hook stick in defect localization.

8.4 Further measures on the accessory (in order to locate the PD source)

If PDs are found, additional measures are performed moving the instrument and checking in which position the acquired amplitude becomes maximum and, in turn, the noise minimum, so that it is possible to find the defect location.

When dealing with buried joints or buried cables, it is not possible to move the instruments. However in case of tests on outdoor terminations it is easy to move the Pry-Cam along the bushing profile with a specific hook stick, in order to find the exact position of the defect (figure 21). In this case a specific safety procedure has to be discussed with the plant operator. Also in this case the purpose is to look for the maximum of the signal amplitude. During this operation, the parameters must he adjusted continuously (gain, trigger and time division) to keep the acquired signal inside the measuring window, obtaining a good diagnostic pattern. During these operations, it is possible to use the "autoset" feature. Also, it can be useful to introduce software filters based on the pulse shape, in order to obtain the measure of the desired phenomenon only. These filters are usually introduced in order to remove disturbing noise coming from corona effect or high-frequency noise generated by electronic devices in the nearby. In figure 22 and 23 other situations where it is possible to perform the localization of the fault in medium voltage (MV) systems by means of the PryCam are shown.

Figure 22 – Localization of the faulty joint in medium-voltage

Figure 23 – Localization of the fault on cable - MV

9 FIELD APPLICATION EXAMPLES

9.1 Measurement on a 500 kV circuit at CESI (Milan)

As an example we report here an application performed on a test circuit at CESI Laboratories in Milan. The circuit was composed by two 500 kV outdoor terminations (OTC and TES type), 6 cable joints, one SF6 back-to-back 'joint' and 7 cable lengths with a conductor diameter of 2500 mm².

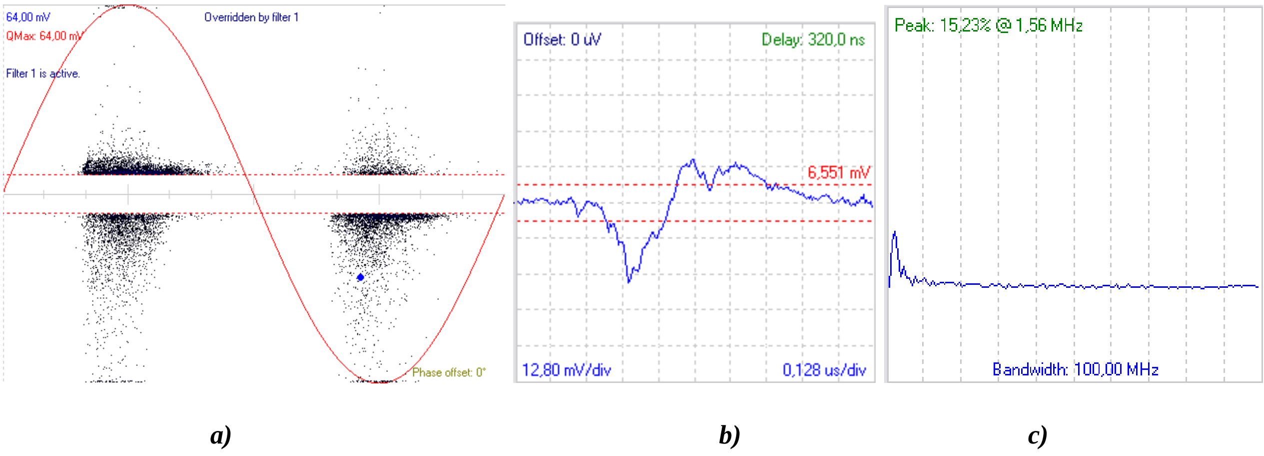


Figure 24 – a) Complete PD pattern, b) PD pulse, c) pulse frequency content of a PD on a OTC 500 kV termination.

In February 2013 a Pry-Cam Grids monitoring system (the fixed version of the Pry-Cam Portable described in the previous paragraphs) begins to acquire PDs with increasing amplitude over time, until the 2nd April 2013 the pattern shown in Fig. 24 was acquired. Due to the importance of the phenomenon it was accurately analysed along with the previous patterns. At first it was suspected that the pattern could be related to a corona effect characterised by very low frequency content pulses as shown in fig. 24, where the peak frequency at 1.56 MHz can be seen. This information lead to the conclusion that the PD were not on the cable segment or joints because at this short distance (< 50 m) the frequency content of internal PD should be considerably higher (8-15 MHz), so the research was focused on the terminations.

Figure 25 – Directional search of the defect.

The search for the PD source immediately revealed that it was located in one of the two terminations, and after a further investigation it was located at about 1/3 of the height of the termination (fig. 25). Subsequent measures showed that the inception voltage was close to 115 kV and the extinction voltage was about 125 kV. Figure 26 show the PD pattern acquired at 300 kV.

It can be seen that the amplitude of the PD signal acquired at the base of the termination at a lower voltage, is greater compared to the one acquired at about 10 m from the termination at 400 kV. Before removing and opening the termination the content of acetylene and other dissolved gas in the insulating oil were carried out. These kind of analysis were requested to a specialised laboratory (report shown in appendix), and from this report it resulted an abnormal concentration of acetylene, a typical sign of partial discharges presence. After this result, the termination was opened and a visual inspection performed: clear traces of a treeing were found on the surface of the stress cone, as shown in fig. 27.

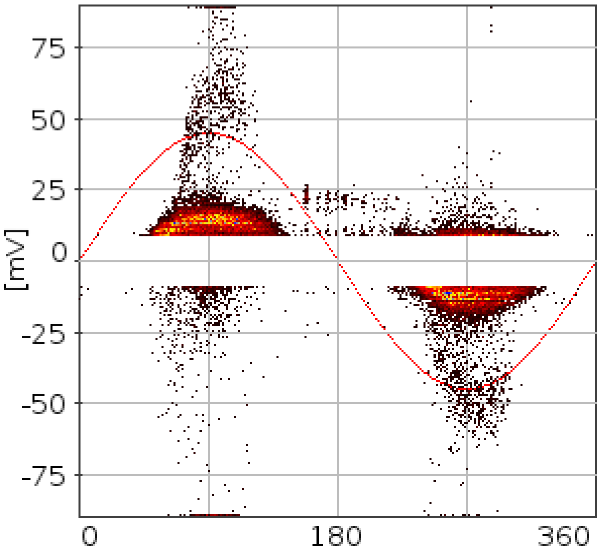


Figure 26 – PD pattern acquired at the termination base.

Figure 27 – Treeing traces on the cone of a OTC 500kV external termination.

10 CONCLUSIONS

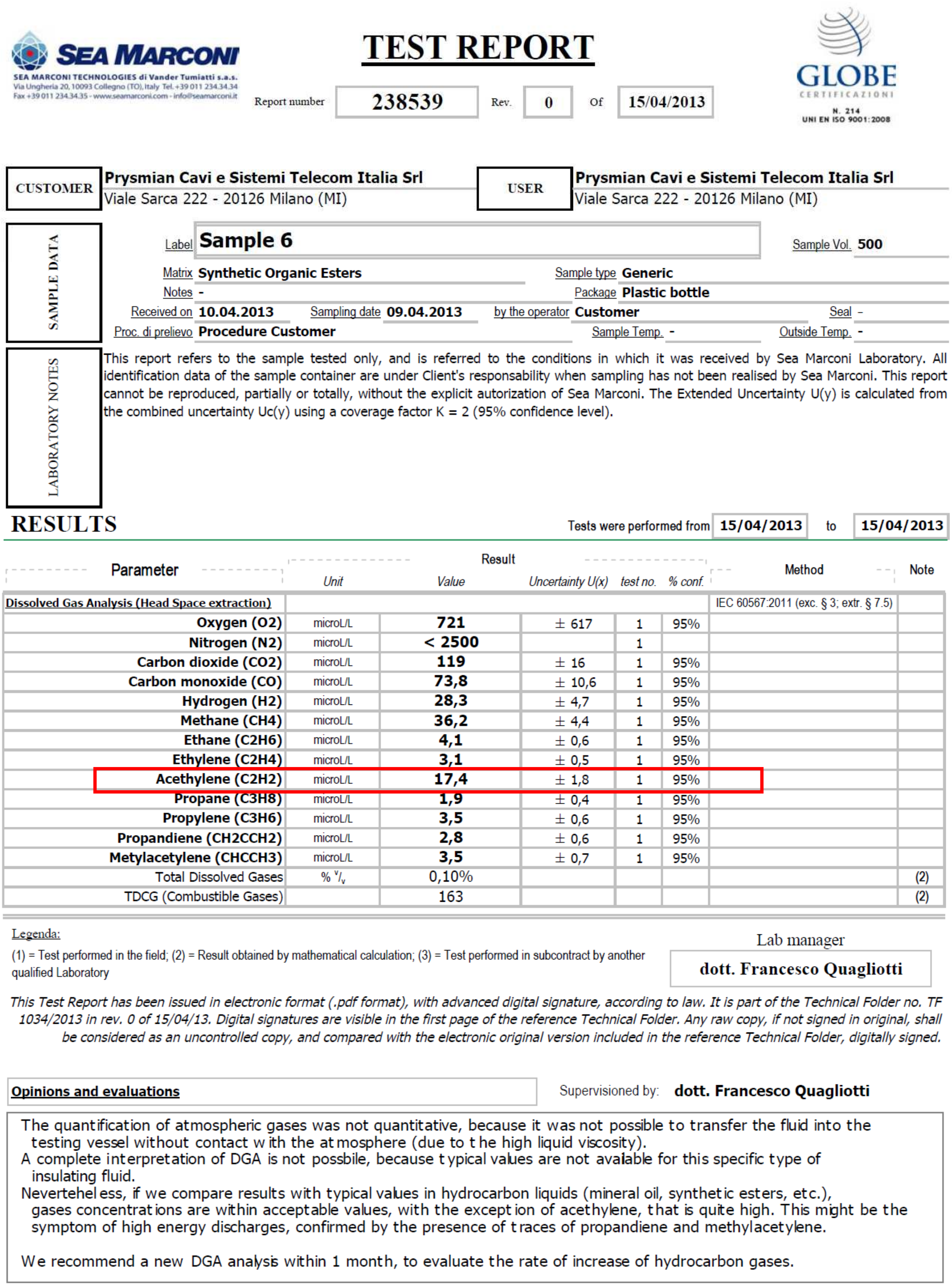
This technical report describes the operating methodology of the Pry-Cam instrument for the detection of partial discharges (PD) in high voltage cable circuits.
In the first part it was discussed the purposes of PD measurements (i.e. “metrological” measure or “diagnostic” measure) and the currently available technologies such as “conventional” or “UHF”. Then the Pry-Cam system and its working principle were introduced so to allow a better comprehension of the latest part of the report dealing with the measurement procedures, in particular on high voltage cable system commissioning.
It was shown that the instrument features, in addition to common functions also available in other PD acquisition instruments, an innovative electromagnetic sensor able to detect either high frequency signals typical of PDs, either the low frequency signal generated by the component supply voltage, to be used as a phase reference. These characteristics allow to easily employing the instrument as in the two most common measurement configuration described in the reference standard [1]. The most important advantage allowed by the Pry-Cam is the possibility to acquire and correlate the PD signal with the voltage phase angle without the need of a galvanic connection or additional sensors.
The calibration procedure used for the instrument is essentially the same employed with traditional instrumentation. It has been described along with the other processing capabilities that can be carried out with the control software.
The possibility of moving the instrument while performing measurements for locating the PD source, even if prevents a full valid calibration, it allows to precisely localise the PD source.

It was described the use of a single Pry-Cam on a single accessory and on a circuit comprising several components (cable, joints and terminations). In this case it is possible to localise the position of the defective point.

11 BIBLIOGRAPHY

[1] IEC 60270 “High voltage test techniques – partial discharge measurements”

APPENDIX: OIL ANALYSIS



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TEST REPORT

Report number **238539** Rev. **0** Of **15/04/2013**

GLOBE CERTIFICAZIONI
N. 214
UNI EN ISO 9001:2008

CUSTOMER	**Prysmian Cavi e Sistemi Telecom Italia Srl** Viale Sarca 222 - 20126 Milano (MI)	USER	**Prysmian Cavi e Sistemi Telecom Italia Srl** Viale Sarca 222 - 20126 Milano (MI)

SAMPLE DATA

Label **Sample 6**
Sample Vol. **500**
Matrix **Synthetic Organic Esters**
Sample type **Generic**
Notes **-**
Package **Plastic bottle**
Received on **10.04.2013**
Sampling date **09.04.2013**
by the operator **Customer**
Seal -
Proc. di prelievo **Procedure Customer**
Sample Temp. -
Outside Temp. -

LABORATORY NOTES

This report refers to the sample tested only, and is referred to the conditions in which it was received by Sea Marconi Laboratory. All identification data of the sample container are under Client's responsability when sampling has not been realised by Sea Marconi. This report cannot be reproduced, partially or totally, without the explicit autorization of Sea Marconi. The Extended Uncertainty U(y) is calculated from the combined uncertainty Uc(y) using a coverage factor K = 2 (95% confidence level).

RESULTS

Tests were performed from **15/04/2013** to **15/04/2013**

Parameter	Result					Method	Note
	Unit	Value	Uncertainty U(x)	test no.	% conf.		
Dissolved Gas Analysis (Head Space extraction)						IEC 60567:2011 (exc. § 3; extr. § 7.5)	
Oxygen (O2)	microL/L	**721**	± 617	1	95%		
Nitrogen (N2)	microL/L	**< 2500**		1			
Carbon dioxide (CO2)	microL/L	**119**	± 16	1	95%		
Carbon monoxide (CO)	microL/L	**73,8**	± 10,6	1	95%		
Hydrogen (H2)	microL/L	**28,3**	± 4,7	1	95%		
Methane (CH4)	microL/L	**36,2**	± 4,4	1	95%		
Ethane (C2H6)	microL/L	**4,1**	± 0,6	1	95%		
Ethylene (C2H4)	microL/L	**3,1**	± 0,5	1	95%		
Acethylene (C2H2)	microL/L	**17,4**	± 1,8	1	95%		
Propane (C3H8)	microL/L	**1,9**	± 0,4	1	95%		
Propylene (C3H6)	microL/L	**3,5**	± 0,6	1	95%		
Propandiene (CH2CCH2)	microL/L	**2,8**	± 0,6	1	95%		
Metylacetylene (CHCCH3)	microL/L	**3,5**	± 0,7	1	95%		
Total Dissolved Gases	% $^{v}/_{v}$	0,10%					(2)
TDCG (Combustible Gases)		163					(2)

Legenda:
(1) = Test performed in the field; (2) = Result obtained by mathematical calculation; (3) = Test performed in subcontract by another qualified Laboratory

Lab manager
dott. Francesco Quagliotti

This Test Report has been issued in electronic format (.pdf format), with advanced digital signature, according to law. It is part of the Technical Folder no. TF 1034/2013 in rev. 0 of 15/04/13. Digital signatures are visible in the first page of the reference Technical Folder. Any raw copy, if not signed in original, shall be considered as an uncontrolled copy, and compared with the electronic original version included in the reference Technical Folder, digitally signed.

Opinions and evaluations

Supervisioned by: **dott. Francesco Quagliotti**

The quantification of atmospheric gases was not quantitative, because it was not possible to transfer the fluid into the testing vessel without contact with the atmosphere (due to the high liquid viscosity).
A complete interpretation of DGA is not possbile, because typical values are not avalable for this specific type of insulating fluid.
Nevertehelless, if we compare results with typical values in hydrocarbon liquids (mineral oil, synthetic esters, etc.), gases concentrations are within acceptable values, with the exception of acethylene, that is quite high. This might be the symptom of high energy discharges, confirmed by the presence of traces of propandiene and methylacetylene.

We recommend a new DGA analysis within 1 month, to evaluate the rate of increase of hydrocarbon gases.