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UHF PARTIAL DISCHARGE DIAGNOSIS OF PLUG-IN CABLE TERMINATIONS

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ABSTRACT

The experiences in on-line application of the ultrawide band partial discharge (PD) detection in high voltage plug-in cable terminations are presented. Issues of sensitivity of capacitive and inductive field couplers (sensors) are discussed. A series of comparative tests was done using an artificial defect to establish a link between peak voltage, as well as the energy of UHF pulses and the corresponding apparent charge, provided with a conventional IEC 60270 method. Examples of the UHF phase resolved PD measurements and measurements with a power detector are given. Experiences from a field testing are reported as well. The diagnostic system can be applied as a quality check on the just assembled terminations, as well as for the purposes of the condition assessment of insulation integrity after years in service.

KEYWORDS

Partial discharge (PD), UHF, on-line diagnostics, termination, sensors.

INTRODUCTION

A failure of a high voltage power cable causes a service interruption, costly location, repairs and loss of revenues. Utility experience shows that poor termination and jointing is a major cause of cable failure. This is due to the fact that, in contrast to the cable itself, these components have more complex structure, sometimes even with several dielectrics, and increased field gradients. But moreover they are assembled and installed under on-site conditions and thus exposed to the higher risk of defects and contaminations.

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 PD activity that inevitably causes material degradation. Several IEC standards, e.g. IEC 60840 [1], prescribe routine tests on the prefabricated components of HV cable accessories to be carried out by manufacturers. Unfortunately, there are no standards for testing a complete accessory yet. 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.

Another application field of the presented test technique is a condition monitoring of cable accessories in order to predict failures before they occur. Those accessories that are about to fail can then be replaced, thereby reducing the risk of cable system failures and improving the overall quality of power supply.

Partial discharge measurement is a well established criterion for the condition assessment and quality control of the high voltage electrical insulation. PD, originated from a microdefect, incepts periodically according to ac cycle of the operation voltage and gradually degrades and erodes the polymeric material, eventually leading to breakdown. To detect such a PD activity under conditions of on-site on-line testing, the ultrawide band PD (UHF PD) diagnosis principle can be deployed. This method is based on sensing the electromagnetic emissions from discharge sites in the insulation. The coupling sensors should be placed possibly close to the test object and effectively screened against outside interferences.

Although there are several well known off-line test techniques, which are successfully applied to diagnose long power cables including their accessories, they all need 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. This contribution discusses the experiences in on-line UHF PD diagnostics of high voltage cable terminations.

PRINCIPLE OF DIAGNOSTICS

The occurrence of partial discharges 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 pulse width of several ns, implying in frequency-domain a bandwidth of several GHz. The electromagnetic emissions propagate in all directions from the PD source. Different materials impose different attenuation rates to the travelling waves. In general, the attenuation of the PD pulses is a function of frequency [2]-[3]. The higher the frequency components will be attenuated rapidly when they travel along the cable. Therefore, detecting PD in the UHF band (300-3000 MHz) has the advantage of the distance selectivity of only several meters. This can be perfectly used for the diagnosis of the concentrated equipment such as transformers, GIS, machines and cable accessories. The distributed equipment, e.g. cables, can be effectively diagnosed in HF and VHF bands.

Fig. 1 demonstrates the principle of UHF diagnosis of the plug-in cable connectors. A portable metallic sleeve is clamped around the cable immediately 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.

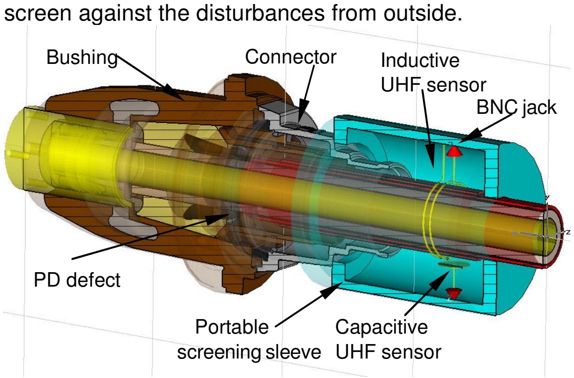

Figure 1: Object and principle of the UHF diagnostics

The sensors are mounted inside the sleeve and terminated with BNC jacks. The capacitive sensor represents a copper disc with the diameter of 2.5 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.

EXPERIMENTAL ARRANGEMENT

Fig. 2 presents an experimental arrangement built in a laboratory. It includes commercial 550 kV GIS (1), HV test transformer (2), power cable (4) connected to the GIS via connector (5) and terminated at SF_6-filled test joint (7) using the connector (6) with an artificial PD defect. The GIS is equipped with a coupling capacitor and a conventional IEC 60270 PD measurement system. An UHF PD detection circuit, shown also in Fig. 6, contains the portable screening sleeve (8) with capacitive and inductive sensors inside, coaxial cables, high pass filter with the cut-off frequency of 200 MHz, a 40 dB preamplifier (9) and an 1 GHz high speed digital oscilloscope (10).

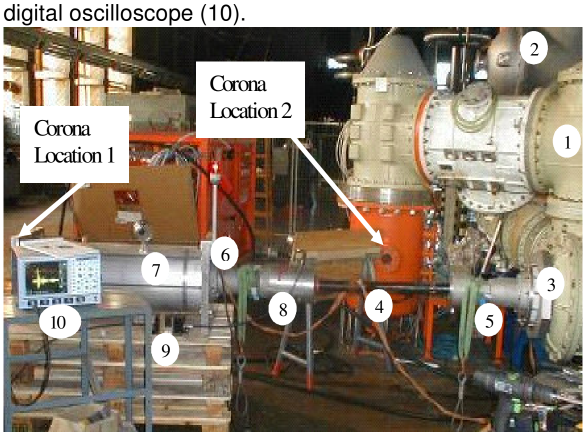

Figure 2: Laboratory set-up

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.

SIMULATION OF EIGENMODE FREQUENCIES

Since the presented UHF PD diagnostic concept implies the measurement of radiated pulses outside the termination housing, it is of high interest to figure out what own resonance frequencies (eigenmodes) this body has. Because once excited, these frequencies will be resonated according to the well known physical phenomenon. Fig. 3 demonstrates the results of eigenmode simulation on a model presented in Fig. 1. Calculation was done considering losses in materials. As a result, Q-factors, a ratio between the total signal power and power losses in materials of the model, were evaluated.

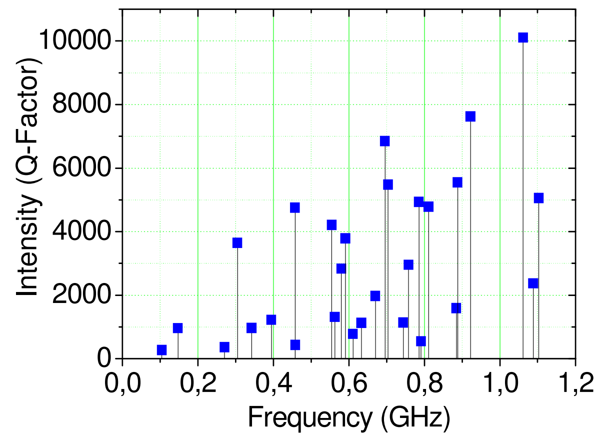

Figure 3: Eigenmode frequencies (simulated)

The eigenmode frequencies are almost uniformly distributed over the range of interest. The range of 550-850 MHz is densely occupied with eigenmode frequencies, which agrees perfectly with the working range of the sensors and hardware used.

LABORATORY MEASUREMENTS

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 [2]. 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

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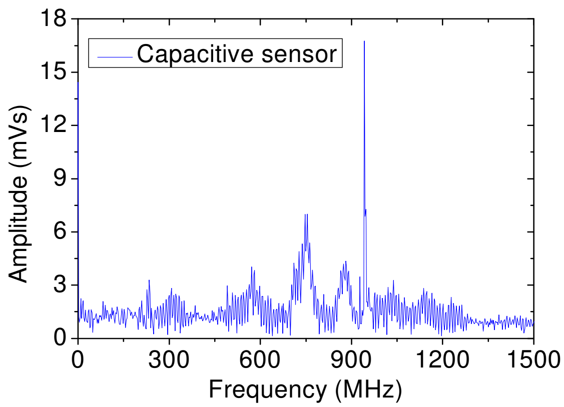

Figure 4: Frequency spectrum of a PD pulse (15 pC) captured with the capacitive sensor in time-domain

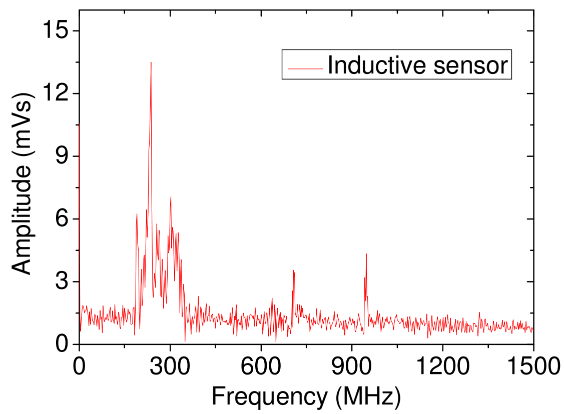

Figure 5: Frequency spectrum of a PD pulse (15 pC) captured with the inductive sensor in time-domain

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 impulses (15 pC measured by the IEC 60270 method) picked up in time-domain by capacitive and inductive sensors are shown in Fig. 4, 5 respectively. It can be seen that the capacitive sensor captures broadband frequency components 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.

Sensitivity of UHF sensors

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, if a termination is faulty or not, a so called sensitivity check must be performed under laboratory conditions. For this purpose a conventional PD

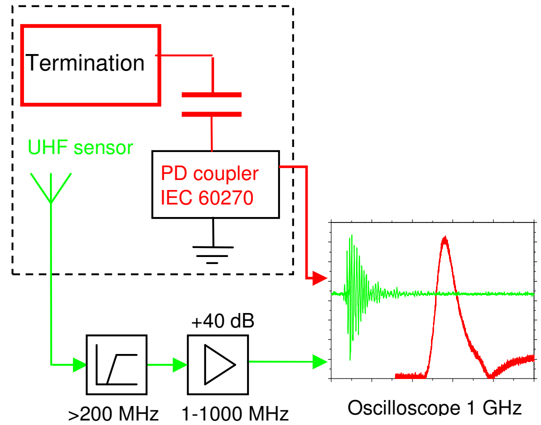

Figure 6: Structural diagram of the comparative measurement between an UHF and IEC60270 PD detecting methods

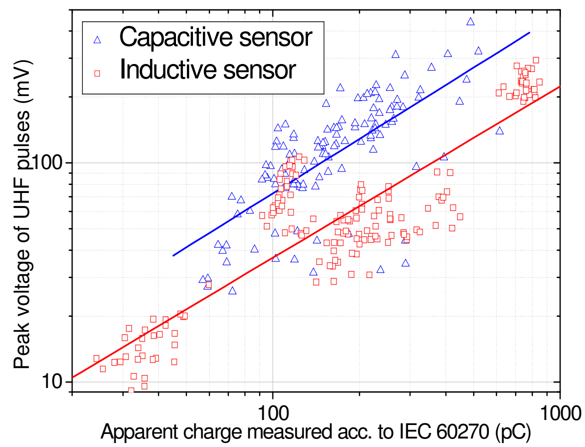

Figure 7: Sensitivity lines of the UHF sensors (without pre-amplification)

measurement according to the IEC 60270 standard is carried out simultaneously with the UHF diagnostics [4]. The structural diagram of the sensitivity check is shown in Fig. 6. As a result, the sensitivity below 5 pC turned out to be detectable by both types of UHF sensors inside the sleeve.

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 farther beneath the stress cone of the termination. AC voltage of 50 kV (one phase, rms) was constantly applied during the test. A 40 dB pre-amplification was omitted due to the saturation effect at the higher levels of discharge activity. The results are shown in Fig. 7. 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 highpass filter downwards and self resonance frequency upwards. The latter is determined by the relation of the inductivity to the parasitic capacitance of the coil.

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 [5]. 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 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 quadropole after a preamplifier, to enable time responses of the same order. Energy of the pulses was calculated according to the formula:

$$E = \frac{1}{50\Omega}\int u^2 dt \qquad (1)$$

Fig. 8 reflects around 200 PD events in the range of 5-900 pC acquired at constantly applied voltage of 50 kV.

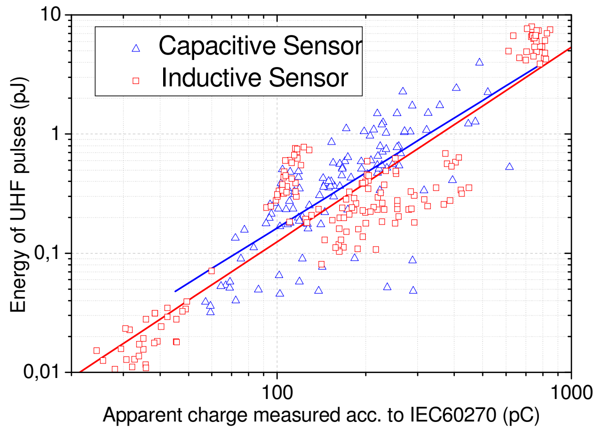

Figure 8: Correlation between the energy of the UHF pulses and the corresponding apparent charge

ENHANCED OPPORTUNITIES OF ON-SITE METHOD'S APPLICATION

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. Fig. 9 shows an example of the so called phase resolved PD measurement using the UHF field sensing technique. Triggering the oscilloscope on the AC sine curve of 50 Hz, the UHF pulse activity can be monitored using "peak hold" mode of the oscilloscope. Clear evidence that defect incepts at the rising part of the applied voltage proves that we deal with an internal PD in this case.

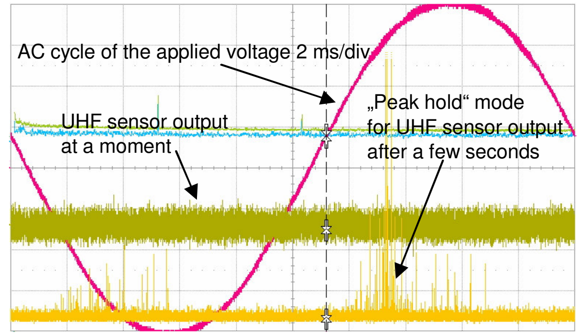

Figure 9: Phase resolved UHF PD measurement with "peak hold" function

Regarding an on-site testing in GIS substations there are very few possibilities to extract each phase signal. Line triggering with the own supply voltage is sufficient to proof an AC cycle relation of repetitive pulses.

UHF PD measurements with Power Detector

The UHF method implies per definition the usage of a high speed digital oscilloscope. It is necessary to resolute events lasting only a few nanoseconds. Thus, for the user this assumes substantial investments into the test equipment and training of workmanship. In attempt to make the diagnosis more affordable the so called power detector (PwD) was developed in the laboratory in place of the filter and pre-amplifier shown in Fig. 6. Basically, a PwD is a linear or logarithmic amplifier that monitors signal's power, not just the voltage output [6]. This allows extremely sensitive triggering. Fig. 10 shows a PD measurement with a magnitude of 3 pC clearly detected by the PwD and concealed for our regular UHF circuitry.

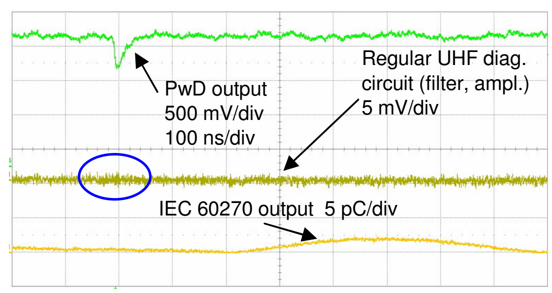

Figure 10: Sensitive measurement with the PwD, regular UHF and according to IEC 60270 (3 pC)

The cost advantage is in the limited output bandwidth of the PwD that allows us to deploy simpler oscilloscopes. Fig. 11 shows a measurement picked up by an oscilloscope with an analogue bandwidth of only 350 MHz. On the other hand having a lower frequency output eliminates an opportunity of spectral analysis and limits the possibilities of results interpretation.

UHF PD measurements with 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.

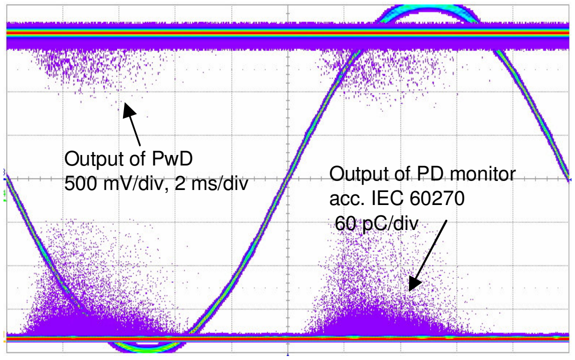

Figure 11: Phase resolved PD measurement carried out with the PwD comparing to the conventional testing

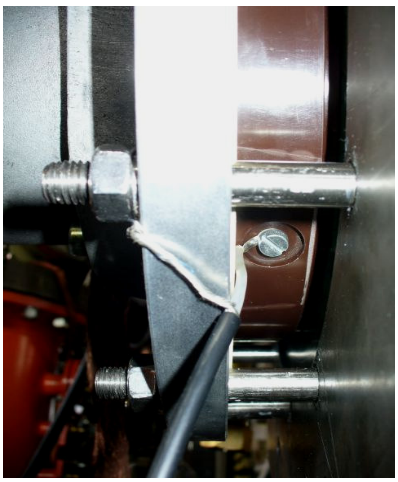

Figure 12: Connection of a coaxial cable to the voltage sensor inside the bushing

Fig. 12 shows a connection of a coaxial cable to the voltage sensor's output. The measuring cable was directly (without filtering and pre-amplification) connected to the 50 Ohm input of an oscilloscope.

A plug-in cable connector with an artificial PD defect was plugged into the bushing equipped with the voltage sensor. A few comparative tests to establish sensor's sensitivity in accordance with the scheme shown in Fig. 6 were conducted. Fig. 13 shows sensor's output at a partial discharge intensity of 100 pC picked up with a oscilloscope in time-domain. 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.

FIELD EXPERIENCE

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.

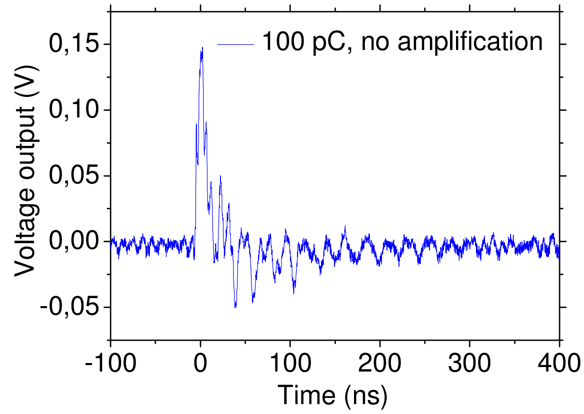

Figure 13: Output of the voltage sensor at 100 pC

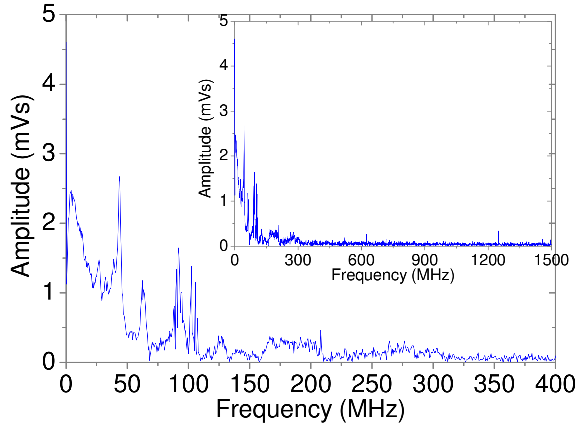

Figure 14: FFT spectrum of the pulse

Figure 15: On-site test set-up: portable screening sleeve with the UHF sensors mounted on each termination in turn

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.

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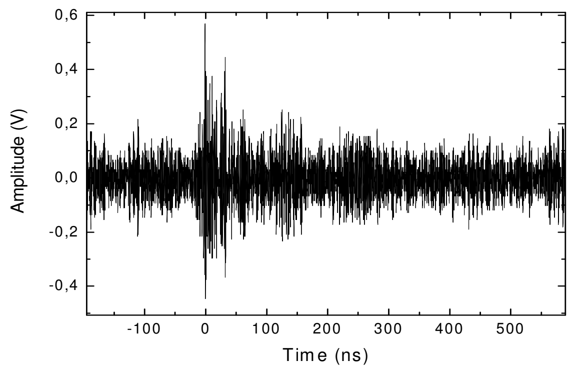

Figure 16: Typical fast pulse emitted by the faulty termination on-site

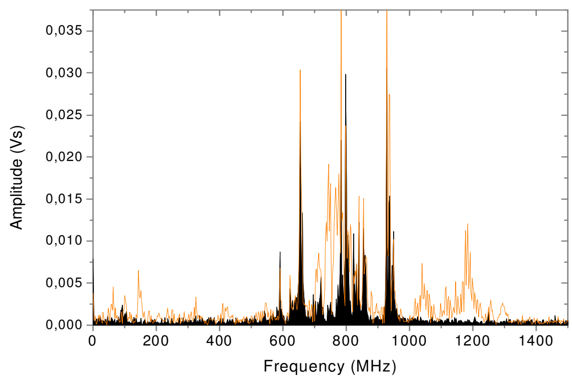

Figure 17: Frequency spectra of the pulse (light curve) vs. background noise (black filled area)

CONCLUSIONS

The experiences in on-line application of the ultrawide band partial discharge (PD) detection in high voltage plug-in cable terminations were 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 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 measurements are effective to cope with repetitive pulse noise,
- Usage of a power detector can reduce costs of the test equipment. Detecting with the PwD showed higher sensitivity but limited options of results interpretation in frequency-domain.

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