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Verification of Insulation Coordination Completed by High-Voltage Testing on Site

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Abstract:

Insulation coordination of substation equipment, cables and power lines is usually verified by type and routine tests in factory. To guarantee the insulation coordination in service it is necessary to demonstrate that insulation of the equipment is without transportation faults and correctly assembled. This is usually done by HV tests on site. The paper informs about the general principles for HV on-site testing as they are prepared by the IEC Working 42.13 for a new part 3 of the IEC Standard 60060. As examples requirements and test equipment for on-site testing of gas-insulated substations (GIS) and HV XLPE cables are described. Finally the relation between on-site testing before commissioning on the one hand and after repair or for diagnostic purposes are considered.

1. Introduction:Insulation Coordination

It is the aim of the insulation coordination to guarantee the reliable power supply, to avoid damages of expensive apparatus and systems for power generation, transmission and distribution systems and – last but not least – to protect the personnel. The principles of insulation coordination, described in the group of IEC Standards 60071 [1], are well developed and have proven their efficiency. Insulation coordination is realized by well-rated withstand voltages for different types of insulations. These withstand voltages must be verified by high-voltage (HV) tests.

It is a general and important principle of the insulation coordination [1] and the HV test technique [2] that the applied test voltage stress shall simulate the stresses which can occur during the later service of the HV apparatus to be tested. A HV test should enable a decision whether a defect in the insulation is dangerous or not for the later operation by failing or passing the test. This means the failure mechanism (caused by the kind of defect and the kind of the voltage stress) in the HV test and the later service should follow the same physical process. To accelerate this process, the test voltages are usually higher than the corresponding stresses during operation. This acknowledged principle for HV testing in the test laboratory of a factory cannot be easily transferred to HV on-site testing [3]. The main problem is the availability of the HV test systems on site, because they must be lightweight, transportable, easy to handle and of low power consumption.

With a **HV type test** the correct and reliable design of the HV insulations of electric power equipment shall be demonstrated. The **HV routine test** shall confirm the correct manufacturing, this means it is shown that the insulation is free of dangerous defects.

The two tests in factory are not sufficient for the verification of insulation coordination when type and routine tests are only related to transportation units (e.g. single bays of a GIS or single drums of a HV cable) and the equipment or system (e.g. a gas-insulated substation or a cable system of several kilometres length) is completed on site. The consequently necessary on-site tests are considered in the following generally.

2. HV On-Site Testing

2.1 Reasons for HV testing on site

HV on-site test are applied [3]

(1) as a part of the commissioning of the equipment on site to demonstrate that transportation from the manufacturer to the site and the erection have not caused any new, dangerous defects in the insulations, which disturb the insulation coordination.

(2) After an on-site repair of the equipment to demonstrate that it was successful and that all dangerous defects in the insulation are eliminated.

(3) For diagnostic purposes to demonstrate that the insulation is still free of dangerous defects and the life-time expectation is sufficiently high.

2.2. General requirements for HV on-site tests

HV on-site tests require mobile HV test systems, which shall be

- of low weight and dimensions,
- of low power consumption,
- simply erectable on site and
- robust against extreme environmental conditions and mechanical stresses during transportation.

It is clear that under on-site conditions the strict requirements, given by IEC 60060 Part 1 and 2 for factory tests, cannot be realized. Therefore a Part 3 of that standard is under preparation [3] [4] which allows

- the application of extended shapes of the HV test voltage (see below),
- larger tolerances for the adjustment of the test voltage height,
- acceptance of larger voltage measuring uncertainties,
- simplified checks of voltage measuring systems.

The following extended shapes of the test voltages are proposed [4]:

Alternating voltage for presentation of service. AC voltage is accepted in a wider frequency range of 10 Hz to 500 Hz (instead of 45 Hz to 60 Hz for factory testing [2]). For on-site testing of equipment the related IEC Apparatus Committee may select a more narrow frequency range, for instance for extruded HV and EHV cables the range 20 to 300 Hz has been standardized [5] (Fig. 1).

The lightning **impulse voltage** aperiodic (as for factory tests [2]) and oscillating impulses are accepted, both with front times between 0.8 and 200 µs and times-to-half-value between 40 and 100 µs (Fig. 2).

For **switching impulse voltage** also aperiodic and oscillating impulses (time-to-peak 100 to 400 µs, time-to-half-value 1000 to 4000 µs) can be applied (Fig. 3).

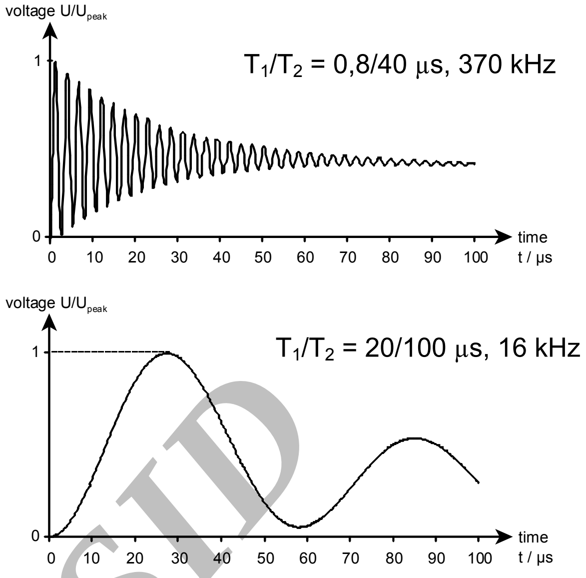

Fig. 2:Lightning impulse voltages for on-site testing

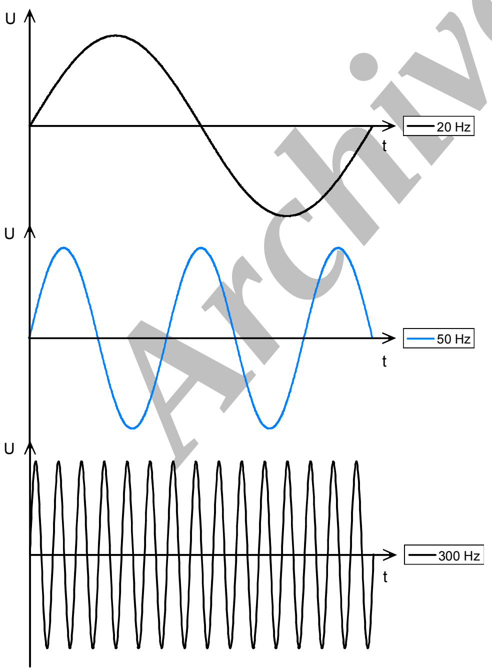

Fig. 1:AC voltages for on-site application according to IEC 62067 [5] and draft IEC 60060-3 [4].

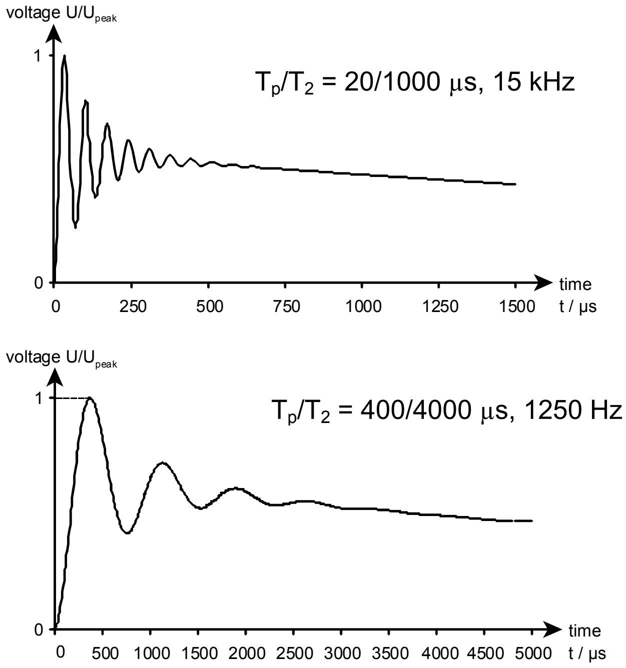

Fig. 3:Switching impulse voltages testing for on-site testing.

3. Generation of AC test voltages on-site

Traditionally AC test voltages are generated by systems based on conventional test transformers with compensation reactors on the low-voltage side at the power frequency (ACTC). But the weight-to-power ratio of an ACTC test system is usually too high for on-site application. More efficient are resonant test systems:

A series resonant test system is an oscillating circuit mainly consisting of a HV inductance L and a capacitive load C (test object). That circuit operates in resonance when the condition "exciting frequency fe is equal to the natural frequency of the oscillating circuit" is fulfilled:

$$f = 1(2\pi \sqrt{LC}) = f_e. \qquad (1)$$

There are two possibilities to reach the resonance condition for a given capacitive load:

- by a reactor of **variable inductance** and a fixed value of the exciting frequency (e.g. f_e=50 or 60 Hz, **ACRL test systems**), or
- by a fixed reactor and the excitation by a voltage of **variable frequency** [4] (e.g. fe=20…300 Hz for extruded cables [5], **ACRF test systems**).

The comparison of the two principles (table 1) shows the clear advantages of frequency-tuned test systems (ACRF). Because of the fixed inductance the ACRF reactors are more compact than tuneable ACRL reactors. Additionally ACRF systems may operate at frequencies below power frequency. This reduction in test power S (equ. (4)) at lower frequencies causes a further reduction in weight and size. ACRF systems have the best weight-to-test-power ratio.

Table 1:Comparison of ACRL and ACRF series resonant test system for on-site application

resonant circuit	ACRL (inductance-tuned)	ACRF (frequency-tuned)
frequency	f_L=50 Hz (60 Hz)	f_F=20...300 Hz (cables)
max test power	$S_{Lmax}=2\pi f{*}CU^2$	$S_{fmax}=2.5\ S_{Lmax}$
quality factor	q_L=40…60	q_F=80…>120
load range	$C_{max}/C_{min}=L_{min}/L_{max}\approx 20$	$C_{max}/C_{min}=(f_{max}/f_{min})^2\approx 225$
feeding power	$P_{eL}=(2\pi fCU^2)q_L$	$P_{eF}=P_{eL} * (f_F/f_L) * (q_L/q_F)$
power supply	single or two phase	Three phase
weight-to-power-ratio[1)]	3…8 kg/kVA	0.8…1.5 kg/kVA
components with moving parts	tuneable reactor regulator transformer	non
number of main components	(6) tuneable reactor HV divider/PD coupler exciter transformer switching cabinet control and meas. rack	(4) fixed reactor HV divider/PD coupler exciter transformer control and feeding unit

1) 50 Hz equivalent power

The principle circuit diagram of an ACRF test system is given in Fig. 4:

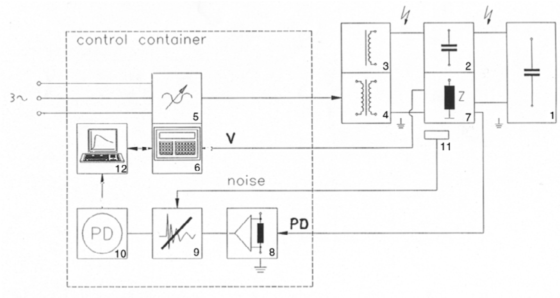

Fig. 4:ACRF test circuit with PD measuring system (explanation of the numbers in the text)

The control and feeding unit is arranged in a cubicle and contains the power switch, the power frequency-converter (5) generating square-wave voltage (20 to 300 Hz), and all control and measuring modules (6). The exciter transformer (4) adapts the square-wave voltage to the HV oscillating circuit, consisting of the test object (1), the coupling capacitor / voltage divider (basic load (2)) and the main component, the HV reactor (3). A PD measuring system (7, 8, 9, 10, 11), especially designed for ACRF testing, enables high sensitivity. A laptop computer (12) is applied for controlling the test system, monitoring the test as well as for the PD diagnostics.

4. Examples for the application of ACRF test systems

In the following some characteristic applications of ACRF systems and their related design are described. Further AC voltage tests using ACRF systems, e.g. of testing power transformers or generators, have been successfully performed and new applications can be expected with the increasing demand for on-site testing.

4.1 Testing of gas insulated substations (GIS)

The on-site testing of GIS is the classical application of ACRF test systems [4] [8]. When the AC voltage testing is combined with a PD measurement of sufficient sensitivity (≤ 5 pC) then all kinds of defects in SF_6 insulated systems can be detected. Today components for “open” and “shielded” ACRF test circuits are supplied. The required frequency range is usually 50…300 Hz, which enables the testing including voltage transformers.

Mobile HV reactors (oil-paper insulated in an insulation tank) for open circuits enable the optimum adaptation of the inductance to the GIS/GIL capacitance by switching in series or in parallel (Fig. 5). For testing of 400 kV GIS three series-connected modular reactors for 230 kV/3 A each are necessary: Their combination covers the wide range of voltages (20 to 680 kV) and of inductance (67 to 600 H) and delivers also the wide range of load 0.5 (up to 680 kV) to 100 nF (up to 230 kV).

When for instance 123 kV GIS including voltage transformers shall be tested and ($U_t \leq 230$ kV) the basic load (divider) is C_{min} = 1 nF, the frequency range 100 to 200 Hz is covered for C_T = 0 to 35 nF. But for testing 400 kV apparatus only the series connection of 3 modules is applicable which means, for f = 100 to 200 Hz up to 3 nF can be tested. Also this is sufficient for many 400 kV GIS. For the extended range 50 to 200 Hz a load up to CT = 16 nF, corresponding to a very large 400 kV GIS or a 400 kV GIL of approximately 250 m length, can be tested. The parallel connection (2 p), (3 p) would even be applicable for cable testing. Fig. 6 shows a modular 680 kV ACRF during testing a 400 kV GIS equipped with bushings.

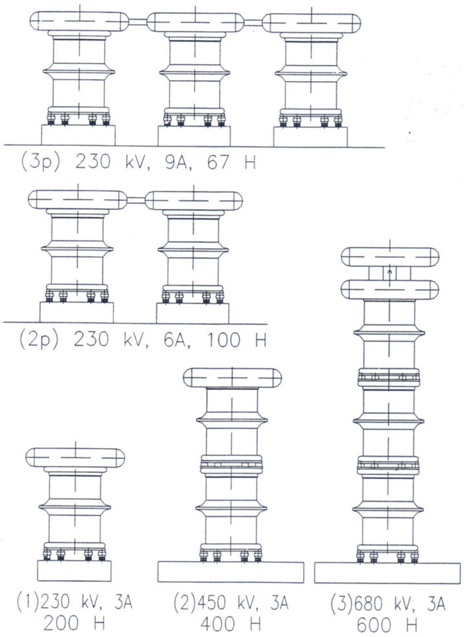

Fig. 5:Combinations of three modular reactors

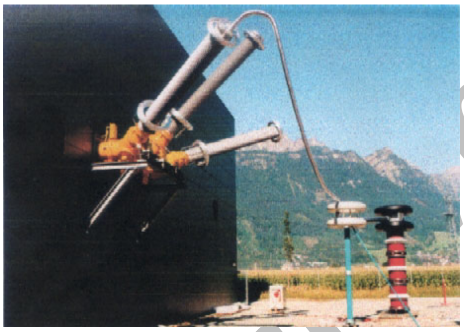

Fig. 6:"Open" ACRF circuit with three modular reactors during testing a 400 kV GIS (Courtesy of Siemens)

SF_6 insulated reactors (Fig. 7) can directly be flanged to the GIS to be tested and the complete HV circuit is metal-enclosed and therefore electromagnetically shielded. The conditions for PD measurement are identically with that in shielded HV test laboratories. The reactors are realised for voltages up to 740 kV, currents up to 1.5 A (short time operation), with a combined SF_6-foil insulation and a disk bushing inside a metal tank. A capacitive probe for the voltage measurement and a temperature sensor for the overtemperature release are integrated in the SF_6 tank.

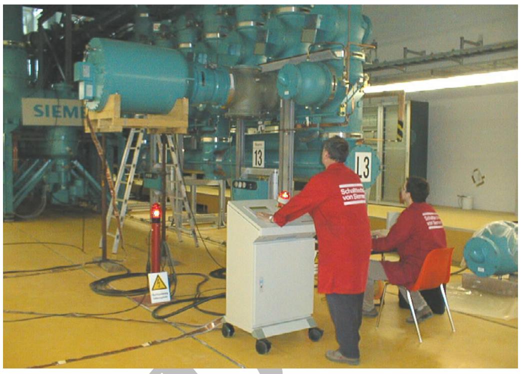

Fig. 7:"Shielded" ACRF circuit with SF6-insulated reactor during testing a 400 kV GIS (Courtesy of Siemens)

It should be mentioned that the shielded SF_6-insulated ACRF circuit is superior to the SF_6-insulated transformer circuit. For identical test voltage the test current generated by help of a SF_6-insulted reactor, is about 5 times higher and the weight about 4 times lower than that of a SF_6-insulated transformer.

PD measurement is more and more performed with the UHF method and sensors built in the GIS.

4.2 Extruded high-voltage cables

According to the basic principles of HV testing (see above), extruded HV cables shall be tested by AC voltage, because e.g. DC voltage testing is not only insufficient, but even dangerous. The only way to provide tremendous power demand up to more than 100 MVA for such tests was the development of ACRF test systems within the last decade.

Research work [6] has shown that the differences in the withstand voltage of XLPE cables at 20 Hz to 50 Hz respectively 300 Hz to 50 Hz are about 10% (Fig. 8). The dispersion of the

50 Hz breakdown voltage is in the same order of magnitude. Therefore the AC voltages 20 to 300 Hz represent power frequency voltages quite well.

Todays ACRF systems for cable testing are characterised by tank type reactors arranged on a trailer (Fig. 9).

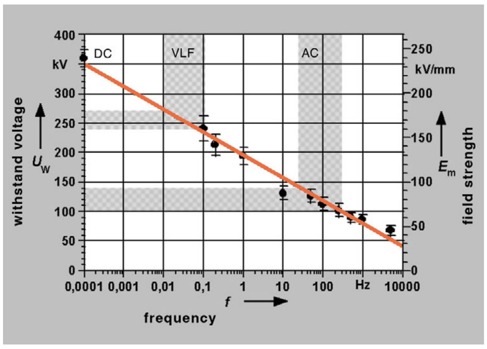

Fig. 8:Withstand voltage and electrical field strength with the confidential range as function of the frequency

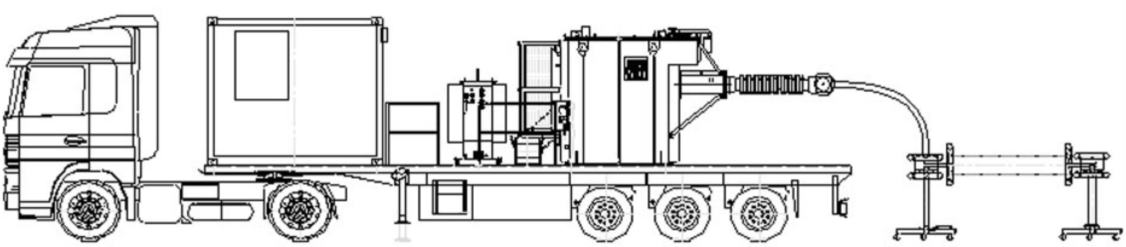

Fig. 9:Frequency-tuned resonant test system 90 A, 150 kV on a trailer with HV filter for PD measurement

The resulting total weight of an ACRF system is about 30 tons. Such systems can be handled by customary truck trailers being modified for this purpose. Fig. 9 shows a trailer for the transportation of test system 90 A, 150 kV. The control and feeding unit is located in an air-conditioned and illuminated 10ft container at the front side of the trailer. This container serves for the operation of the system. It has a door, windows and a board mains. The resonant reactor is located above the trailer axles, its bushing projects to the rear side. The exciter transformer is standing between the container and the resonant reactor. The trailer has a foldable roof and side canvas to protect the system against bad weather during transport and parking. The quality factor of ACRF circuits reaches values above 200 at approx. 50 Hz. This means the necessary feeding power is below 1% of the real test power.

For higher test voltages two reactors of this type can be switched in series (Fig. 10) or for higher test current in parallel. In both cases the frequency converters operate in parallel, one as the master and the other as the slave.

Fig. 10:Series connection of two reactors (Courtesy of CEPCO / Saudia Arabia)

The efficiency of withstand on-site testing is improved by combination with a sensitive PD measurement. The IEC 60270 method of PD measurement with an external coupling capacitor is – because of the damping of the PD signal when travelling along the cable – limited to cables of few kilometres length, for cables longer than 4 km non-conventional PD measurement by help of PD sensors in the joints is recommended. For the detailed description of afterlaying withstand testing including such a PD measurement by directional couplers for a 6.3 km longer 400 kV XLPE cable system in Berlin see reference [7].

4.3 Medium voltage cables

After ACRF systems have been introduced successfully for the on-site testing of HV cables there is a certain logic to apply this principle also on the testing of medium-voltage cables, especially under the point of view of diagnostics.

For medium voltage cables the diagnostic testing with very-low-frequency (VLF) voltage has been introduced about 15 years ago. VLF voltage is far from 50/60 Hz voltage (Fig. 11) and causes different voltage distributions and consequently withstand voltages about twice compared with 50/60 Hz (Fig. 8). Therefore only the application of an ACRF test system in line with the principles of insulation coordination enables withstand and PD tests under conditions directly comparable to the stresses during service and testing in factory.

Fig. 12:Mobile ACRF systems for 36 kV/10 A

Fig. 12 shows a medium voltage ACRF system with a rated voltage of 36 kV/10 A for testing cables up to about 7 km length. The total system weight is about 1400 kg. The reactor tank contains besides the active part a voltage divider. The test voltage is led out via a plug-in connection with a bushing or an adapter cable with termination. The system can be completed by a PD and tanδ measuring system and computer control.

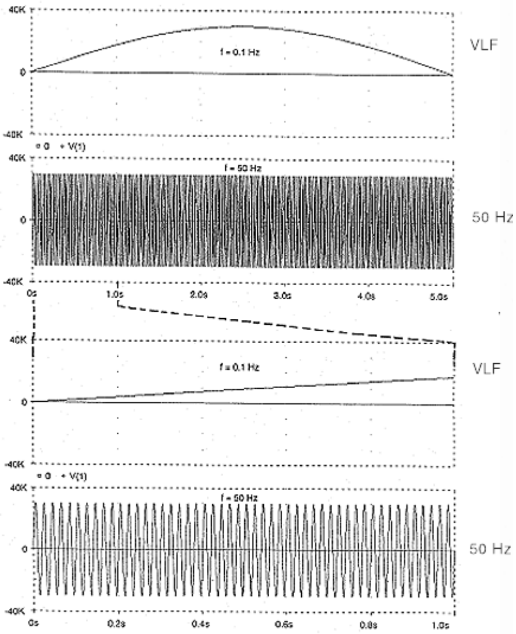

Fig. 11:Very-low frequency (VLF) and 50 Hz alternating voltage waveshapes

4.4 Voltage transformers

For commissioning and diagnostics conventional air-insulated voltage transformers are investigated by off-line PD measurement at AC voltage generated ACRF circuits. For minimum weight of the test system a SF_6-insulated reactor with a bushing has been applied. A test frequency >80 Hz guarantees on the one hand that any saturation of the core of the voltage transformer under test is avoided. On the other hand PD noise signals from the surroundings which are synchronous to the power frequency can be indicated as a background noise in the PD pattern (Fig. 13) which does not influence the measuring result even if th noise signal (E in Fig. 13) is much higher than the PD signal (C).

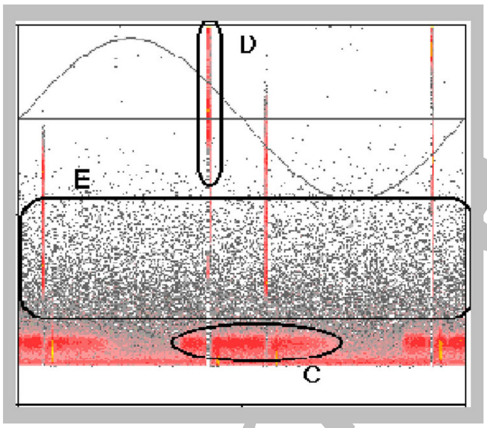

Fig. 13.PD pattern of a measuring transformer synchronized to 81 Hz (area C indicates an internal failure, area E the 50 Hz background noise and D the pulses from the frequency converter, courtesy of ABB)

5. Conclusion

Nowadays insulation coordination should not only be a matter of factory tests, also on-site tests before commissioning and after repair should be included in the systems of test. IEC Technical Committee provides a horizontal standard for withstand voltage testing on site in relation to factory tests and insulation coordination. The related IEC Standard 60060-3 is expected in late 2004 or early 2005. The necessary mobile HV test systems have been developed. The most important test voltage is AC voltage which can be generated up to the highest test voltage and power by frequency-tuned resonant circuits (ACRF). Reactors and all other components of ACRF circuits have been adapted to the different test objects to enable an efficient and smooth test procedure on-site.

6. References

[1] IEC-Publ. 60071 (1993):
Insulation co-ordination, Part 1: Definitions, principles and rules

[2] IEC-Publ. 60060:
High-voltage test techniques Part 1 (1989):
General definitions and test requirements, and Part 2 (1994): Measuring systems

[3] Hauschild, W. et al (CIGRE WG 33.03 – TF 04)
Requirements for HV withstand testing on site 11th ISH London (1999), paper 1.41.S3

[4] IEC 42/176A/CD "Revised – IEC 60060-3 Ed. 1.0 : High-voltage test techniques Part 3 : Definitions and requirements for on-site tests"

[5] IEC 60840: 1999 and 62067: 2002 : Cables with extruded insulations and their accessories for rated voltages 30 to 150 kV respectively 150 up to 500 kV.

[6] E. Gockenbach; W. Hauschild: The selection of the frequency range for HV on-site testing of extruded insulation cable systems, IEEE Insulation Magazine 16 (200) 6, pp. 11-22

[7] W. Hauschild; W. Schufft; R. Plath et. Al: The technique of AC on site testing of HV cables by frequency-tuned resonant test systems CIGRE Session (2002), Report 33-304