Voltage tests to assess medium-voltage cable systems.

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The service reliability of medium voltage cable systems is currently proved with DC voltage test. For paper-insulated, oil-impregnated cables the DC voltage test provides satisfactory results, but fails for PE(polyethylene) /XLPE (crosslinked polyethelene) cables. The authors present comparative tests with various alternative voltage types which come into consideration for on-site testing of medium- voltage cables. The results will be discussed with regard to the fundamental possibilities and limits of voltage tests.

1. General

Medium-voltage cable systems are tested for various reasons to check the system's readiness for connection and to prevent breakdowns during operation. For example, tests are carried out after new cables are installed to reveal any faults caused by transportation or installation. Tests are also carried out in connection with the re-commissioning of a cable system, for example following repair, in order to reveal any further weak points in the insulation other than at the fault repaired or to be able to monitor the quality of a repair. Furthermore, for some time, old PE/XLPE-insulated cables in particular have been tested for a rough assessment of their aging condition.This is mainly carried out to reveal water-tree weak points which would cause the cable to fail in the foreseeable future.
For paper-insulated, oil impregnated cables a DC voltage test has been established over many years for monitoring the service reliability of cable systems. With this cable type the DC voltage test reveals potential hazardous breakdowns with a sufficient level of reliability without damaging the cable. However, DC voltage is not suitable for testing cables insulated with plastics[1]as massive weak points cannot reliably be detected even using very high test levels and, furthermore, it is not possible to exclude the risk of initiating damage which is not discovered during test duration. Therefore, for a long time, there has been an international search for test methods which can be used as a replacement or alternative for DC voltage.
Up to now it has not been possible to include alternative methods in the existing VDE (Association of German Electrotechnical Engineers) regulations (VDE 0298 TI) due to the lack of the required comparative tests and experience (with these alternative voltage types).
In order to be able to remove the existing uncertainty regarding on-site testing of medium-voltage cables insulated with plastics, which has also been reflected in a footnote to the corresponding VDE regulations, a research project ("Test procedures for assessing installed medium-voltage cables") was started in 1989 at the Technische Universitat Berlin (Berlin Technical University), Institut fuer Hochspannungstechnik (Institute for High-Voltage Engineering), with the participation of Bewag, Berlin, EWE AG, Oldenburg, Siemens AG Berlin Geschaeftsbereich Starkstromkabel und -Leitungen (power cables and lines section) and VEW AG, Dortmund.

The aim of this research project was to investigate the suitability of the following methods for on-site testing of medium -voltage cables (PE/XLPE and paper insulated, oil impregnated cables)using comparative laboratory tests and on-site tests:

- Very Low Frequency (VLF) 0.1Hz sinusoidal voltage.
- VLF 0.1 Hz cosine-square wave voltage.
- Oscillating Voltages,about 1 to 12 kHz
- 50 Hz Resonance Voltage

The present report gives an overview of the essential results of these tests. Recommendations for the testing of installed medium-voltage cables can be derived from these results.

2. Types of test voltage

2.1 VLF 0.1 Hz sinusoidal voltage and cosine square wave voltage.

The advantage of a test voltage source with the frequency of 0.1 Hz compared to 50 Hz AC voltage is that the reactive power requirement is 500 times less. 0.1 Hz voltage test sources can thus be set up correspondingly easily and are relatively easy to transport so that testing large capacitance's (for example, cable systems) on site presents no problem.
For the laboratory tests a laboratory system [1; p. 129] was used which allowed testing of short length cable (6 to 10 m) with up to $V_{Eff.} = 100$ kV. For testing on site there is already a 0.1 Hz sinusoidal voltage source commercially available. Its output voltage is however limited to $V_{Eff.} = 33$ kV.
A commercially available test voltage source was used to generate the cosine square wave 0.1 Hz voltage in the laboratory and on site: its circuitry is also reproduced, in [1: p. 131], where the measured shape of the output voltages of both 0.1 Hz voltage sources are represented.

2.2 Oscillating voltages.

Oscillating voltages can be produced relatively cheaply on site by using a normal DC voltage test unit, a triggered spark gap and a high voltage air coil.
The cable to be tested serves as a capacitor and is charged with the DC test unit to the required test voltage level and discharged via a triggered spark gap onto the air coil. The resulting voltage pulse which

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oscillates symmetrically around the zero point (1 to 12 kHz) has to be repeated several times for the test (for example, 50 times). In this way very high test voltages can be created relatively easily on site which, in principle, also qualifies this type of voltage for testing high-voltage cables [2].

2.3 DC voltage and 50 Hz AC voltage.

For on site tests with AC voltage in the range of the power frequency, a resonance system with the frequency converter and inductive resistors has been commercially available for some time [3.]. Instead of such a resonance system, for the present tests a conventional high voltage transformer was used in the laboratory to produce a 50 Hz high voltage.
The DC voltage included in the tests for comparison was produced in the laboratory with half-wave rectification from a 50 Hz high voltage instead of using conventional on-site test systems.

3. Laboratory tests and results

3.1 Service-aged XLPE cables

In order to investigate the ability of the various types of voltage to reveal water-tree weak points in XLPE cables, 6m cable lengths from two service-aged 10 kV XLPE cables were used as test objects:

- Cable A: Vented trees on the inner semi- conductive layer spanning up to 65% of the insulation. Cable service aged for about 12 years;
- Cable B: Vented trees on the outer semi-conductive layer spanning up to 85% of the insulation. Cable service aged for about 11 years.

In order to obtain a value for the strength of the service-aged XLPE cables dependent on their water tree damage, which is important for determining the suitable test level, cables A and B were subjected to the various types of voltages in the form of residual strength test (step voltage tests) [1:pp.127-152].

Fig.1. Breakdown voltages of service aged short lengths of cable from 2 manufacturers (6m lengths, cable A, cable B) with various types of voltage.

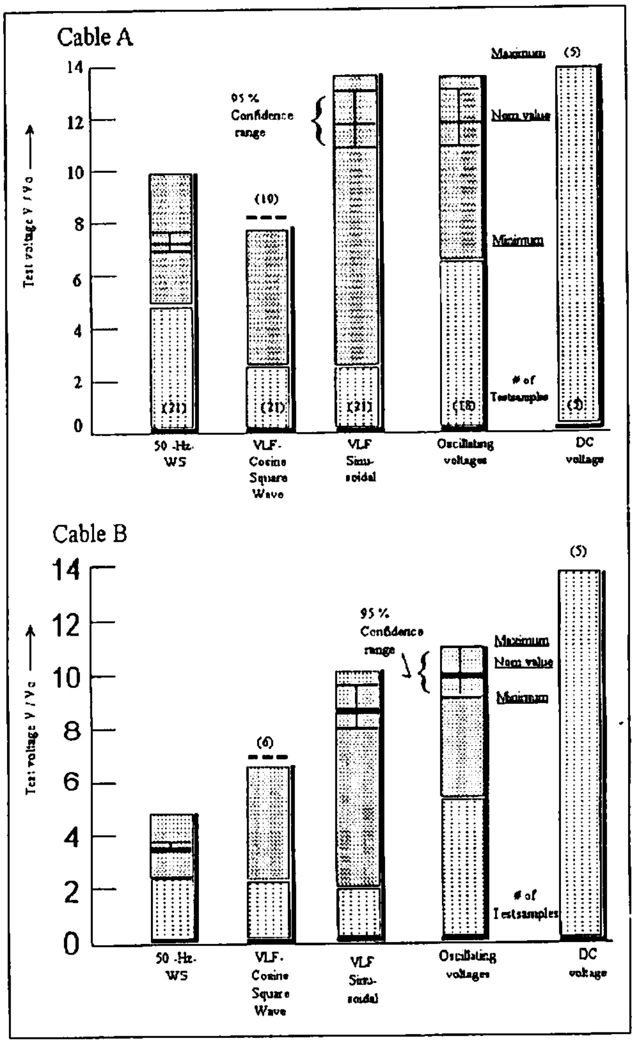
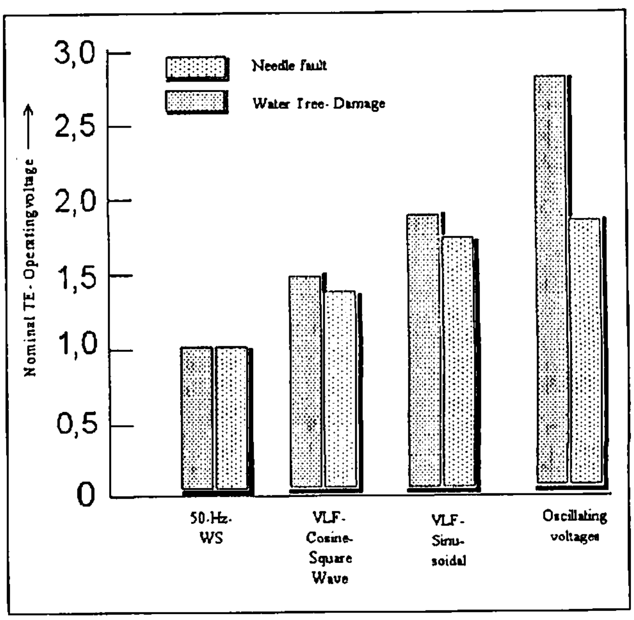
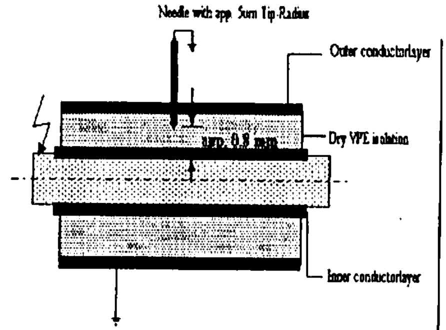


Fig. 2. Partial discharge inception voltage of service-aged 10kV XLPE cable pieces with artificial needle faults or alternative of service-aged 10 kV XLPE cable pieces with water-tree damage: Weibull rated values related in each case to the voltage with 50 Hz AC voltage.





Test Voltage Type	Level	Duration	# Test objects	Faults-occur.
50-Hz-AC (Reference -value)	2Vo	30 min	10	10
VLF-Sinu-soidalVoltage	3Vo	30min	5	5
VLF-Cosine Square Wave	3Vo	30min	5	5
Oscillating Voltage	4Vo	50 Pulses	5	5
DC Voltage	8Vo	30min	6	0
DC Voltage	10Vo	30min	6	0

Figure 3. Schematic illustration of an artificial needle fault in a 10 kV-XLPE cable and the results of the voltage tests on these test objects with various voltage types.

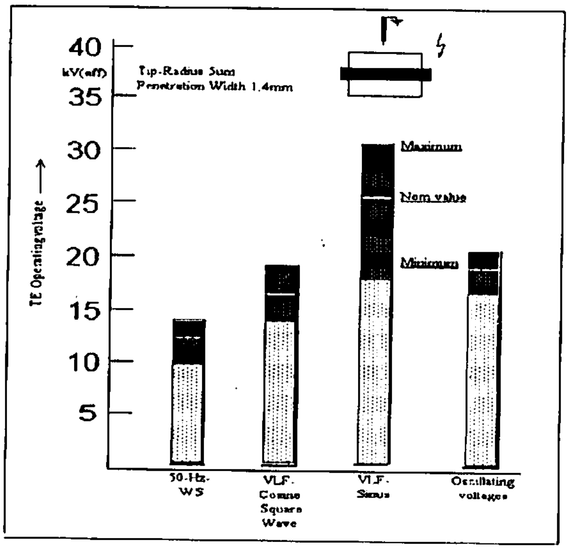


Figure 4. Partial discharge inception voltage of new, dry 10 kV XLPE cables with artificial needle faults at various voltages.

The possibility of damage having been initiated by the voltage test with the levels and duration's discussed here (AC voltage 50 Hz 2 Vo/30 min.; VLF 3 Vo / 30min.; oscillating voltages 4 Vo/50 pulses) was investigated by checking after the voltage tests in an FGH step test with 50 Hz AC voltage, whether the residual strength had decreased in relation to untested cables.

The test results on service-aged XLPE cables show (Fig. 1) that unexpected high voltage levels are required to reveal water tree weak points, as appearing in cables A and B. These levels are much higher than the levels discussed for on- site testing today, with which, therefor, only extreme water-tree damage can be detected (for example, almost completely penetrated water trees). Particularly impressive, however, is the confirmation that, even using very high test levels, extremely serious water-tree faults in XLPE cables can not be detected with DC voltage, except for those bridging the complete insulation thickness. At the same time the residual breakdown strength test shows that with the various test voltage types there are, as expected, differences in the residual strength levels of the cables and that there is a ranking with respect to the level of voltage required for the detection of water-tree faults. This ranking (lowest breakdown voltage level with 50 Hz AC voltage,then VLF cosine square-wave voltage, VLF sinusoidal voltage and the highest breakdown voltage level with oscillating voltages) is obviously, according to Fig. 1, not dependent on the type and extent of the water-tree damage of the cables tested.

Accidental damage by voltage testing with the above-mentioned levels on service-aged cables could be observed in none of the cases (no reduction in strength on six test objects per type of voltage).

However, with tests in the form of step-voltage tests, it is unclear at what voltage the breakdown process begins (i.e. when the transition from a water tree to an electrical tree takes place) and how long it takes until the sample breaks down. As these findings are, however, of great significance when determining the suitable test duration's for on-site voltage tests, additional tests in the form of a step time to breakdown test with the various test voltage types were carried on 6 m long short lengths of service-aged XLPE cable B.

The step time to breakdown test selected [4] consists of a sequence of 60-minute voltage tests which are each interrupted for a partial discharge check with 1 Vo/50 Hz AC voltage in order then, if no partial discharges > 1 pC were measured, to continue with voltages increasing by 1 Vo at a time. In this way the partial discharge inception voltage (for example, the transition from a water tree into an electrical tree) can be recognized with the various voltage types and can be used as an important quality characteristic for the suitability for voltage testing. In addition, the step time to breakdown test produces valuable information regarding the time to breakdown of water-tree damaged XLPE cables under constant test voltage stress, which, in turn, is of great interest in determining a suitable test duration.

In Fig. 2, the partial discharge inception voltages established for seriously water-tree damaged XLPE cables with the various voltage types are represented as Weibull rated values. A ranking for the voltage types can be seen here too; it coincides with the ranking observed with the breakdown tests. In Fig. 2 the partial discharge inception voltage values of needle faults in service-aged XLPE cables test objects are also represented; these values, in turn, also allow the same ranking to be observed as with the water-tree damaged test objects. Consequently, a partial discharge inception can be obtained with 50 Hz AC voltage on water trees and also on needle faults with the lowest, in terms of comparison, voltage levels.The partial discharge inception voltage value using VLF cosine square-wave voltage were about

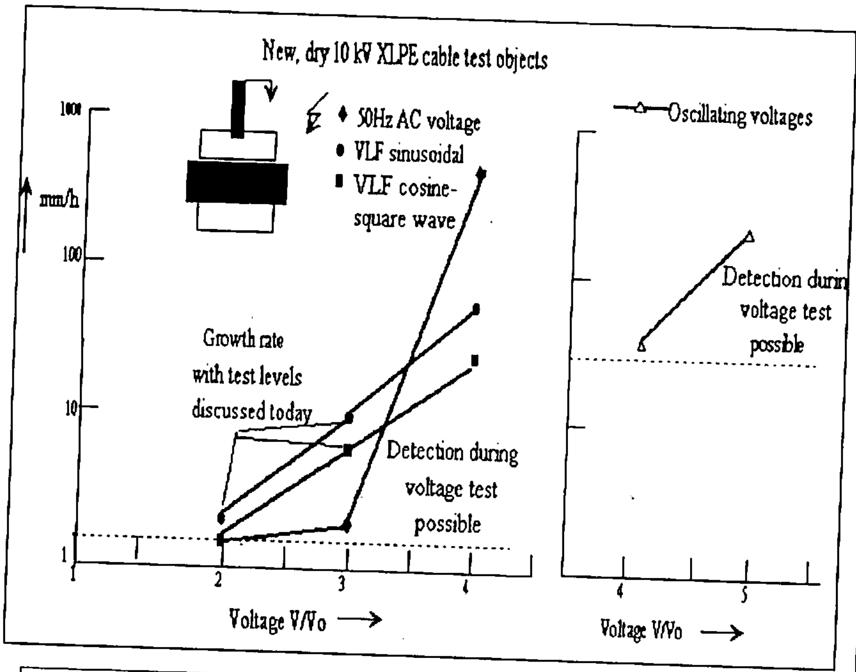
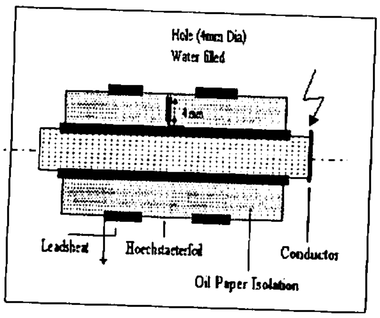


Fig. 5. Mean channel growth rate PD pre damaged needle faults in new, dry 10 kV XLPE cable insulation at different voltage levels.



Test Volt. type	Level	Duration	# of test samples	# of failures
50-Hz-AC Ref. Value	2Vo	30 min	10	10
VLF-Sinusoidal Volt.	3Vo	30 min	5	5
VLF-Cosine Squ. Wave	3Vo	30 min	5	5
Oscillating Voltage	4Vo	50 Pulses	5	5
DC Voltage	8Vo	30 min	6	0
DC Voltage	10Vo	30 min	6	0

Fig 6. Diagram of an artificial wet fault in a 20 kV paper-insulated, oil-impregnated cable and results of the voltage tests on these test objects with the various voltage types.

1.4 times higher; these values were, however, clearly exceeded by the values obtain with VLF sinusoidal voltage. The highest partial discharge inception voltage values in the service-aged dielectric were observed with oscillating voltages for both water-tree weak points and needle faults.

Furthermore, the tests showed that, with a test with oscillating voltages /50 pulses, there was a clear risk of initiating accidental damage.

3.2 New XLPE cables / XLPE cable lengths with needle fault.

New XLPE cable short lengths with artificial needle fault were tested to find out if the voltage tests with the parameters discussed here allow faults to be detected. The electrical residual breakdown strength of those samples can be determined at 2 Vo (50 Hz AC voltage). Fiq. 3 shows both the test levels and durations discussed here for the alternative voltage types and the results of the voltage tests. It can clearly be seen that this service hazardous fault cannot be detected by a DC voltage test in accordance with the current VDE regulations, even with increased test levels, for example 10 Vo. On the other hand, all the alternative voltage types allowed reliable detection of the fault. The impressive aspect of this is how seriously the insulation must be damaged by the needle(undamaged residual insulation thickness only about 0.8 mm) to lead to breakdown with the test levels discussed.

The partial discharge inception voltage at weak points and the channel growth rate at a fixed test voltage level after the initiation of the first partial discharge are of great importance for the suitability of a voltage type for testing PE/XLPE-insulated cables. The microscopic tests of XLPE cable lengths with needle fault under high voltage served to determine the partial discharge inception voltage and to determine the channel growth rate with the various voltage types. The results of the partial discharge inception voltage measurements of needle faults in new, dry XLPE insulation are reproduced in Fig. 4.

A ranking of the types of voltage can clearly be seen, although it is different to the order of priority observed in service-aged cables. The highest partial discharge inception voltage values with the greatest dispersion were observed on these new, dry test objects with needle faults using the VLF 0.1 Hz sinusoidal voltage. The values for 50 Hz AC voltage are, however, lowest here as well and are exceeded by the values for VLF 0.1 Hz cosine square-wave voltage by a factor of about 1.4. The rated value for the partial discharge inception voltage with oscillating voltages slightly exceeds the VLF cosine square-wave voltage value and is in this case (new, dry XLPE insulation) lower than the value established for VLF sinusoidal voltage.

To establish the channel growth rate, i.e. the time until breakdown after the first partial discharge initiation, XLPE cable test objects (new and dry/service-aged and wet) were damaged with a needle fault which produced a uniform first disruption of partial discharge structures (length about 120 um). These definitely partial discharge-damaged test objects were then subjected to time to breakdown tests with the individual types voltage at various voltage levels (for example 2, 3 and 4 Vo). The growth could be observed through a microscope with the help of video technology. The time until breakdown and the gap distance enables to calculate the growth rates, which are represented in Fig. 5 for a new, dry insulation.

Fig. 5 shows clearly that this fault is reliably detected with all types of voltage at the test levels discussed here within a test duration of 60 min. It is also clear that the growth is markedly slowed with 50 Hz AC voltage in the range 2 to 3 Vo (on account of the gas pressure formed in the partial discharge channels). With this low growth rate in the range of the test level there is the risk that the weak points, for example, will be converted into partial discharge channels by means of the low partial inception voltage demonstrated by the 50 Hz AC voltage. Then the problem is that during a test duration of , for example, 30 minutes, this fault will not be brought to breakdown. A comparatively high channel growth speed could be observed with the two VLF voltages; however with the same voltage level, the channels grow slightly faster with sinusoidal voltage than with VLF cosine square wave voltage. Such fault is also reliably detected with oscillating voltage within 50 pulses with the test level discussed today. However, a comparison with the DC voltages is not possible here.

In general, a lower channel growth speed was observed with service-aged XLPE insulation, which makes clear that a test duration of 60 minutes is to be recommended, particularly when testing aged cable lengths.

Table1. Evaluation table for the selection of a suitable voltage type for testing installed medium voltage cables (+ = good, 0 = less good, - = bad).

Assessment criteria	Type of voltage	50 Hz AC Voltage (resonance)	VLF Cosine - Square Wave Voltage	VLF Sinusoidal Voltage	Oscillating Voltage	DC Voltage
Service aged XLPE cable	Low brakdown Voltage	+	+	0	0	–
	Low partial discharge inception Voltage	+	+	0	–	
	High channel growth rate 1.)	0	+	+	(-)	
New XLPE cable with needle voltage fault	Low breakdown voltage	+	+	+	0	–
Low partial discharge inception voltage	Dry	+	+	–	0	
	Wet	+	0	–	(0)	
	High Channel growth	—	+	+	(0)	
Artificially Wt-aged XLPE cable	Low breakdown voltage	—	+	+	0	—
Paper insulated-oil impregnated cable	Low breakdown voltage		+	+	0	—
	Comments	Not suitable for paper insulated-oil impregnated cables		additional tanδ measurement possible	additional PD-measurement possible	

1) Results with the test voltage levels discussed today

() Impulse-like stressing.

3.3 Tests on paper- insulated, oil-impregnated cables.

Mixed cable networks, i.e. both PE/ XLPE and paper insulated oil impregnated cables, are used widely by many power supply companies in one system.Thus there is a desire also to be able to reliably detect typical faults in paper insulated, oil impregnated cables with the alternative test voltage, as was previously guaranteed by a DC voltage test.

A typical fault in a paper insulated, oil impregnated cables, for example, moisture penetration of the dielectric on account of damage to or corrosion of the metal sheathing. Therefore short lengths of paper insulated, oil impregnated cables with an artificially created humid fault were tested with the various types of voltage. The fault was formed in such away that it would be reliably detected by DC voltage test in accordance with VDE 0255.

The results in Fig. 6 show that all alternative types of voltage, using the indicated test levels and durations, are able to detect this fault with comparatively low voltage levels just as reliably as DC voltage test. However, there is the one restriction that the resonance AC voltage is suited only for testing short length's of paper insulated, oil impregnated cables on account of the high dielectric loss factor of paper insulated cables.

4. Experience with alternative test voltage types on site.

The VLF 0.1 Hz cosine square-wave voltage was introduced in 1987 at EWE Aktiengesellschaft in Oldenburg to test the medium-voltage cable system (20 kV) which consists mainly of XLPE cables. At first tests were carried out with a test level of 3 Vo and a test duration of 30 minutes. This test replaced the DC voltage test with 4 Vo (see footnote VDE 0298 T1) which had previously also been used at EWE Aktiengesellschaft for service-aged XLPE cables. Within the framework of this test two general observations were made: markedly more faults were detected in cables insulated with plastics than with DC voltage but there were some breakdowns in cables in service only a short time after the test. The second observation caused the test duration to be increased from 30 minutes to 60 minutes while maintaining the test level at 3 Vo. Since changing over in 1990 the number of cable failures following testing fell markedly. [1; pp. 221-225].

The previously represented results of the laboratory tests agree well with the results of the on-site tests at EWE and tend to agree with those at VEW AG, Dortmund and Bewag, Berlin, as it was also established the laboratory that a test with VLF cosine square wave voltage 3 Vo/ 30 minutes, better 60 minutes, was suited for detecting service hazardous weak points in XLPE cables.

Moreover there are also first experiences from on-site tests using a resonance AC voltage, which are also largely in agreement with the observation made here (danger of damage by means of low channel growth rate simultaneous low partial discharge inception level).

There is as yet no experience with on-site voltage tests with VLF sinusoidal voltage. This type of voltage was only used to test the on-site dissipation factor measurement, the result of which are reproduced in[5].

5. Conclusions.

On the basis of the present results of the comparison of the various voltage types, the suitability of the individual voltages for testing medium-voltage cable systems is evaluated in Table 1.

The following conclusions can be drawn for the voltage testing of medium-voltage cable systems:

- Even seriously service hazardous weak points in PE/XLPE cables are not detected with a DC voltage test even with increased test levels.
- Voltage tests with the alternative voltage types (VLF sinusoidal, cosine square-wave voltage, 50Hz AC voltage and oscillating voltages) are in principle suitable for detecting faults in PE/XLPE cables.
- Using the test levels discussed here (50 Hz AC voltage: 2 Vo;VLF: 3 Vo; oscillating voltages: 4 Vo) it is possible to detect severe service hazardous faults.
- Less serious weak points of PE/XLPE cables could be detected with higher test voltage levels, but with a higher risk of further damage and the danger of unwanted breakdown in cables which are still service reliable.
- Extension of the duration of 30 min. discussed today for the test with 50 Hz AC voltage and VLF voltages to 60 min. is to be recommended. This applies particularly for testing service-aged XLPE cable systems.
- With oscillating voltages, either the number of impulses should be increased to more than 50 initiating unwanted further damage by the test here as well.
- Typical faults in paper-insulated, oil -impregnated cable can be detected with the alternative voltage types even at lower voltage levels compared with a DC voltage test in accordance with VDE.

For on-site voltage tests(yes/no result delivered) particularly on cables insulated with plastics, the is VLF cosine square-wave voltage is comparatively best suited as relatively low partial discharge inception voltage values arise with, at the same time, relatively high channel growth speeds. The possibility of detecting serious, i.e, service hazardous faults is therefore relatively high here and the risk of further damage relatively low. A voltage level of 3 Vo and a test duration of 60 minutes are recommended today as-test parameters.

For extended evaluation of service-aged PE/XLPE cables, the use of sinusoidal VLF voltages with accompanying dissipation factor measurements can be proposed as this allows the possibility of obtain more information about the condition of the insulation than with a pure test (yes/no result) without the cable being damaged [5].

For checking newly installed XLPE cable systems, i.e. to detect defective fittings, the partial discharge measurement with oscillating voltages or with unipolar impuls voltage [6; 7] represents the possibility of obtaining a result regarding the quality, for instance, the installation work. however, on-site partial discharge measurement is currently still under development.

6. Bibliography

[1] Krefter, k.h. (ed.): Pruefungen zur Beurteilung von Kabelanlagen in Mittelspannungsnetzen. Tagungsband VDE.-Fachtagung Bochum, 1991. (Tests for assessing cable systems in medium-voltage networks. Conference book of the VDE specialist conference at Bochum in 1991).

[2] Aucourt, H., Boone W., Kalkner, W. et al.: Recommendations for a new after-laying test method for high-voltage extruded cable systems. Cigre Session 1988, Paris. Contribution 21-105.

[3] Jaeckle, E.: Pruefung von Kabelanlagen mit Resonanz-Pruefgeraeten. (Testing cable systems with resonance tests units). Elektrizitaetswirtschaft JG. 86 (1987), pp. 260-262.

[4] Bach, R.,; Kalkner, W.; Plath, R.: Untersuchungen zur Vor-Ort-Pruefung von Mittelspannungskabeln. ETG-Fachtagung Wuerzburg 1992. (Studies on on-site testing of medium-voltage cables. ETG specialist conference in Wuerzburg 1992), pp. 317-326.

[5] Bach, R.; Kalkner, H.; Oldehoff, H.: Verlustfaktormessungen bei 0.1 Hz an betriebsgealterten PE/VPE-Kabelanlagen. (Dissipation factor measurements at 0.1 HZ on service-aged PE/XLPE cable systems). Electrizitaetswirtschaft 1993, Volume 17/18.

[6] Krage, I; Kalkner W.: PD detection and -localization using unipolar impulse voltage for on-site testing of polymer- insulated cables. 8th ISH, Yokohama 1993.

[7] Plath, R.; Strehl, Th.; Kalkner, W.: Oscillating voltages for on-site PD detection and Voltage testing of extruded power cables. 8th ISH, Yokohama 1993.