AFTER-INSTALLATION TESTING OF HV/EHV EXTRUDED CABLE SYSTEMS – PROCEDURES AND EXPERIENCES

Ulrich HERRMANN, IPH Berlin, (Germany), herrmann@iph.de
Andreas KLUGE, IPH Berlin, (Germany), kluge@iph.de
Ronald PLATH, IPH Berlin, (Germany), plath@iph.de

ABSTRACT

This paper provides an insight into 9 years of IPH experience in after-installation tests of HV/EHV extruded cable systems. From the start, AC tests of very long length of EHV cable systems were performed in combination with sensitive PD measurements to achieve best possible test efficiency.

KEYWORDS

Power cables, testing after installation, partial discharges

INTRODUCTION

In 1998, IPH began to test extruded HV and EHV cable systems after installation. From the very beginning, powerful mobile resonant test systems as well as the ability to perform sensitive on-site PD measurements were indispensable to test very long EHV cable systems. Based on first experiences at 400 kV prequalification tests at CESI (1993-1997), PD sensors directly installed in cable accessories seemed to provide the only solution to achieve excellent PD detection sensitivity independent from the length of the cable system.

Since 1998, approx. 3000 km of HV cables and numerous EHV cable systems were successfully tested.

RELEVANT STANDARDS

Two international standards cover after installation tests of extruded cable systems: IEC 60840:2004 (third edition, effective since April 2004, for cables of rated voltages from 30 kV (U_m = 36 kV) up to 150 kV (U_m =170 kV) [1] and IEC 62067:2001 (first edition, effective since October 2001, for rated voltages above 150 kV up to 500 kV (U_m = 550 kV) [2].

Both IEC standards defined, for the first time, identical requirements for the shape of suitable AC test voltage and for the time of its application:

- substantially sinusoidal waveform
- frequency between 20 and 300 Hz
- time of voltage application equal to 1 hour (at 1 U_0 / 24 h - see remarks below).

For after-installation tests, PD measurements are actually not required by IEC standards.

TEST VOLTAGES

The AC test voltage level for the on-site test of new cable systems depends on the cable rated voltage: it is between 1.7 U_0 and 2.0 U_0 for rated voltages between 30 kV and 150 kV, (according to table 4 in [2]). At higher rated voltages the test voltage levels decrease from 1.4 U_0 (220-230 kV) to 1.3 U_0 (275-345 kV), 1.2 U_0 (380-500 kV) and 1.1 U_0 for cables of 500 kV rated voltage (according to table 10 in [1]). Additionally, IEC 62067 specified testing with 1.7 U_0 / 1 h, for all rated voltages > 150 kV. Both IEC standards accept testing with 1 U_0 / 24 h. The cable system's manufacturer and the user should agree on the test voltage level and the test procedure. To the authors' experience, test voltage levels often exceeded IEC recommendation. Typical test voltage levels were 160 kV for rated voltage 63/110 kV and 254 kV for rated voltage 127/220 kV.

Frequency Range

For AC testing on-site, IEC 60060-3 [3] enables the use of frequency-tuned resonant test systems in the extended frequency range 10-500 Hz. For HV/EHV extruded cable systems, IEC 60840 and IEC 62067 the frequency range is 20-300 Hz. Within this range, AC frequency has only little impact on the short-duration withstand voltage of extruded cables, only round about 10% [4]. The influence on the PD characteristics (PD magnitude, PD pattern) is low as well [5]. Due to the comparable physical processes, an AC voltage test in the frequency range between 20 and 300 Hz is a well-founded alternative to 50/60 Hz tests.

AC online voltages

Line-to-ground voltage

Both IEC standards offer line voltage testing (1 U_0 / 24 h) as an alternative procedure. Obviously, there is no need for an extra test voltage source. In contrast to this advantage there are several disadvantages, namely:

- failures cause a powerful short circuit (line power)
- line voltage testing is not capable of finding even severe defects (without PD measurements)
- tests at rated voltage can uncover neither any subsequent impact of transient overvoltages during normal operation nor any performance losses due to degradation effects
- no incremental increase of the test voltage with PD measurements taken at each step, is performed. This would allow failures to be detected at the lowest possible voltage. Instead, a switch-on transient is produced.
- line voltage usually introduces a high level of interference, which may impact the quality of PD measurements
- line voltage testing removes the opportunity from interference separation by AC phase correlation (difference in AC line and test voltage frequency)
- low test voltage levels may lead to very long PD inception delays

Low efficiency of tests with line-to-ground voltage were confirmed by a CIGRE report on *Experiences with AC tests after installation of polymeric (E)HV cable systems* [6]. Consequently, after-installation testing with 1 U_0 / 24 h **cannot** be recommended.

Phase-to-phase voltage

When a three-phase HV transformer with a fully insulated neutral is connected to a cable system, testing with AC phase-to-phase voltage becomes possible by grounding one phase, resulting in 1.7 U_0 at both non-grounded phases and 1.0 U_0 at the neutral [7]. This test method bears the risk of unpredictable transient overvoltages when switching such a transformer to the line. Of course, all general disadvantages of online tests apply also to phase-to-phase voltage tests. Due to the higher voltage level (compared to line-to-ground voltage), the failure risk for the involved equipment (power transformer, eventually voltage transformers, compensation reactors) will increase. It is absolutely recommended to carry out in-depth transient network analysis in advance and to calculate the failure costs for a worst-case scenario and to compare it with (low power) offline test costs and risks.

Variable line voltage

If a line reactor for compensation is installed, after-installation tests can be performed with reduced test power. In [8], a combination of regulation transformer, test transformer and variable inductances was used to test a 27 km long extruded 275 kV cable system with 1.3 U_0. At line frequency, of course, the line reactor will limit the maximum test voltage level due to core saturation. This test method seems to be far too complex to become widely accepted.

AC offline voltages

AC offline test voltages according to IEC standards can be generated in two different ways:

- by a reactor with variable inductance and fixed excitation frequency, e.g. 50 or 60 Hz (ACRL test systems)
- by a reactor with fixed inductance and frequency-tuned voltage excitation (ACRF test systems)

ACRL test voltage

ACRL test systems base on reactors with movable air gaps. Due to design limits, the adjustable range of inductance is usually small. The testing range is *proportional* to the inductance range.

ACRF test voltage

A fixed inductance has no movable parts, resulting in lower costs and lower losses compared to a variable inductance. Low losses resp. a high quality factor ensures a favourable power-to-weight ratio. Other advantages of ACRF resonant test systems are: low feeding power, low discharge power in case of breakdown or flashover and high load range. So only the second way offers a feasible approach to on-site tests with mobile resonant test system. The wider testing range, proportional to the *square* of the test frequency range, is another benefit of the ACRF test system [9,10].

Alternative test voltages

Well established for after-installation tests of extruded medium voltage cables, two types of alternative test voltage try to enter the field of HV/EHV cable testing.

DAC

Damped AC voltages, e.g. oscillating waves were investigated as a suitable after-installation test voltage for extruded HV/EHV cable systems, especially because of their simple generation principle [11,12,13]. With the availability of commercial ACRF test systems, oscillating waves fall into oblivion. Since longer, oscillating waves in combination with PD measurements returned for testing of extruded medium voltage cables. Actually, oscillating waves are re-proposed for HV extruded cable testing including PD measurements [14].

VLF

Very low frequency, e.g. 0.1 Hz, is actually applied for testing extruded medium voltage cables only. In principle, VLF testing of HV cable system would be possible.

Actually, both alternative test voltages are not in accordance with IEC standards for after-installation tests of extruded HV/EHV cable systems. Investigations on DAC and VLF performance showed less efficiency compared to AC 50/60 Hz voltage testing [15,16,17] and led to the CIGRE recommendation for after-installation tests of extruded HV/EHV cable systems [18]. For PD measurements, the PD rate is much lower than for AC 50/60 Hz voltage. Statistical evaluation of PD measurement results requires much longer test time.

DC voltage

There is widespread consent among the international community that HVDC on-site testing of extruded cables is not effective:

- risk of flashover on terminations (especially GIS)
- possible space charge effects with DC testing
- inefficiency of DC testing in detection of even severe faults (no PD, no electrical treeing at DC)
- breakdown of joints and terminations because of difference in stress control between AC and DC testing; faults induced by DC testing

DC testing of extruded cable systems is not in accordance with IEC standards.

ACRF TESTING

High test power, especially for long cable lines, can only be effeciently generated by mobile resonant test systems, where the weight-to-power ratio and feeding power demand is relatively low and the transport volume is acceptable [19]. At resonance, the feeding power is essentially reduced to the real-power loss in the test circuit. For generation of test voltages by resonant circuits, only the real-power loss has to be delivered by the resonant test system in order to maintain the test voltage. The quality factor Q is calculated from the ratio of reactive power and real power. The quality factor considers both the losses incurred in the resonant reactor and the losses of the cable (test object). The losses of the resonant reactor are by far higher than those of extruded cables. In order to achieve a high quality factor, it is very important to have a low-loss resonant reactor. Modern radial-core resonant reactors achieve a quality factor beyond 100.

ACRF test system

An ACRF system mainly consists of a reactor with fixed

Return to Session

inductance (optionally with taps), the capacitive load (test object) and a control module with frequency converter unit. Resonance is reached by tuning the frequency of the converter unit. In series resonant circuit, the test voltage is a pure sinusoid, but its frequency depends on load capacitance, which varies between test objects. For a constant inductance L there is a minimum resonant frequency for a maximum load capacitance. The frequency increases with decreasing load capacitance. In addition to the test voltage, the maximum load capacitance and the acceptable frequency range are a decisive design criteria for the fixed HV reactor of the ACRF test system.

Combination of resonant test systems
One advantage of ACRF test systems is the modular structure: resonant reactors can be combined in series or parallel connection to adapt to certain test parameters.

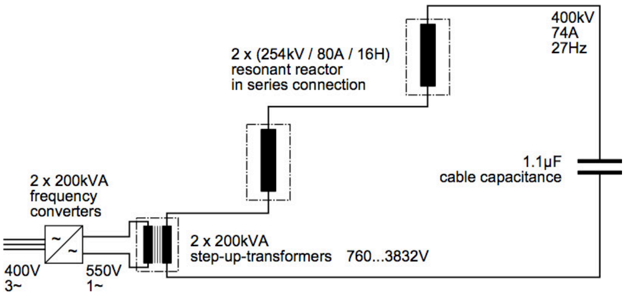

Figure 1: Combination of resonant test systems (connected in series)

Fig. 1 shows a test set-up with two resonant reactors in series connection. This circuit was used to test 6.3 km of 400 kV XLPE cable system [20,21].

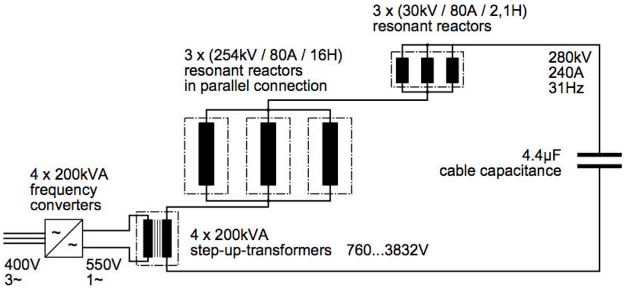

Figure 2: Combination of resonant test systems (connected in parallel)

For testing 20 km of 400 kV XLPE-insulated cable system with 280 kV, three resonant reactors were put in parallel connection. Another 30 kV resonant reactor was connected in series to reach the required test voltage level (see fig. 2) [22, 23].

Quality factor
The estimation of the power demand for a resonant test is based on the quality factor. Due to the very low losses of extruded cables, the quality factor depends practically only on the resonant reactor loss. The reactor loss itself depends on the frequency.

Fig. 3 shows the quality factor measured at maximum test voltage level in more than 250 resonant tests. Besides very few exceptions, the quality factor always exceeded 100, so providing the lower limit estimation for Q and the upper limit for the actual power demand. The quality factor increases with frequency, from 100 at 25 Hz to reach the maximum (220) at approximately 65 Hz (ωL/R behavior). For higher resonant frequencies, the quality factor decreases and converges to 100 at 300 Hz (skin and proximity effects, core losses). The real power demand for the resonant test system varies between 1% (worst case) and 0.45% (optimum) of the reactive test power.

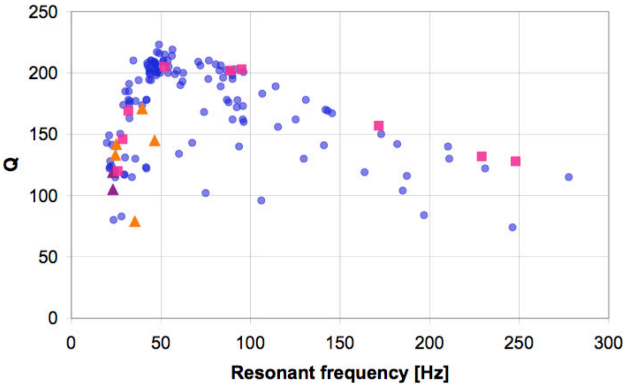

Figure 3: Quality factor dependency on frequency

Blue circle:	one resonant reactor
Red square:	two resonant reactors in series connection
Orange triangle:	two resonant reactors in parallel connection
Violet triangle:	three resonant reactors in parallel connection

System perturbation
Depending on the frequency converter design of the ACRF test system, system perturbation may depend on the ratio of line to test frequency. If the frequency ratio becomes approximately an integer (e.g. 60/30 or 50/25 Hz/Hz), the three-phase supply current can become asymmetric.

ON-SITE PD MEASUREMENTS

Although each single cable and accessory is subject to routine tests at the manufacturer lab, transport, cable laying and installation can lead to unnoticed defects. External damages due to cable laying are usually detected by DC testing of the oversheath. In consequence, after-installation tests of the insulation can focus on defects in cable accessories, e.g. interfacial problems, improper positioning, cuts or scratches, contaminations etc. Such defects do not necessarily lead to breakdown within testing time, bearing the risk of breakdowns later in service. Sensitive on-site PD measurements significantly reduce this risk [24, 25, 26].

On-site PD measurement procedure depends on the voltage level of the cable system under test. For EHV, all after-installations tests were carried out with PD sensors built-in the accessories or with external inductive PD sensors at e.g. cross-bonding links. The choice of PD sensors changed with the evolution of PD measurement systems.

In 1998, UHF *directional coupler sensors* (DCS) were chosen because of their inherent capability to suppress any external interference and so to make high-sensitive and unambiguous PD detection possible, even under noisy on-site conditions [26]. Since then, DCS were rarely used, mainly for two reasons: the evaluation of PD signals from

DCS required high-speed data acquisition and processing, which was (and still is) expensive and bulky. The second reason was the missing acceptance by most cable manufacturers. The cable manufacturers preferred to use their own *capacitive* PD sensors, because these sensors were practically part of the accessory design and no additional component. To achieve similar immunity to interference for capacitive PD sensors compared to DCS, the PD measurement system evolved with two new properties: digital bandpass filtering with variable center frequency and bandwidth to easily optimize SNR for different PD sensors as well as synchronous multi-channel PD detection for distributed PD evaluation [28,29].

The combination of capacitive PD sensors and multi-channel PD detection worked fine for tunnel-laid cable systems. But for direct buried cable systems, PD sensor coaxial cables bear the risk for tightness problems. In this case, the only alternative to dedicated PD sensors inside cable accessories is inductive PD detection at the cross-bonding (CB) link boxes, because these boxes are usually accessible. Long HV/EHV cable systems, where PD detection at the terminals cannot provide sufficient sensitivity, make use of CB to minimize losses. Inductive PD detection on CB links proved as a sensitive alternative for PD detection at the CB joints [30].

Test set-up for on-site PD measurements

The test set-up for on-site PD measurements should be corona-free. Therefore, corona protection spheres, toroids and metallic pipes of suited diameter have to be used. Sufficient clearance from HV connections to any part of the construction should prevent PD from earthed or potential free components.

Figure 4: Corona-free test voltage connection

Fig. 4 shows the test set-up for a 345 KV cable system. In this case, the outdoor terminations were located on a platform 11 m above ground [31].

The series connection of two resonant reactors is shown in fig. 5. To prevent from corona at 450 kV test voltage, the diameter of the pipes was 200 mm.

Fig. 6 shows the test set-up for 380 kV test voltage and PD measurements. In this case, close-by circuits in operation may cause interferences.

STATISTICS

Since 1998, IPH carried out numerous after-installation tests of HV/EHV extruded cable systems. Fig. 7 shows the number of tests with respect to the test voltage levels. Approximately half of all tests were carried out with test voltage levels between 128 and 160 kV. The highest realized test voltage was 450 kV line-to-ground.

Figure 5: Series connection of two resonant reactors

Figure 6: 380 kV test set-up in a substation

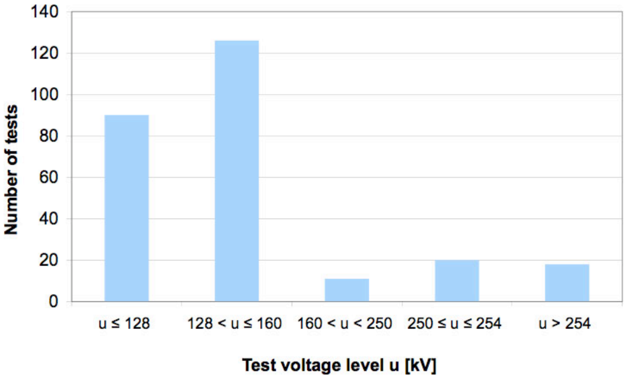

Figure 7: Distribution of test voltage levels

The main part of tests (approx. 50%) was related to cable lengths between 1 and 5 km, 24% were longer than 5 km (see fig. 8). Short cables were usually tested in parallel to ensure a resonant frequency below the upper limit of 300 Hz. In some cases, a HV capacitor was connected in parallel to the cable under test to reduce the resonant frequency or in series to extend the testable length of cables.

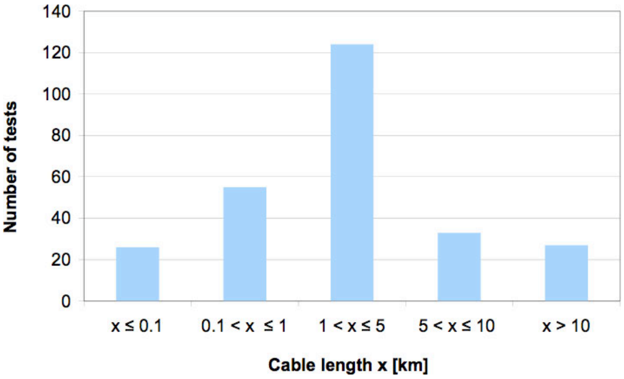

Figure 8: Distribution of tested cable lengths

Though on-site PD measurements are actually not required by IEC standards, the number of after-installation tests with PD measurements is clearly increasing (see fig. 9 and 10). According to their importance, **all** tests on EHV cable systems carried out by IPH included synchronized distributed multi-channel PD measurements.

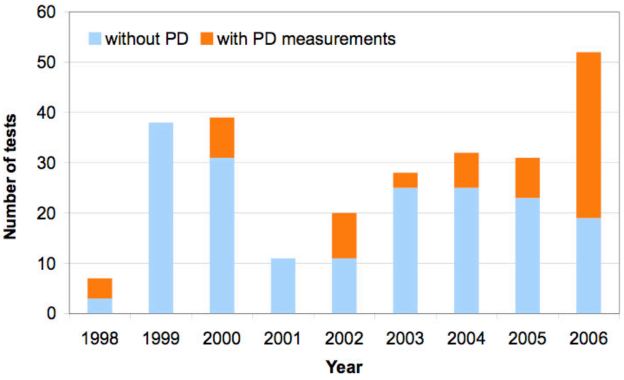

Figure 9: Number of tests with/without PD

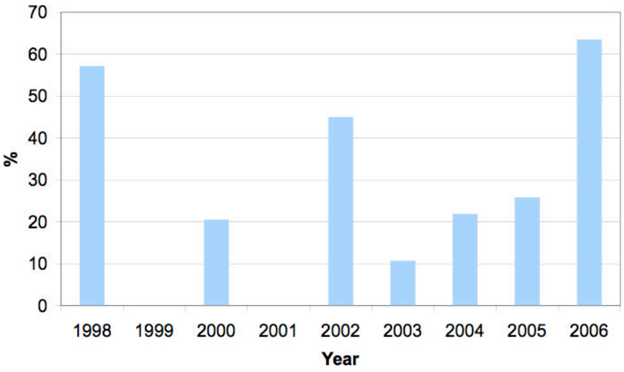

Figure 10: Proportion of tests with PD measurements

For HV cable systems, PD detection was usually performed at the terminations only, preferably by synchronized PD detection at both cable ends. Synchronized two-side PD measurements enable time-of-arrival PD localization. In contrast, single-side PD detection is restricted to TDR (time domain reflectometry) for PD localization, which results in lower sensitivity and accuracy.

TEST EXAMPLES

Test	Data	Test voltage
	km/nF	kV/Hz
Bewag Berlin/FRH1 1998 2 systems	6.3 km 1170 nF	400 (15 min) 350 (45 min) 26 Hz
Dublin 1999 2 systems	13.4 km 2546 nF	178 (60 min) 25 Hz
Bewag Berlin/FRH2 2000 2 systems	5.7 km 1010 nF	400 (15 min) 350 (45 min) 28 Hz
Taiwan 2002 4 systems	2.5 km 570 nF	250 (60 min) 53 Hz
Goldisthal 2002 2 systems	0.35 km 94 nF	450 (60 min) 92 Hz
Taiwan 2003 4 systems	2.5 km 570 nF	250 (60 min) 53 Hz
Bewag Berlin/FRH1 2003 re-test	6.3 km 1170 nF	290 (5 min) 242 (60 min) 26 Hz
Bewag Berlin/FRH2 2005 re-test	5.7 km 1010 nF	290 (5 min) 242 (60 min) 28 Hz
Dartford 2005 2 systems	2.65 km 650 nF	280 (60 min) 49 Hz
Elstree 2005 1 system	20 km 4400 nF	280 (60 min) 31 Hz
Wind farm Jüterbog 2005 1 system	35.3 km 9020 nF	160 (30 min) 23 Hz
Fehmarn 2006 1 system	31.06 km 8950 nF	160 (30 min) 23 Hz
Arneburg 2006 1 system	24.8 km 3340 nF	160 (30 min) 22 Hz

Table 1: Tests examples

CONCLUSIONS

AC after-installation testing with 1 U_0 / 24 h shows poor test efficiency. If higher test voltage levels are inapplicable, PD measurements are recommended to improve test efficiency.

AC resonant testing in combination with distributed multi-channel PD measurements using PD sensors at each accessory ensures best test efficiency for EHV extruded cable systems, independent from the cable system length.

For HV cable systems, however, PD detection is usually restricted to the accessible terminations. Consequently, PD sensitivity will decrease with increasing cable length.

After-installation tests cannot assess defects, which will slowly develop in service, e.g. due to thermal-mechanical degradation or leakage in fluid-filled or pressured-gas accessories. Such failures may be detected by continuous monitoring.

Return to Session

REFERENCES

[1] IEC 62067 Ed.1 2001-10, *Power cables with extruded insulation and their accessories for rated voltages above 150 kV (U_m = 170 kV) up to 500 kV (U_m = 550 kV) - Test methods and requirements*

[2] IEC 60840 Ed.3 2004-4 *Power cables with extruded insulation and their accessories for rated voltages above 30 kV (Um = 36 kV) up to 150 kV (Um = 170 kV) - Test methods and requirements*

[3] IEC 60060-3 Ed.1.0, 2006-02, *Definitions and requirements of on-site tests*

[4] E. Glockenbach, W. Hauschild, 2000, *The selection of the frequency range for HV in-side testing of extruded cable systems*, IEEE Insulation Magazine 16, 6, pp.11-16

[5] D. Pepper, 2003, *Grundlagenuntersuchung zum Teilentladungsverhalten in kunststoffisolierten Mittelspannungskabeln bei Prüfspannungen mit variabler Frequenz*, PhD, Technical University of Berlin

[6] CIGRE TF 21-05, 2001, *Experiences with AC tests after installation of polymeric (E)HV cable systems*, CIGRE technical report

[7] A.N. Verveen, G.C. Paap, 1991, *A 50 Hz after laying test for high-voltage extruded insulation cables*, Jicable'91, paper B.3.3

[8] H. Ota, M. Ichihara, S. Kitai, Y. Maruyama, M. Fukasawa, H. Takehana, N. Miyamoto, 1995*, Application of advanced after-laying test to long-distance 275 kV XLPE cable lines,* IEEE Trans. Pow. Del., Vol. 10, No. 2, pp. 567-579

[9] F. Bernasconi, W.S. Zaengl, K. Vonwiller, 1979, *A new HV-series resonant circuit for dielectric tests*, 3rd ISH Milan, paper 43.02

[10] W. Hauschild, W. Schufft, W. Spiegelberg, 1997, *Alternating voltage on-site testing of XLPE cables: The parameter selection of frequency-tuned resonant test systems*, 10th ISH Montreal, Vol. 4, pp 75-78

[11] E. Dorison, C. Aucourt, 1984, After laying test of HV and EHV cables, Jicable'84, paper BV-5

[12] F. Farneti, F. Ombello, E. Bertani, W. Mosca, 1990, *Generation of oscillating waves for after-laying test of HV extruded cable links*, CIGRE Session, paper 21-110

[13] R.C.A.M. Kovoets, 1990, *A new after laying dielectric test for underground high-voltage extruded cables*, Conference Record of the 1990 IEEE International Symposium on Electrical Insulation, Toronto, Canada

[14] E. Gulski, J.J. Smit, S. Meijer, P.P. Seitz, E.R.S. Groot, 2006, *On-site PD diagnosis of transmission power cables,* Conference Record of the 2006 IEEE International Symposium on Electrical Insulation, pp. 93-96

[15] H. Auclair, W. Boone, M.S. Papadopoulos, 1988, *Development of a new after laying test method for high voltage power cable systems*, CIGRE Session, paper 21-06

[16] C. Accourt, W. Boone, W. Kalkner, R.D. Naybour, F. Ombello, 1990, *Recommendations for a new after laying test method for high voltage extruded cable systems*, CIGRE Session, paper 21-105

[17] K. Uchida, H. Tanaka, K. Hirotsu, 1996*, Study on detection for the defects of XLPE cable lines,* IEEE Trans. Pow. Del., Vol. 11, No. 2, pp. 663-668

[18] CIGRE WG 21.09, 1997, *After laying tests on high voltage extruded insulation cable systems*, Electra No. 173, pp. 33-41

[19] W. Hauschild, W. Schufft, R. Plath, U. Herrmann, K. Polster, 2002, *The technique of AC on-side testing of HV cables by frequency-tuned resonant test systems*, CIGRE Session, paper 33-304

[20] R. Plath, U. Herrmann, K. Polster, R. Heinrich, W. Kalkner, J. Spiegelberg, P. Coors, 1998, *On-site PD measurement on an extra-high voltage XLPE cable line,* Jicable'98

[21] C.-G. Henningsen, K.-B. Müller, K. Polster, R.G. Schroth, 1998, *New 400 kV XLPE long distance cable systems, their first application for the power supply of Berlin,* CIGRE Session, paper 21-109

[22] S. Sutton, R. Plath, G. Schröder, 2007, *The St. John´s Wood - Elstree experience – testing a 20km long 400kV XLPE-insulated cable system after installation*, Jicable'07

[23] R. Plath, G. Schröder, S. Sutton, 2007, *PD measurements on extra high voltage cable accessories during commissioning an exeptionally long 400 kV XLPE-insulated cable system*, 15th ISH, Ljubljana, Slovenia (accepted – not yet published)

[24] E. Pultrum, E.F. Steennis, M.J.M. Van Riet, 1996, *Test after laying, diagnostic testing using partial discharge testing at site*, CIGRE Session, paper 15/2/33-12

[25] CIGRE WG 21.16, 2001, *Partial discharge detection in installed HV extruded cable systems*, CIGRE technical report no. 182

[26] E. Pultrum, S.A.M. Verhoeven, 2004, *Testing of Extruded Cables: experience in Type Testing, PQ Testing and Test After Installation. What do we learn from it? ,* CIGRE Session, paper B1-104

[27] R. Plath, R. Heinrich, K. Rethmeier, W. Kalkner, W. Weißenberg, 2003*, Sensitive PD detection on high voltage XLPE cable lines using field coupling sensors,* Jicable'03, paper C8.2.6

[28] R. Plath, 2005, *Multi-channel PD measurements*, 14th ISH, Beijing, China

[29] R. Plath, 2005, *Digital measurements and analysis of partial discharges - drawbacks and new opportunities,* Highvolt Kolloquium, Dredsen, Germany

[30] W. Weissenberg, F. Farid, R. Plath, K. Rethmeier, W. Kalkner, 2004, *On-site PD detection at cross-bonding links of HV cables*, Cigre session, paper B1-106

[31] J. Kaumanns, E. Plieth, R. Plath, 2003*, On-site AC testing and PD measurement of 345 kV/2500 mm^2 XLPE cable systems for bulk power transmission,* Jicable'03, paper A8.4

GLOSSARY

ACRF	Frequency Tuned Resonant Circuits
ACRL	Inductively Tuned Resonant Circuits
CB	Cross-Bonding
DAC	Damped AC voltage
DCS	Directional Coupler Sensor(s)
HV/EHV	High Voltage/Extra High Voltage
PD	Partial Discharge(s)
Q	Quality Factor
TDR	Time Domain Reflectometry
VLF	Very Low Frequency