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Application of UHF method for on-line PD diagnostics of cable terminations

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SUMMARY

Several IEC standards, e.g. IEC 60840, prescribe routine tests on prefabricated components of HV cable accessories to be carried out by manufacturers. But an improper assembly done under on-site conditions can strongly affect the long-term performance of the completed accessory. Therefore, to make sure that the assembly was done immaculately, a quality check is often desired by utilities. The presented method can be used for this purpose.

To detect a partial discharge activity under conditions of on-site on-line testing, UHF PD diagnosis principle can be used. This method is based on sensing the electromagnetic emissions from discharge sites in the insulation. A portable screening sleeve with mounted capacitive and inductive sensors is clamped around the plug-in cable termination, while the cable system is in operation. The sleeve shields the UHF sensors against outside interferences, thus, a sensitive PD measurement even in a noisy environment is possible. Nanosecond pulses emitted from the PD fault site and captured with different sensors are consequently pre-amplified, filtered and recorded by a programmable oscilloscope, which is remotely controlled by a notebook with the written software. As diagnosis parameters the pulse's shape, its spectral characteristics and repetition rate are considered. Phase resolved PD patterns are taken to figure out if the pulse activity is power cycle related.

The calibration of the UHF method in terms of amount of charge is impossible, but comparative PD measurements can be performed on laboratory test set-up using both the UHF method and the conventional method according to IEC60270. A sensitivity below 5 pC turned out to be detectable by the presented UHF method. Besides the sensitivity check, a spatial selectivity of the UHF method was investigated by exposing the test setup to the corona interferences generated on a protrusion in SF_6 and air. The corona discharge at two origins in turn was induced, such as inside the GIS behind a 2m-long cable part, and second, in the immediate proximity of the sensed termination, namely inside the SF_6-filled end joint. In both cases the effective PD detection was not affected.

Several on-site/on-line measurements, as well as laboratory experiments given in the paper demonstrate the effectiveness of the on-line ultra wide band PD detection. The method can be applied to proof the quality of assembly work during the commissioning, as well as on a regular basis after many years in service to detect aged and risky terminations as a part of the condition-based maintenance.

KEYWORDS

On-line diagnostics, cable termination, partial discharge (PD), ultra-high frequency (UHF), sensitivity check.

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1. INTRODUCTION

A failure of a high voltage power cable causes a service interruption, costly location, repairs and loss of revenues. Modern plug-in cable connectors (terminations) for GIS and transformers are made from silicone rubber. The electrical life span of this high polymeric material normally exceeds 40 years, but only in absence of partial discharge (PD) activity that inevitably causes material degradation. Several IEC standards prescribe routine tests on the prefabricated components of HV cable accessories to be carried out by manufacturers. The conventional IEC 60270 method, which can be calibrated, is always applied during quality assurance testing on the components in the factory in those cases. An inaccurate assembly done under on-site conditions can strongly affect the long-term performance of the complete accessory. Therefore, to make sure that the assembly was done properly, a quality check on-site is often desired by utilities.

Partial discharge detection is a well established criterion for the condition assessment and quality control of the high voltage electrical insulation. The occurrence of PD in electrical insulation is always associated with the emission of electromagnetic pulses. A typical PD pulse has a rise time of less than 1 ns and a width of a few ns, implying in frequency-domain a bandwidth of several hundreds of MHz. The ultra-wide band PD (UHF PD) diagnosis is based on capturing those pulses. This method yields higher signal-to-noise ratio under on-site conditions comparing to the conventional IEC 60270 PD measurement.

Although there are several well known off-line test techniques, which are successfully applied to diagnose power cables including their accessories, they all need a line disconnection, load flow re-dispatching and a separate voltage source to energize the cable line apart from the network. The on-line test approach overcomes these difficulties allowing sensitive measurement on the terminations, while the cable is in normal operation.
Once excited, the electromagnetic emissions propagate in all directions from the PD source. Different materials impose different attenuation factors to the travelling waves. In general, the attenuation of the PD pulses is a function of frequency [1]. The higher frequency components will be attenuated rapidly when they travel along the cable. Therefore, detecting PD in the UHF band (300-3000 MHz), that has only a few known discrete interferences, also has the advantage of the distance selectivity of only several meters. This can be perfectly used for the diagnosis of the cable accessories.

Fig. 1 demonstrates the principle of on-line UHF PD sensing in the plug-in cable connectors. A portable metallic housing is clamped on the cable behind the connector and fulfils two functions: firstly, as a housing for field couplers (antennas) and secondly, as a grounded screen against the disturbances from outside. The sensors are mounted inside the enclosure and terminated with BNC jacks. The capacitive sensor represents a copper disc with the diameter of 2 cm, soldered to the copper pin in the middle. The inductive sensor is a two-winding coil made from an insulated wire. One end of the coil is grounded; the other end is connected via BNC jack to a measuring coaxial cable RG-214.

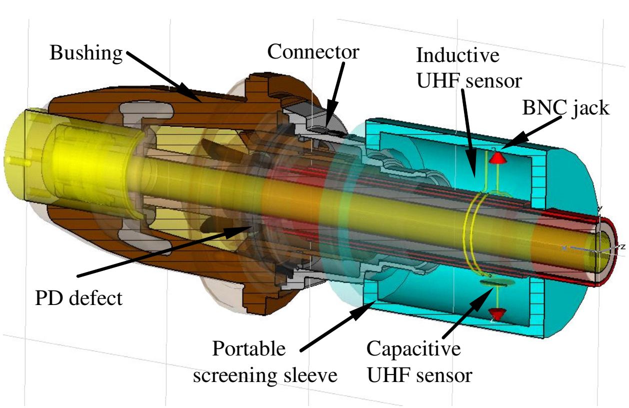

Fig. 1: Object and principle of the UHF diagnostics

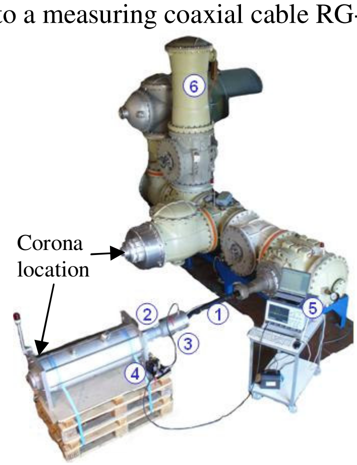

Fig. 2: Laboratory set-up and locations of corona

2. EXPERIMENTAL ARRANGEMENT

Fig. 2 presents an experimental arrangement built in a laboratory. It includes:

- a commercial 550 kV GIS equipped with a coupling capacitor (6) and a conventional IEC 60270 PD measurement system,
- a 2 m long power cable 35/60 kV (1) terminated at SF_6-filled test joint via a termination size 4 up to 72,5 kV (2) with a built-it artificial PD defect,
- an UHF PD detection circuit, shown also in Fig. 5, that contains the portable screening sleeve (3) with capacitive and inductive sensors inside, coaxial cables RG-214, high pass filter with the cut-off frequency of 200 MHz, a 40 dB or 25 dB preamplifier (4) and an 1 GHz high speed digital oscilloscope and a notebook (5).

Power supply of the measurement circuit is realized via insulating transformer. An artificial insulation defect was built-in to initiate a discharge at interfaces between materials. This kind of fault is very typical for defects in cable accessories. For that purpose a plastic lath covered with some silicon grease was introduced along the boundary between the cable insulation and a stress cone. The intensity of PD was influenced by changing the penetration depth of the lath.

3. LABORATORY MEASUREMENTS

3.1. Sensor types and functionality

In general, the field emissions caused by PD pulses can be coupled in a capacitive or inductive manner.

Capacitive couplers (sensors) use the electric component of the transient field. The capacitive coupling generally depends on the dimensions of the sensor, distance to the test object and the electric field strength of the emitted waves. In the vicinity of the PD source, the discharge pulses are carried by a small portion of the neighbouring materials and they need some space until they will distribute uniformly along the circumference of the accessory or cable [1]. Therefore to increase the spatial detection sensitivity of capacitive sensing one needs to put several sensors along the circumference or simply move the single sensor along the circle.

Inductive sensors, also called high frequency current transformers (HFCT), are usually made in form of coil or toroid. They couple the magnetic component of the field. Thus, the voltage induced in the coil is proportional to the rate of change of the current passing through the coil. The magnetic coupling depends on the number of turns, distance to the test object, the magnetic field strength outside the cable and the frequency. Sensor coils can have a ferrite core. In that case they are more sensitive, but no longer linear, which is undesirable from the calibration point of view. Their advantage over the capacitive sensors is that they control the whole circumference of the cable.

The Fourier transforms of the internal PD impulses (15 pC measured by the IEC 60270 method) picked up in time-domain by capacitive and inductive sensors are shown in Fig. 3, 4 respectively.

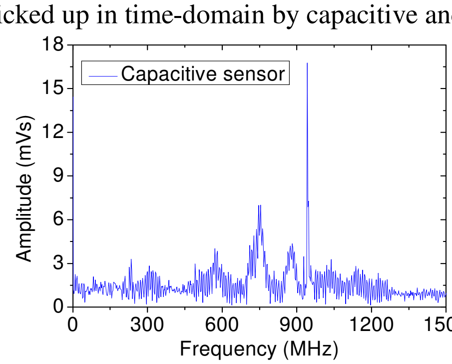

Fig. 3: Frequency spectrum of a PD pulse (15 pC) captured with the capacitive sensor

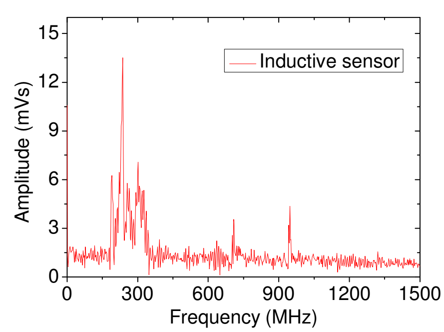

Fig. 4: Frequency spectrum of a PD pulse (15 pC) captured with the inductive sensor in time-domain

It can be seen that the capacitive sensor captures broadband frequency components of an internal PD in a range of 500-1000 MHz. The inductive sensor provides a different FFT spectrum with the highest signal-noise ratio in a range from 200 (filter's cut-off frequency) up to 350 MHz. Two main narrowband interferences of approx. 730 and 940 MHz can be found in all laboratory measurements, these are the local DVB-T and GSM signals accordingly.

3.2. Sensitivity of UHF sensors

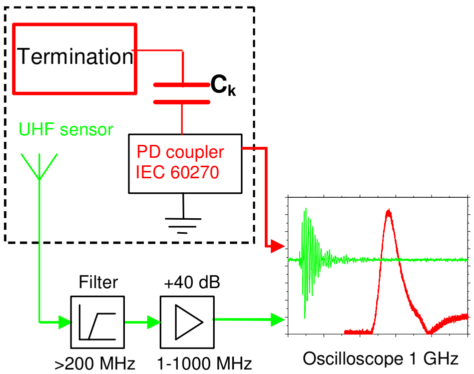

Fig. 5: Structural diagram of the comparative measurement between UHF and IEC60270 PD detecting methods

It is known that the calibration of the UHF method in terms of apparent charge is impossible. Hence in order to be able to judge in the future, whether a termination is faulty or not, a so called sensitivity check must be performed under laboratory conditions. For this purpose a conventional PD measurement according to the IEC 60270 standard is carried out simultaneously with the UHF diagnostics. The structural diagram of the sensitivity check is shown in Fig. 5. The apparent charge signal is taken immediately out of the coupling quadrupole and calibrated using a standard charge injector. As a result, the sensitivity below 5 pC turned out to be detectable by both types of UHF sensors inside the screening housing.

To establish functionality between the key parameters of both methods, namely the peak voltage of the UHF pulses and the corresponding values of the apparent charge, a series of simultaneous measurements was performed. The PD intensity was increased by pushing the plastic lath of the artificial PD defect farther beneath the stress cone of the termination. AC voltage of 50 kV (single phase, rms) was constantly applied during the test. A pre-amplification was omitted due to the saturation effect at the higher levels of discharge activity. The results are shown in Fig. 6. Comparing the sensors it can be seen that capacitive coupling has generally a higher sensitivity, than the inductive one. This is due to the narrower band of the inductive sensor, limited by the high pass filter downwards and self resonance frequency upwards. The latter is determined by the relation of the inductivity to the parasitic capacitance of the coil.

3.3. Correlation between the UHF pulse energy and apparent charge

Several publications note that energy is more objective criterion to compare the UHF and IEC60270 methods [2-3]. The latter reacts on a charge, which eventually represents the stored energy. Peak voltage, on the contrary, is more a parameter of the discharge current growth rate and can differ

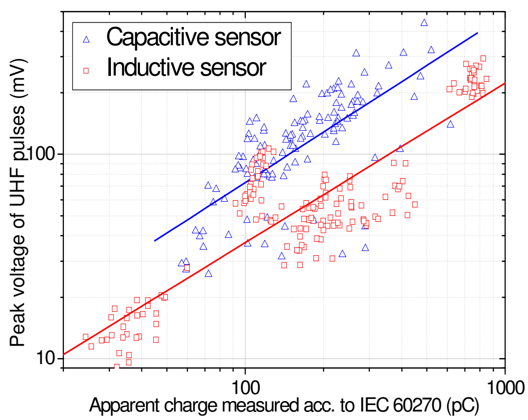

Fig. 6: Sensitivity lines of the UHF sensors

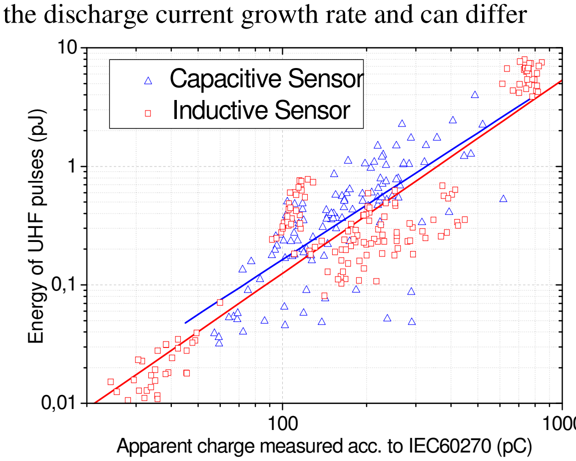

Fig. 7: Correlation between the energy of the UHF pulses and the corresponding apparent charge

greatly for different types of PD defects and strongly depends on damping characteristics of materials on the way from defect's origin to the sensors. A series of laboratory measurements was made on the termination with an artificial defect to establish the correlation between the UHF pulse energy and the apparent charge. The IEC 60270 signals were taken directly at the output of the quadrupole after a preamplifier, to enable time responses of the same order. Energy of the pulses was calculated according to the formula:

$$E = \frac{1}{50\Omega} \int u^2 dt \, , \tag{1}$$

where u is a voltage output from the UHF sensor.
Fig. 7 reflects around 200 PD events in the range of 5-900 pC acquired at constantly applied voltage of 50 kV. A general trend in the energy (voltage) gain with rising value of apparent charge is evident. But certainly its slope will be affected by the type and origin of a PD defect.

3.4. Susceptibility to corona disturbances

Regarding an on-site application of the method, continuous background interference has to be considered. Most demanding type of the interference, in terms of the pulse-phase appearance, is a corona discharge [4]. To be sure that the detected pulse activity originates within the tested termination and does not come from some other place, for instance neighbouring GIS or aerial feeder, the following measurement series was carried out. The laboratory test setup was supplemented with two sources of corona discharges at protrusion in air or SF_6. A 10 cm long aluminium wire was attached to the HV electrode of the test joint instead of a removed dummy connector as marked in Fig. 2. The test joint was sealed with a so called gas seal and alternatively filled with either SF_6 or air at atmospheric pressure. Sensors were located at the connector plugged into the test joint as in the previous tests.

The measurement results of the corona disturbance originating in the test joint were produced at 3 kV, when the corona discharge intensity on the tip of the wire comprised 35 pC, as measured acc. to IEC60270. In the graphs shown in Fig. 8 the Fourier transforms of the signals picked by the disc and coil sensors are plotted respectively. In time-domain the pulses looked very similar to the internal PD defect in the insulation. But the FFT spectrum of the impulse picked up by the capacitive sensor facilitates a clear distinction between the corona in both air and SF_6 in the range of 300-500 MHz and the PD discharges in the range of 700-1000 MHz (see Fig. 3 to compare). The inductive sensor, on the contrary, sees the corona in the air with a very similar Fourier spectrum as a real PD (see Fig. 4) in the range of 200-350 MHz. Only corona in SF_6 can be well differentiated from an internal PD by the inductive coupler.

Later a protrusion was attached to a HV electrode of a separate GIS segment filled with air or SF_6 under normal pressure. The AC voltage was raised up to 4 kV until IEC60270 reading reached 150 pC. No impulse activity could be registered by both sensors. This is due to the high attenuation of the UHF waves between the protrusion and the sensors (approx. 2 m of the GIS and 2 m of the cable).

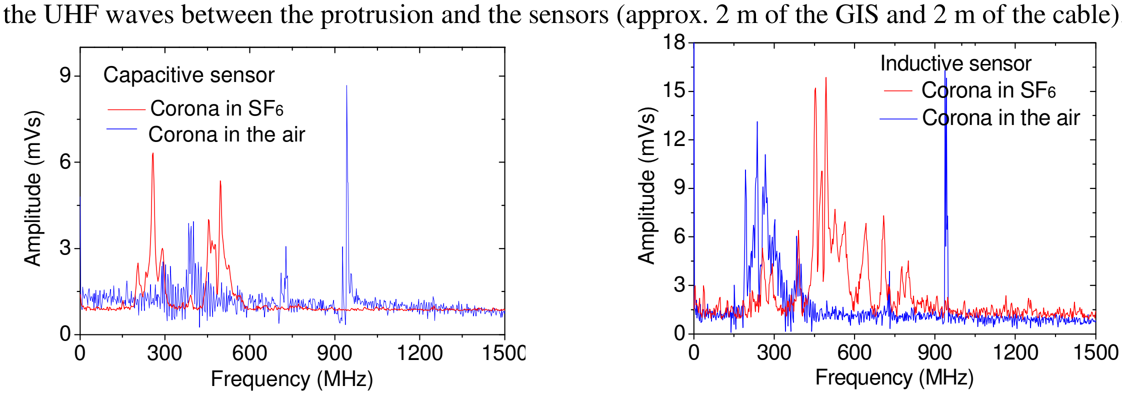

Fig. 8: Frequency spectrum of the corona pulse of 35 pC originated in SF_6 or air inside the test joint and captured with the capacitive (left) and inductive (right) UHF sensors

4. ENHANCED OPPORTUNITIES FOR METHOD'S APPLICATION ON-SITE

4.1. Phase resolved UHF PD measurements

Often in a noisy on-site environment a repetitive pulse activity picked up by the diagnostic system can be falsely interpreted as possible PD. It is known that partial discharges in electrical insulation only occur at certain moments depending on the phase of applied voltage. So one can easily differentiate between power cycle related pulses and the rest. To enable an automated acquisition of UHF PRPD patterns a software was written, which remotely controls the oscilloscope and collect the key parameters of UHF pulses into a database over numerous trigger events. Here the UHF signal is used to trigger the measurement; the exact phase angle is calculated for each trigger event using the value of applied voltage measured with a divider in the laboratory.

Fig. 9 and 10 represent the simultaneous measurement on the lab setup by both the IEC 60270 and the UHF methods. The images shown stand for an inner PD activity recorded over 5 min. The UHF PRPD image counts over 2500 PD pulses triggered. The shape and phase position of both patterns are very similar.

The PRPD images of the corona discharge activity (protrusion in the air) inside the test joint as described in 3.4 are shown in Fig. 11 and 12. The only difference in these patterns is that the UHF PD image has a gap at voltage peak. This could be a result of the glow discharge that has no ultra-high frequency components at the voltages higher than certain values [5]. Nevertheless, based on the UHF PRPD images one can easily differentiate between the internal PDs and corona interferences on-site.

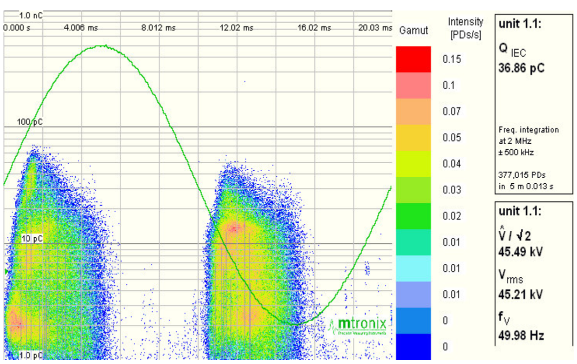

Fig. 9: PRPD image of internal PD acc. IEC60270 (<80 pC at 45 kV)

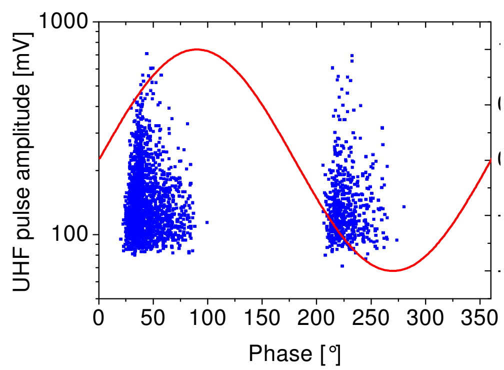

Fig. 10: UHF PRPD image of internal PD picked by via capacitive UHF sensor by the programmed oscilloscope

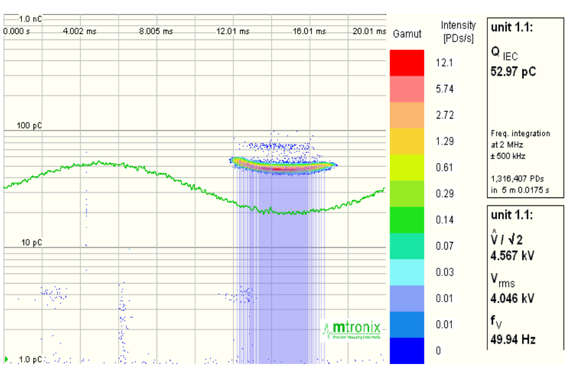

Fig. 11: PRPD image of the corona discharge inside the test joint acc. IEC60270 (50 pC, 4,5 kV)

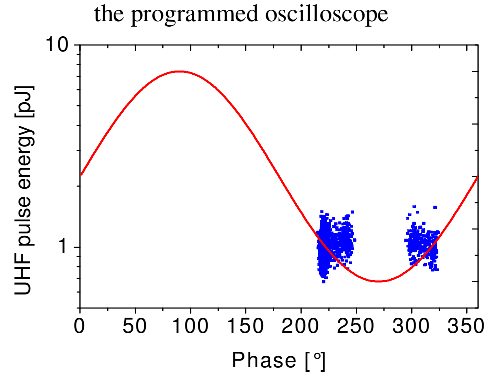

Fig. 12: UHF PRPD image of the corona picked by the capacitive coupler:

Regarding an on-site testing in GIS substations there are very few possibilities to extract each phase signal. The own supply voltage of the oscilloscope or a specially developed "phase signal box" are sufficient to proof an AC cycle relation of repetitive pulses. In this case one receives the PRPD pattern over a 50 Hz sine signal, which is shifted to an unknown degree with respect to the original.

4.2. PD detection using an integrated voltage sensor

A significant number of plug-in connecting systems are equipped with a capacitive voltage sensor, integrated in the bushing. The output signal of this sensor is normally used to signalize if the operating voltage is applied or not. It can be used for PD diagnosis as well.

A plug-in cable connector with an artificial PD defect was plugged into the bushing equipped with the voltage sensor. The measuring cable was directly (without filtering and pre-amplification) connecting the sensor output to the 50 Ohm input of an oscilloscope. A few comparative tests to establish sensor's sensitivity in accordance with the scheme shown in Fig. 5 were conducted. Fig. 13 shows sensor's output at a partial discharge intensity of 100 pC picked up with an oscilloscope. An FFT transform of this signal is given in Fig. 14. Frequency components below 100 MHz dominate in the signal that allows a usage of oscilloscopes with narrow bandwidth. Maximal sensitivity without any amplification lies below 10 pC.

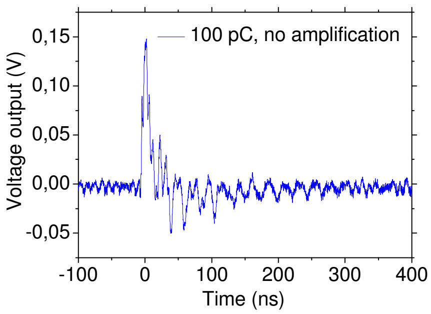

Fig. 13: Output of the voltage sensor at 100 pC

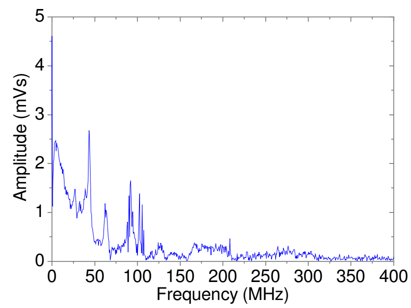

Fig. 14: FFT spectrum of the pulse

5. FIELD EXPERIENCE

Fig. 15: On-site test set-up

On-site PD measurements were made on cable terminations in the manhole of GIS, while the cables were in service. The portable screening sleeve equipped with a set of UHF sensors was clamped around each termination in turn as shown in Fig. 15. A 40 dB pre-amplification was generally used during the on-site testing. Fig. 16 shows a typical pulse signal taken on-site on a faulty termination with a 3 GHz oscilloscope. The frequency spectrum of this pulse and the spectrum of background noise are plotted in Fig. 17. Besides some discrete broadcast and GSM frequency spikes there are several other broadband frequency components that clearly indicate the presence of PD activity.

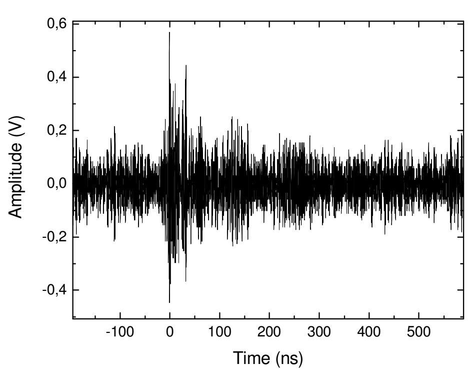

Fig. 16: Typical fast pulse emitted by the faulty termination on-site

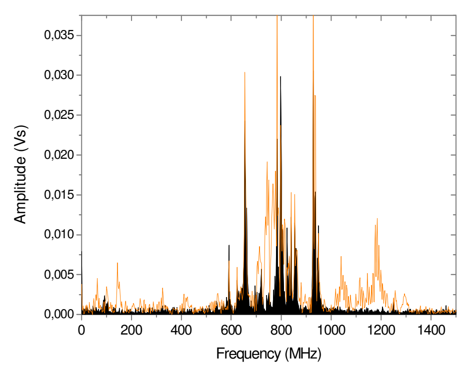

Fig.17: Frequency spectra of the pulse (light curve) vs. background noise (black filled area)

6. CONCLUSIONS

The experiences in on-line application of the ultra-high frequency partial discharge (PD) detection in high voltage plug-in cable terminations are discussed in the paper. The presented UHF PD detection method can be applied to proof the quality of assembly work during commissioning, as well as on a regular basis after years in service to detect aged and risky terminations as a part of the condition-based maintenance. The UHF sensors developed can be used without screening sleeve too, if there are any difficulties with mounting, with lower sensitivity though.

Comparative study of capacitive and inductive UHF PD sensors, as well as other laboratory tests has been shown:

- the sensors used were effective in the frequency range of 500-1000 MHz for the capacitive and 200-350 MHz for the inductive ones respectively,
- The maximal sensitivity of the screened sensors is below 5 pC for both types,
- A correlation between the key parameters of the UHF method, namely peak voltage output and energy of the pulses and the apparent charge of IEC 60270 method has been established for both types of sensors,
- Phase resolved UHF PD measurements are effective to cope with repetitive pulse noise. The technique can also be used to recognize the different types of possible PD defects on-site, if a database of typical defect PRPD patterns is collected in the laboratory previously.

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