On-Site Partial Discharge Measurements on Premoulded Cross-Bonding Joints of 170 kV XLPE and EPR Cables

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Abstract: A total number of 15 premoulded joints of three 170 kV cable circuits (XLPE and EPR) were equipped with partial discharge (PD) sensors. The developed sensors are based on inductive high frequency coupling of partial discharge pulses occurring in the joints. The PD activity of each joint was monitored during an after laying AC acceptance test. The test voltage of 190 kV was generated by means of a frequency-tuned series-resonance test set. The signals of the PD sensors were assessed with a spectrum analyser in a frequency range form 15 to 50 MHz, allowing a good separation of noise from PD signals under high interference levels. The investigation demonstrated the feasibility of on-site PD measurements on joints during after laying tests.

Keywords: On-site partial discharge diagnostics, premoulded cable joints, series-resonance test set, high voltage cable testing.

I. INTRODUCTION

The Electricity Board of the City of Zürich (Elektrizitätswerk der Stadt Zürich, EWZ) is supplying the city area of Zürich with a total load of 500 MW from four coupling points with the national grid. The 14 local substations 170 kV/24 kV (U_m acc. to IEC 71-1) are fed and interconnected without overhead lines by a 170 kV cable network. The cable network has a length of 242 km. As the neutrals on the 170 kV side are solidly grounded, cable shields must be grounded at both cable ends, and the low-resistivity shields have to be cross-bonded.

Until 1975, all cables installed were of paper-oil impregnated insulation types. Since then, mainly EPR and XLPE cables were added. The quantity and types of the installed equipment are shown in Table I.

TABLE I
EWZ 170 KV CABLE NETWORK

170 kV cables	total	insulation	
		paper-oil	polymer
No. of circuits	29		
cable length [km]	242	176	66
No. of partial lengths	468	360	108
terminations	174	120	54
joints	327	249	78
stop joints	18		

PE-947-PWRD-0-04-1997 A paper recommended and approved by the IEEE Insulated Conductors Committee of the IEEE Power Engineering Society for publication in the IEEE Transactions on Power Delivery. Manuscript submitted December 31, 1996; made available for printing June 9, 1997.

The general service experience with oil-paper cables is excellent. No fault has occurred over a period of more than 40 years. Cable samples inspected after this period have shown virtually no ageing. In order to achieve similar standards with EPR and XLPE cable lines at EWZ, these have been engineered in the same way, using appropriate design for cables, accessories, laying systems, and careful cable laying and mounting done by the manufacturers. The cable ducts consist of blocks of protective tubes connecting the easily accessible joint boxes. Thus, the conditions for mounting and operation are most favourable in the urban environment.

The physical behaviour under dielectric stress of polymeric insulation materials is different form that of oil-paper insulation systems in at least two aspects: they show an ageing at an unknown long term rate, and they have no "self-healing" properties. While the manufacturer's quality management covers all single components (cables and accessories), the laying and mounting activities on site are demanding and can imply risks.

To reduce these risks, EWZ performs AC after laying tests since more than 4 years, testing 170 kV cables with lengths up to 5 km. It is believed that after-laying AC tests together with PD measurements allow to establish a quality record that can be extended through lifetime by regularly repeating PD measurements under operating conditions [1]. For this purpose special PD sensors for accessories (joints & terminations) have been developed.

II. PRACTICE OF FIELD TESTING OF HV CABLES IN SWITZERLAND

Because of its higher sensitivity in detecting laying and assembling faults in HV cables and accessories, AC after laying tests of newly installed cable circuits are widely preferred over DC testing in Switzerland [2]. Since 1980 modular on-site testing equipment based on frequency-tuned series-resonance is readily available [3] and is being used for cable and GIS testing. There exists considerable experience with AC testing using this type of test-set, in particular with XLPE and EPR insulated cables [2]. The lightweight and modular test set can be used also under difficult testing conditions, as in the present case, where the equipment had to be brought to an underground substation.

The tendency in on-site after laying tests is going beyond mere withstand testing, i.e. combining withstand tests with some kind of diagnostic measurement [1]. For extruded high voltage cables and their accessories the detection of partial discharges is regarded to be the most efficient and most sensitive diagnostic method. It is believed that also minor faults in accessories, not directly leading to breakdown during the AC withstand test, can be detected with appropriate PD sensors. Series-resonance test sets generate a distortion-free and partial discharge-free AC test voltage with a frequency close to power frequency. Therefore, these test sets are well suited for performing PD measurements. The deviation from power frequency in frequency-tuned resonance test sets is an advantage, making it easy to discriminate PD signals correlated to the test voltage from external noise.

III. ON-SITE PD TESTING OF CABLES AND THEIR ACCESSORIES

Several methods to detect PD in HV cables and their accessories have been described in the literature (see for example [4] for a review of activities in Japan). If it is the aim to detect PD occurring in the cable itself, detection techniques operating in a frequency range of not more than a few MHz have to be used due to the high attenuation at higher frequencies in shielded polymer-insulated cables [5;12]. The high interference level in this frequency range requests sophisticated methods for noise suppression [6;7]. Another testing philosophy regards primarily testing of the accessories as relevant, as mentioned above. For this purpose, PD detection techniques operating at higher frequencies (tens of MHz) can favourably be employed [8;9].

IV. PREMOULDED JOINTS

For polymer-insulated cables, premoulded slip-on joints are increasingly being used. Their significant advantages over conventional taped joints are:

- Production of the active part under optimal conditions in the factory;
- each joint is routine tested in the factory before installation;
- reduction of risk of introducing imperfections during jointing work.

Fig. 1 shows the general design of the 170 kV premoulded joint with cross-bonding of cable shields, which has been equipped with a partial discharge sensor. The active part of the joint consists of a one-piece premoulded silicone body.

Table 2 shows the relevant parameters of the performed HV tests in the factory.

TABLE 2
ROUTINE TESTS FOR PREFABRICATED 170 kV JOINTS

Withstand test, 30 min	250 kV
PD measurement (< 5 pC)	130 kV

V. DESIGN OF PARTIAL DISCHARGE SENSOR

The outer shield of the joint body is connected to the cable shield by means of copper braids. In case that the joint includes a shield break (insulated joint), these copper braids are connected on one side of the joint only (Fig. 1). In order to form a HF current transformer (CT) one of these braids was passed through a ferrite core (∅ 36 mm). The pick-up winding consists of just one turn, the ends of which are lead to a coaxial connector at the housing of the joint. Fig. 2 shows a photo of the CT-sensor, mounted in its final position.

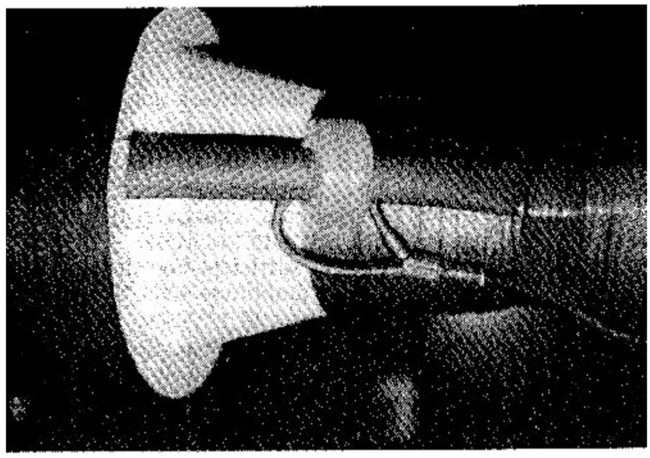
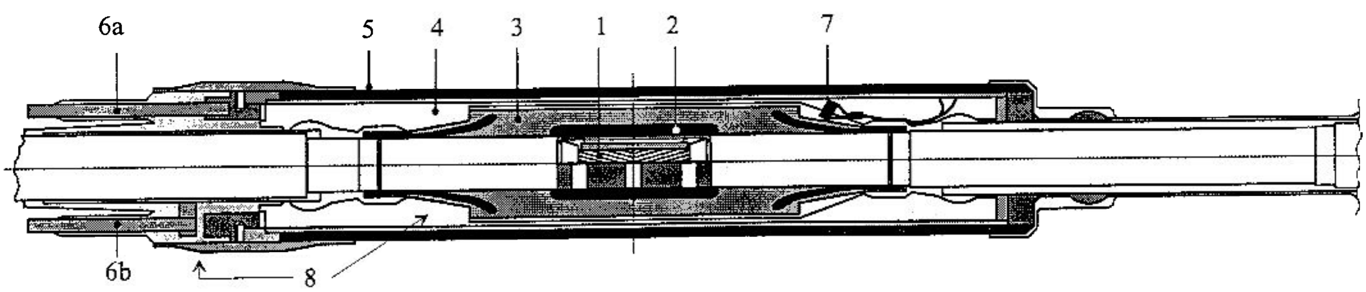


Fig. 2. Installed PD sensor (premoulded body on the left side).

This very simple sensor design has the advantage of requiring only minor modifications in the design of the joint. The use of a CT provides a galvanic separation between the shield of the HV cable and the measuring circuit, which is important for noise suppression. In the present situation of insulated joints, no service or short circuit currents pass through the connection which is used for signal coupling, i.e. it is only charged with the capacitive current of the outer shield of the joint. Though a higher sensitivity (better coupling) would have been achieved by making more turns with the copper braid, or by opening the second copper braid which is shunting the HF transformer with a low impedance, or using a 50 Ω resistor instead of the HF transformer, it was decided to sacrifice higher sensitivity for the benefit of safety.



1. Conductor
2. HV electrode
3. Premoulded body
4. Air or filling materials
5. Protection casing
6. Cross-bonding leads
   a: connection to right side
   b: connection to left side
7. PD sensor
8. Shield interruption

Fig. 1. Premoulded 170 kV joint with cross-bonding of shields.

VI. HIGH FREQUENCY CHARACTERISTICS OF THE PD SENSOR

The high frequency characteristics of the chosen coupling device (PD sensor) were investigated experimentally on a full-scale joint, which was fitted with two short (ca. 0.5 m) lengths of 170 kV cable. Both ends of the cables were terminated with coaxial connectors, hence allowing HF measurements at low voltage levels. The output signal from the tracking generator of a network analyser or an impulse generator was applied through a 10 dB attenuator (for impedance matching) to the conductor of the HV cable on one side, meanwhile the other side was terminated by a 35 Ω resistor (matching approximately the characteristic impedance of the HV cable). The output of the PD sensor was connected to the 50 Ω input of the network analyser or of a fast digitising oscilloscope.

The partial discharge sensor with this very simple design, providing only a loose coupling between primary and secondary winding, shows a bandpass characteristics with a passband ranging from 12 MHz to 40 MHz. As will be shown later, the sensitivity is sufficient for detecting PD occurring in the joint with an amplitude of a few pC (see Sect. VII below).

VII. PD SENSOR CALIBRATION

A. HV set-up

For calibration purposes the above described sensor was installed in a full-scale insulated joint. The joint was fitted with two 170 kV XLPE cables about 5 m in length which were provided with HV test terminations (stress controlled by de-ionised water). The experiments were performed in a shielded laboratory.

B. PD measuring system

The PD sensor installed in the joint was directly connected to a preamplifier (30 dB, 0.01 - 200 MHz) and from there by means of a 20 m long coaxial cable to a spectrum analyser (HP 8591 E). The spectrum analyser was either used in the standard scanning mode to monitor the spectrum of the output of the PD sensor, or in the "zero span" mode at a fixed centre frequency. In this mode the spectrum analyser works like an oscilloscope, filtering the signal with its bandpass filter of a pre-selected resolution bandwidth and centre frequency. A conventional PD measuring system (Bridge detector, type Nonius-NKF, C_c = 37 nF) calibrated according to IEC 270 was available for direct comparison of the partial discharge amplitudes measured with the PD sensor.

C. Measurement Results

1) Calibration: From the specifications of the PD sensor with its bandpass filter characteristics (see Sect. VI), it is not self-evident that a calibration in terms of apparent charge according to IEC 270 is possible. The accuracy of the quasi-integration which is needed for the determination of the apparent charge depends on the extension of the flat portion of the spectrum of the partial discharge pulses to be measured [10]. The subsequently presented measurements of partial discharges occurring in the joint itself suggest that the conditions for correct quasi-integration are fulfilled under the given circumstances even with centre frequencies of the bandpass filter in the order of 20 MHz.

The conventional PD detector using a coupling capacitor and the PD measuring system based on the inductive PD sensor were calibrated simultaneously with a charge of 10 pC. For the scaling of the PD sensor with regard to PD amplitude the spectrum analyser was operated in the zero-span mode and was set to a resolution bandwidth of 5 MHz at a centre frequency of 25 MHz. The result of this scaling is a relation of µV/pC for the video-out signal of the spectrum analyser.

2) PD measurements with artificial defects: For reference the completely assembled 170 kV joint was first tested to be partial discharge-free up to a voltage of 130 kV. As a first experiment, a wire was fixed at the high voltage electrode of one cable termination to produce a corona discharge in air. The corona was recorded with a magnitude of 4-6 pC with the PD sensor and with 3 pC with the conventional PD measuring system, respectively (see also Table 3). Subsequently, the PD behaviour of two types of artificial defects in the joint were investigated: an air gap under the deflector at one end of the joint (produced by the insertion of a nylon strap between cable insulation and joint body) and a delaminated semiconducting layer (layer removed on a surface of about 1 cm^2 and loosely covered with a grounded aluminium foil). The results of the PD measurements with the two measuring systems at different voltage levels are shown in Table 3.

It can be seen form Table 3 that there exists quite a good agreement between the results obtained with the two measuring systems. The deviation can largely be attributed to the different evaluation methods of the mean discharge magnitude on an analogue and a digital read-out.

TABLE 3
COMPARISON OF PD SENSOR TO CONVENTIONAL MEASURING SYSTEM WITH ARTIFICIAL DEFECTS

Defect	Voltage [kV]	PD sensor [pC]	Syst. acc. to IEC 270 [pC]
Corona in air	15	4-6	3
Air gap at interface with cable	60	90	70
Delaminated outer semiconducting layer	90	15	8
	100	20	15
	110	22	35

D. Scaling of PD amplitude for on-site measurements

It has been shown in the last section that in a laboratory set-up the PD sensor shows consistent results as compared to a measuring system according to IEC 270. However, such a calibration procedure will not be possible for on-site measurements, since the higher frequencies of the impulses used for calibration will be attenuated on their way of several hundred meters from the cable termination to the joints. The attenuation of extruded high voltage cables with semiconducting shields is in the order of 5 dB/100 m at 20 MHz [5;11]. As a consequence, the quasi-integration with a bandpass at a centre frequency of 20 MHz will fail. An indirect calibration by means of foil electrodes as described in [6] could not be used, since such electrodes were not available in the design of the joint.

Therefore, it was decided to scale the partial discharge amplitudes measured on-site by comparison with frequency spectra measured in the same type of joint with artificial defects in the laboratory. From Fig. 3 it can be seen that partial discharges with a magnitude of 50 pC produced in the joint (air gap under the deflector) exhibit an averaged magnitude of the spectrum with shares of about -55 dBm (30 dB preamplifier, 300 kHz resolution bandwidth). With a noise level of about -72 dBm it was possible to detect PD down to a magnitude of about 4 pC in the laboratory. The measurements (spectra) taken in the field were compared to these scaling measurements.

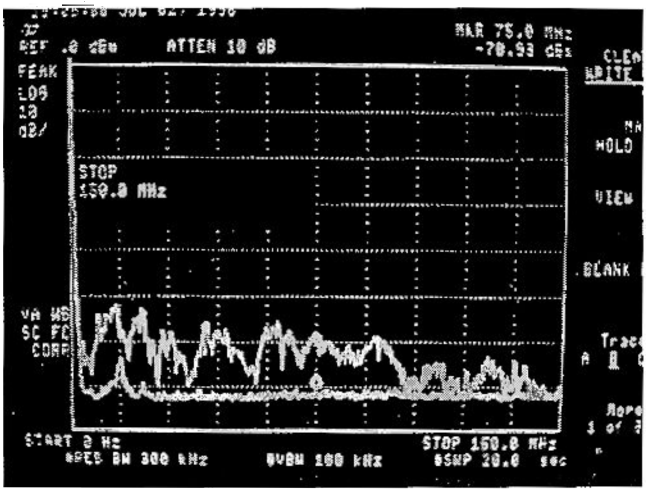


Fig. 3. Upper trace: Spectrum of partial discharges with a magnitude of 50 pC acquired with the PD sensor in the frequency range up to 150 MHz; lower trace: noise level of the measuring system.

VIII. ON SITE AC WITHSTAND TEST INCLUDING PARTIAL DISCHARGE MEASUREMENTS

A. Cable circuits

The general specifications of the tested cable circuits are summarised in Table 4.

TABLE 4
DATA OF THE TESTED CABLE CIRCUITS

Cable circuit	Type	Length [m]	Total no. of joints (No. of joints with PD sensor)
1	GCUW-T (EPR) U_m: 170 kV, 300 mm^2	799	3 (3)
2	XDCUW-T (XLPE) U_m: 170 kV, 300 mm^2	2021	9 (6)
3	GCUW-T (EPR) U_m: 170 kV, 300 mm^2	1046	6 (6)

B. Test procedure

The installed and jointed 170 kV XLPE and EPR cables were subjected to a AC withstand test at 190 kV for 15 minutes. Before and after this test, a partial discharge measurement at 130 kV of a duration of two minutes each had to be passed. It was agreed that the test was passed if no breakdown or flashover occurred during the withstand test at 190 kV and if no partial discharges were detected at 130 kV before and after the withstand test.

C. Series-resonance test set for generation of test voltage

The on-site tests of the three cable circuits were performed with a modular, frequency-tuned series-resonance test set [2;3]. Several reactor modules (50 H, 200 kV, 6 A, 450 kg) were connected in series and parallel to the high voltage cable under test to form a series-resonance circuit. Fig. 4 shows a schematic diagram of the series-resonance test circuit used for the three cable circuits.

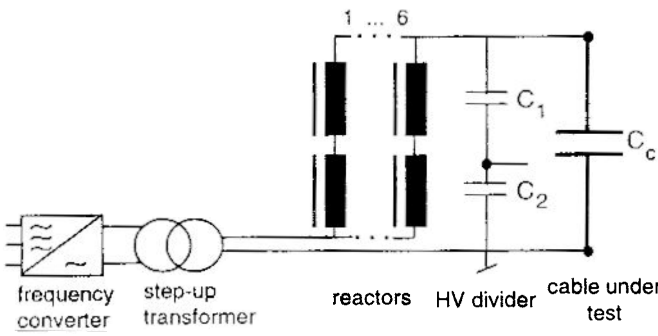


Fig. 4. Circuit diagram of the series-resonance test set.

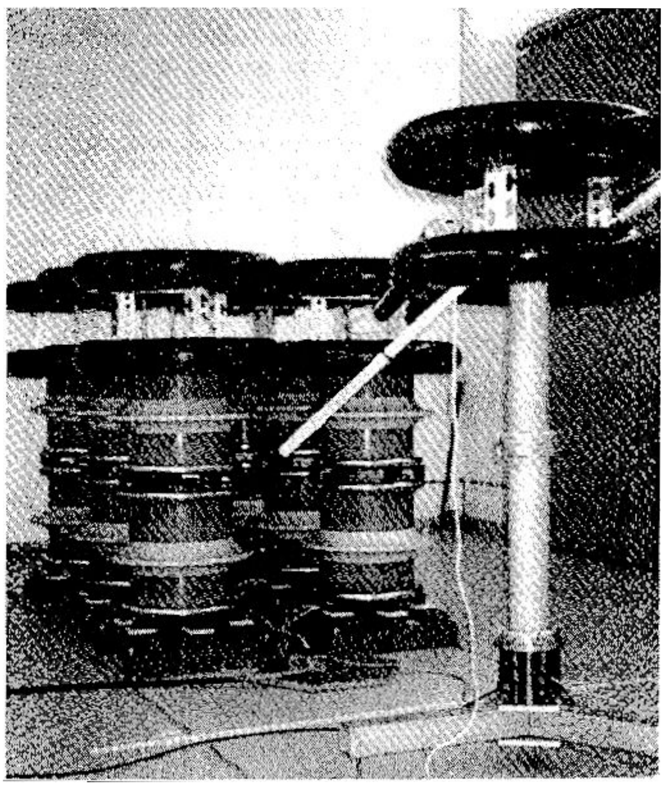


Fig. 5. Series-resonance test set used to test cable circuit no. 3.

The series-resonance circuit was fed from a pulse width modulated IGBT-frequency converter (maximum output: 200 kVA). A typical resonance circuit used to energise a polymer insulated high voltage cable has a very high quality factor of in the order of 100. Therefore, the frequency converter has only to deliver approximately 1% of the total generated reactive power to compensate for the losses in the circuit (see Table 5). A picture of the reactors used to test cable circuit no. 3 is shown in Fig. 5.

TABLE 5
DATA OF THE SERIES-RESONANCE TEST SET

Cable circuit	Cap. per phase [nF]	No. of reactors	Inductance [H]	Resonance frequency [Hz]	Current [A]	S @ 190 kV [kVA]
1	131	4	53	60	19.8	3762
2	283	8	26.5	58	9.5	1805
3	180	12	17.67	89	19.2	3648

D. On-site partial discharge measurements

The on-site partial discharge measurements were performed with the equipment described in Sect. VI. Instead of the 30 dB preamplifier used in the laboratory, a battery operated 34 dB amplifier with a bandwidth of 400 MHz was used on site. The preamplifier was placed in the manhole close to the joint, whereas the rest of the partial discharge recording equipment was set up in a van. The resolution bandwidth of the spectrum analyser was set to 300 kHz with a sweep time of 2 s.

Prior to partial discharge testing, the interference level in a frequency range up to 50 MHz at each joint was recorded without test voltage applied. It was found that the interference level can vary quite considerably from joint to joint and is not constant in time. Fig. 6 shows an example of a joint with a very low interference level. Up to a frequency of about 12 MHz some short-wave radio transmitters are visible. The interference level in the range from 20 MHz to 50 MHz corresponds to the noise of the preamplifier used (-66 dBm).

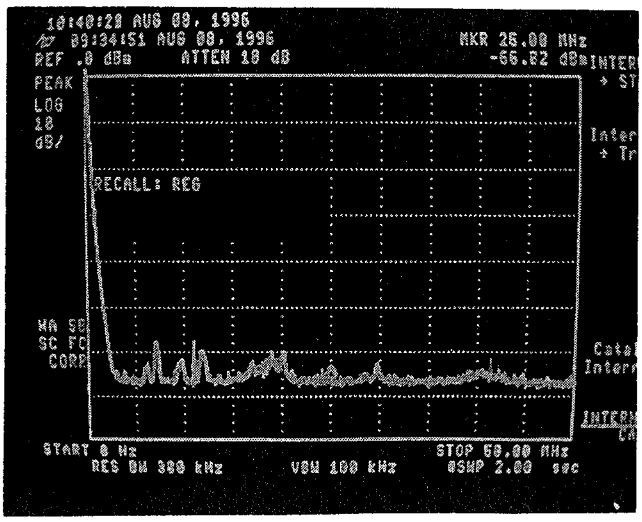


Fig. 6. Joint with a low interference level.

Fig. 7 shows a measurement on another joint exhibiting quite a high interference level. In addition to the radio transmitters, perturbations in the 27 MHz CB band are visible.

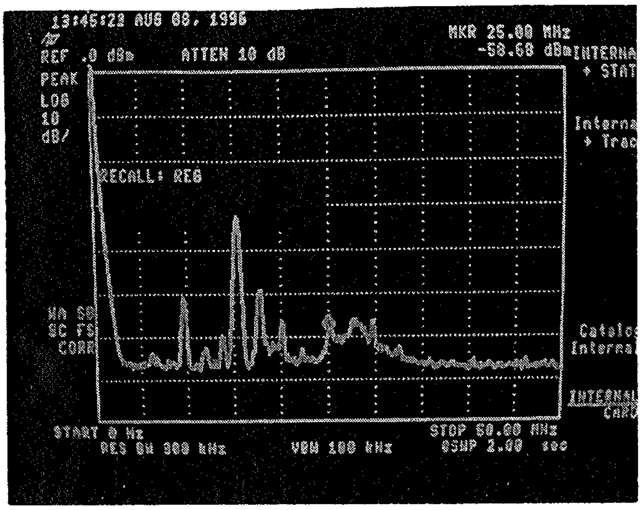


Fig. 7. Joint with a high interference level.

The measurements of the interference levels have shown that it is always possible to find frequency ranges, where no external noise is present. For the PD measurements with applied test voltage, it was decided to operate the spectrum analyser in the standard scanning mode, as shown in Figures 6 to 8. In case that any significant deviation of the spectrum under applied voltage form the previously recorded interference spectrum would have been detected, the spectrum analyser would have been switched to the "zero span" mode, to check whether the detected signals are phase correlated with the test voltage, i.e. to decide whether they are PD or just external noise. The synchronisation of the spectrum analyser with the test voltage was done by means of a LF-current transformer, circumferencing the cable under test.

Fig. 8 shows a spectrum obtained during the partial discharge measurement at 130 kV, for the same joint as shown in Fig. 6. By comparing the two figures, no modification in the spectrum above 15 MHz can be found. Below this frequency, perturbations originating from the frequency converter can be observed. Though not requested for acceptance of the cable circuits, PD measurements were also performed at 190 kV.

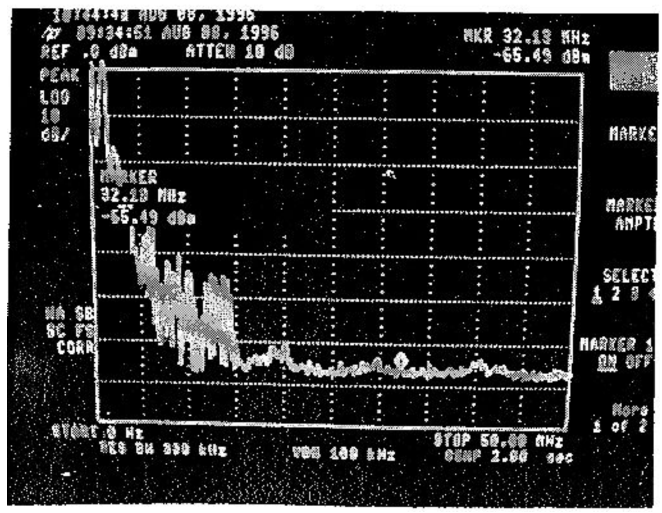


Fig. 8. Partial discharge testing at 130 kV.

E. Results and discussion of on-site measurements

A total number of 15 joints have been partial discharge tested on-site. The achieved sensitivity can be estimated by comparing the 'scaling' spectrum of Fig. 3 with the noise level in the spectra obtained on-site. From Fig. 3 can be seen that partial discharges with a magnitude of 50 pC produced in an artificial defect, yield spectral shares of about -55 dBm (measured with a +30 dB amplifier in the lab), i.e. -51 dBm with the +34 dB amplifier used on site. Considering the noise level of -66 dBm between 20 MHz and 50 MHz in the on site measurements (see Figures 6-8), it can be concluded that partial discharges of 50 pC would have been detected with a signal to noise ratio of about 15 dB. From this figure, a lower detection limit of 15 pC can be estimated, if a signal to noise ratio of 6 dB is considered as necessary for unambiguous detection of PD.

During the on-site testing with 130 kV and 190 kV no partial discharges were detected in none of the 15 examined joints.

A lot of interference from radio transmitters and from the frequency converter is present in the frequency range below 20 MHz. Additional investigations have shown, that this interference is not coupled inductively through the PD sensor, but capacitively by the shield of the high voltage cable into the PD sensor arrangement.

IX. CONCLUSIONS

The feasibility of partial discharge detection on 170 kV slip-on joints as an additional diagnostic method during AC withstand tests was clearly demonstrated.

By comparison with scaling measurements done on a full-scale joint in the laboratory, it has been shown that with the developed PD sensor a detection limit as low as 15 pC under on-site conditions can be achieved without special noise suppression techniques (digital filters).

As the sensor is based on a simple principle requiring no modification of the active part of the joint, it easily can be installed without additional risk for the safety of the joint and may become standard practice in the future.

Future work aims at the improvement of noise suppression by using a completely symmetric design of the sensor, and the adaptation of a similar sensor technique to cable terminations. More work is needed to characterise the long-term PD behaviour of typical failures in premoulded joints.

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XI. ACKNOWLEDGEMENTS

Two of the authors (T.H. and T.A.) gratefully acknowledge helpful discussions with Prof. W. Zaengl of ETH Zürich and with R. Bräunlich and M. Hässig of FKH.

XII. BIOGRAPHIES

Thomas Heizmann (M' 89) was born in Zürich, Switzerland, on June 26, 1961. He was graduated from Swiss Federal Institute of Technology (ETH), Zürich, in 1987. Since 1987 he was teaching and research assistant at the High Voltage Engineering Group of ETH from where he received his PhD (Dr. sc. techn.) degree in 1994.
Presently, Dr. Heizmann is senior assistant at the High Voltage Engineering Group of the Swiss Federal Institute of Technology and collaborator of the high voltage research commission (FKH) of the Swiss power utilities and industry in Zürich.

Thomas H. Aschwanden (M' 85) was born in Glarus, Switzerland, on December 11, 1951. He received his Dipl. Ing. and Ph.D. degrees in electrical engineering from the Swiss Federal Institute of Technology (ETH) in 1978 and 1985. In 1985 he joined the Weber Research Institute, Polytechnic University of New York, and has worked there as a research associate in the field of electrophysics and pulsed power technology.
In 1987 he became senior assistant of the High Voltage Engineering Group at the Swiss Federal Institute of Technology (ETH) in Zürich. Since 1990 he is head of the High Voltage Research Commission (FKH) of the Swiss power utilities and industry.
The research and development activities of Dr. Aschwanden include electrophysics, high voltage measurement and testing, EMC, pulsed power, dielectric materials and insulation technology, lightning protection, diagnosis and on-site testing of high voltage apparatus and systems.

Heinz Hahn was born in Geneva, Switzerland in 1955. He was graduated from "Ecole d'Ingenieurs", Geneva, in 1984 in electrical engineering. He spent 4 years with ABB Sécheron where he was responsible of the HV transformer testing laboratory. He joined Cableries de Cossonay in 1987. Mr. Hahn is currently working as senior engineer in R&D of HV cable accessories.

Michel Laurent was born in Lausanne, Switzerland in 1940. He was graduated from "Ecole d'Ingenieurs", Geneva, in 1965 in electrical engineering. He joined Cableries de Cossonay in the same year. He worked for this company since then, except for one year spent with Phelps Dodge Cable&Wire, Yonkers, USA. His activities covered R&D, engineering, installation, both for HV cables and accessories. Mr. Laurent is currently in charge of R&D for HV accessories within Alcatel Cable

Luigi Ritter was born in Zürich, Switzerland, on May 25, 1940. He received his Dipl.-Ing. degree in Electrical Engineering in 1966. In 1967 he joint the ABB High Voltage Switchgear R&D department in Baden, Switzerland. In 1969 he joined the Elektrizitätswerk der Stadt Zürich (Electricity Board of the City of Zürich). Since 1981 Mr. Ritter is the head of the Engineering department; he is in charge of planning and realising HV substations and cable lines.