DEVELOPMENTS IN POWER ENGINEERING AND THEIR DEMANDS ON HIGH-VOLTAGE TEST EQUIPMENT

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Abstract: All components used in an electric power system must display a high reliability because their failure would cause immense economic losses and may even cost human lives. The reliability of such insulation systems is verified by high voltage tests, whereby the shape and the peak value of the test voltage are derived from the stresses which occur in reality in the electric power system. There has thus always been a demand for high voltage test equipment which provides the higher test voltages levels for the increased transmission voltage and power levels. The introduction of new insulating materials, for example in extruded cables and gas-insulated switchgear, also requires suitable test procedures and adequate test equipment.

1. Introduction - historical overview

The beginning of the Industrial Age in the second half of the 19th century also heralded the practical use of electric power. The mechanical work previously done by human workers and animals, by steam and water, was increasingly taken over by electric motors. The open flame, until this time the only source of light, was replaced by the considerably safer electric light bulb. The first three-phase transmission of electric power was implemented by *Oskar von Miller* in 1891, spanning a distance of 175 km between Lauffen am Neckar and Frankfurt am Main with a transmission voltage of 15 kV. Already at an early stage, it was recognised that safety and reliability would be assigned outstanding importance with regard to the widespread introduction of electric power. There have thus been systematic high-voltage tests since the beginning of the century. The safety and reliability of the insulation were initially demonstrated with voltage tests which simulated the operating voltage, i.e. AC and DC voltages. Already at this time, the test voltage levels were always defined in a specific ratio to the operating voltage, as was later laid down in the standards for insulation co-ordination /1/. The constantly increased transmission voltages, for example between the first 110 kV transmission between Riesa and Lauchhammer in Saxony in 1911 and the first 1200 kV transmission link between Ekibastuz and Kokchetav in the former Soviet Union in 1985, called for high-voltage test systems which were able to produce not only the defined test voltages, but also the even higher voltages required for development studies on the insulation systems to be used at such voltage levels. Figure 1 shows the development of the transmission voltages during the course of the century alongside the maximum available AC test voltages /2/. Figure 2 shows the first 1 MV AC cascade from the company Koch & Sterzel in Dresden, which dates from 1923, and the world's largest AC and switching voltage test system (3 MV, 12,6 MVA), which was produced by Siemens in 1990, also in Dresden.

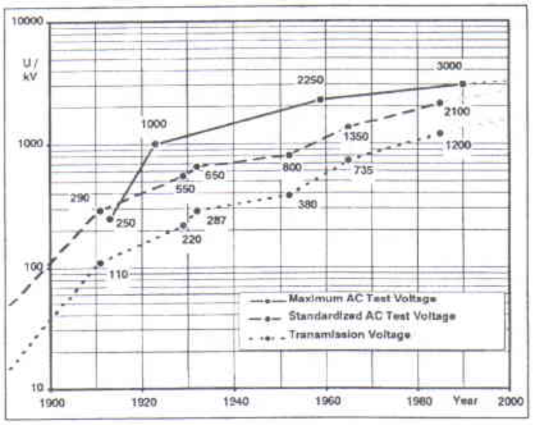


Fig. 1: Development of transmission voltages and AC test voltages

It was not only the increased transmission voltage levels which placed new demands on the test voltages to be generated, but also the new phenomena which now had to be mastered. During the twenties, for example, overvoltages caused by thunderstorms represented a serious problem for the reliability of the electric power supplies. As a consequence, tests were introduced during the thirties using lightning test voltages, which were generated with impulse generators based on the multiplier principle patented by *Erwin Marx* in 1928 /3/. Following investigation of the overvoltages which can arise through switching operations in the power system, it was recognised that tests needed to be performed with switching voltages, which then became standard in the sixties. Such switching voltages were similarly generated with impulse generators based on *Marx'* principle /4/, though at the same time also with switching voltage extensions for AC test systems. In connection with the fundamental studies for high-voltage DC transmission in the seventies, powerful DC test systems were developed whose output voltage was superimposed with an AC voltage /5/. Recent years have seen the introduction of so-called BIAS tests, in which the poles of a contact gap are subjected to different voltage forms, e.g. to AC and switching voltage or AC and lightning voltage. Tests with impulse voltages with rise times in the sub-microsecond range (VFT – Very Fast Transients) are currently being introduced into the system of standards for high-voltage testing, in order to be able to simulate the very steep overvoltages which are produced in the power system, for example, by the switching of gas-insulated switchgear (GIS) /6/.

The introduction of new insulating systems, such as power cables insulated with polyethylene (PE, XLPE) and switchgear filled with the insulating gas SF_6 (GIS), at the end of the sixties also demanded new test technologies.

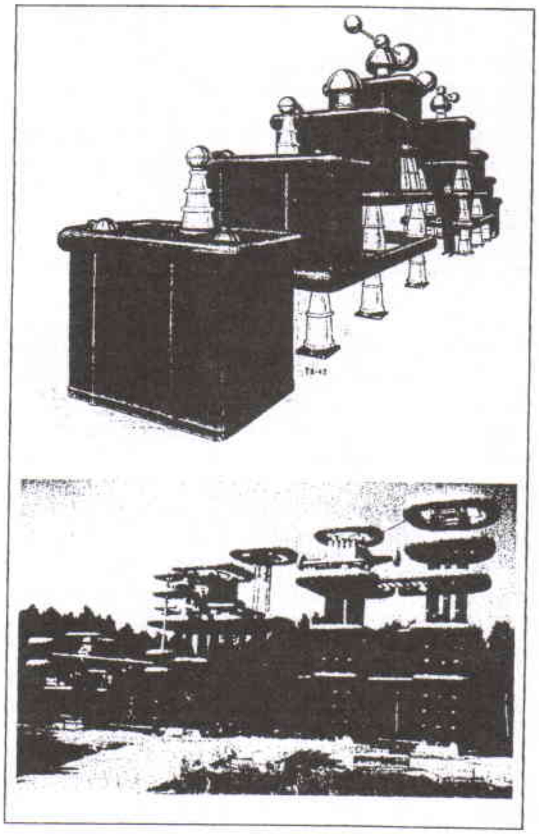


Fig. 2: AC cascade 1 MV (Koch & Sterzel, Dresden) dating from 1923, and AC and switching voltage test system 3 MV, 12.6 MVA (Siemens, Dresden) built 1990

It was in this connection, therefore, that resonant test systems with variable inductance came onto the market for routine and type tests for these polyethylene-insulated cables. Highly sensitive partial discharge (PD) measurements in screened test rooms were introduced as additional quality-assurance measures.

The tests to detect fixed disturbances faults in GIS are best carried out with oscillating lightning impulse voltages. Consequently, locally mounted impulse generators were equipped with external reactor coils /7/.

2. Current developments in power engineering

There are currently at least two developments in power engineering which are of relevance for high-voltage testing:

We are witnessing, for example, the ever more widespread installation of cable systems, especially in the conurbation. This may also be the result of a dwindling acceptance for new overhead distributions. But essentially it is a question of greater supply reliability and the continuous availability of electric power, which is one of the fundamental location benefits of the highly developed industrial nations. Major European cities such as London, Copenhagen and Berlin, for example, are installing ring- or secant-operated 380 kV cable systems /8/, see figure 3. For these vital supply lines it is necessary to develop appropriate test procedures to confirm the insulating properties not only of the cables themselves, but also of the corresponding cable joints and sealing ends. At the same time, however, such cable systems demand increased attention over the decades of their expected service life. The partial discharge behaviour of the relatively susceptible cable joints is thus watched over with the aid of specially developed monitoring equipment.

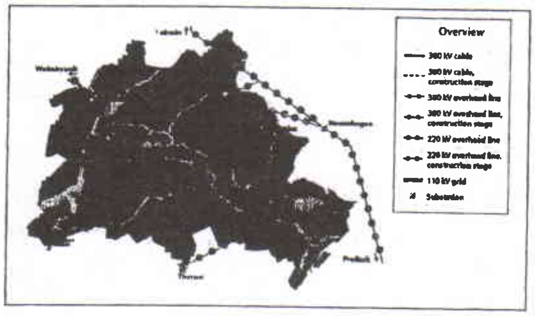


Fig. 3: 380 kV cable system in Berlin

A second, more significant topic is the deregulation of the markets for electric power, i.e. the markets for power generation, transmission and distribution, see

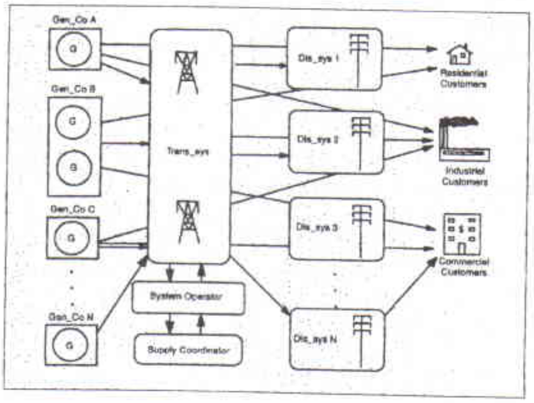


Fig. 4: Power generation, transmission and distribution /9/

figure 4. It seems that the future will bring an electric power exchange similar to that which already exists for mineral oil and other important raw materials and resources. This would mean that major consumers such as industrial enterprises, but also local power distribution companies, would be able to decide on a daily basis, whether they wish to use or distribute electricity generated from German coal, in French nuclear power stations or in Norwegian hydro-electric plants. One prerequisite is the feasibility of the transmission of larger amounts of power over long distances. Submarine DC cables are gaining in importance, especially for the spanning of seas and oceans, as are also HVDC back-to-back links for the coupling of major networks. Figure 5 shows the HVDC links in Northern Europe /10/.

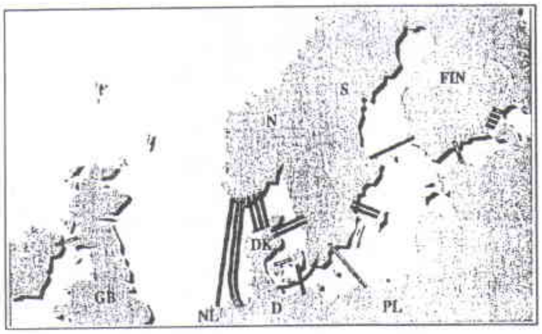


Fig. 5: Existing (black) and planned (grey) HVDC links in Northern Europe

2.1. On the on-site testing of high-voltage cables

The manufacturers subject their polyethylene-insulated high-voltage cables to complex and time-consuming routine tests. Between the testing and commissioning of the cable, however, it is impossible to exclude the risk of damage during transport and installation or the possibility of errors when completing the cable with joints and sealing ends. Such faults and errors need to be recognised reliably by way of appropriate on-site test methods. Since DC testing on installed cables has been shown to be unsuitable, it is now a commissioning test with AC voltage and partial discharge measurements, comparable to the routine tests, which is considered the most meaningful method for the testing of the installed cable. However, there are currently technical limitations on the performing of on-site AC voltage tests and partial discharge measurements:

One limitation is the enormous reactive power demand for 50 Hz AC voltage tests. Table 1 shows the test currents and test powers for cable systems with a length of 10 km for the common system voltages. For the performing of on-site AC voltage tests with test powers of several 10 MVA, we can practically exclude conventional AC test systems such as transformers and resonant circuits on a 50 Hz basis on account of their high specific weight of 3 - 20 kg/kVA and their high, two-phase supply power consumption. In view of the fact that a test voltage should generally come as close as possible to the level of stress occurring in actual operation, resonant test systems on the basis of resonant circuits with variable frequency are the only practical solution. Such test systems were introduced at the end of the seventies as an interesting alternative for an essentially realistic on-site testing of gas-insulated switchgear (GIS) /11/ and were later also used for commissioning tests on high-voltage cables /12/. The great advantages of resonant test systems with variable frequency are the extremely low specific weight of 0.5 - 2 kg/kVA, a high quality factor (test power to supply power) compared to resonant test systems with variable inductance and thus a lower demand on the feeding power to be provided on-site. The so-called control and feeding units, which include an inverter unit, for resonant circuits with variable frequency can be fed from the low-voltage mains, i.e. unlike test transformers or conventional resonant circuits with variable inductance they take the test power in three-phase form. One special feature is to be noted in the deviation of the test frequency from the operating frequency, which is scarcely relevant from a physical point of view, as has been underlined by appropriate studies, but may well still lead to subjective reservations. Table 2 contains a comparison with conventional test systems.

Syst. volt..	Test voltage*	Capacit. (10 km)	Test curr. (10 km)	Test pow. (10 km)
kV	kV	µF	A	MVA
60	70 ($2U_0$**)	1,7-3,8	40-80	3-5
110	130 ($2U_0$)	1,3-2,9	50-120	7-15
150	150 ($1.7U_0$)	1,3-2,7	60-130	9-19
220	180 ($1.4U_0$)	1,3-2,7	70-140	12-24
275	210 ($1.3U_0$)	1,2-2,1	80-140	17-29
400	280 ($1.2U_0$)	1,1-1,9	100-170	27-47

* - acc. to recommendation of CIGRE WG 21.09

** - U_0 = phase-to-earth voltage

Table 1: Required 50 Hz test currents and powers for high-voltage cables with a length of 10 km.

Resonant test systems with variable frequency (figure 6) comprise a frequency converter, which also provides for control of the test system, a field-circuit transformer, a resonance reactor with constant inductance, which can be designed with taps, and a capacitive load, which includes the capacitive voltage divider for measurement of the test voltage. The resonance is achieved through matching of the output frequency of the rectifier unit to the resonant frequency of the test circuit, which is determined by the inductance of the resonance reactor and the load capacitance. The current level of development permits resonant test systems with variable frequency to be

	On-site AC test systems on the basis of		
	High-voltage transformers	Resonant circuits with	
		variable inductance	variable frequency
Frequency	50 / 60 Hz	50 / 60 Hz	25 – 300 Hz
Perf. factor $q = S_{test} / S_{supp}$	5	40 ... 100	70 ... 200
Supply	single-/two-phase	single-/two-phase	three-phase
Specific weight	> 20 kg/kVA	5 ... 8 kg/kVA	0.6 ... 1.5 kg/kVA
Max. test power	500 kVA	4 MVA	35 MVA

Table 2: Comparison of AC test systems for on-site testing of high-voltage cables

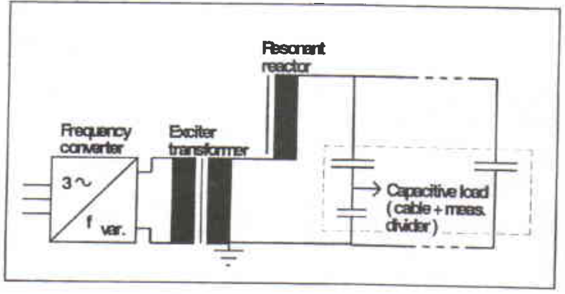


Fig. 6: Resonant test system with variable frequency - block diagram

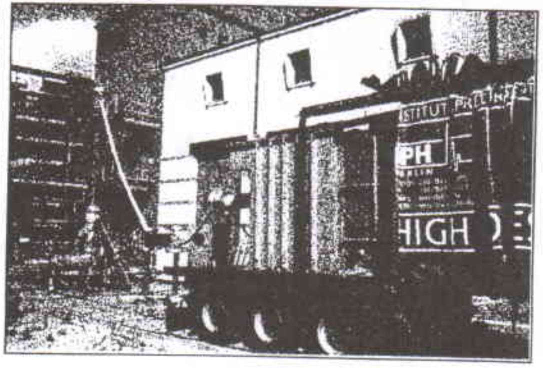


Fig. 7: On-site test system for high-voltage cable 254 kV, 80 A

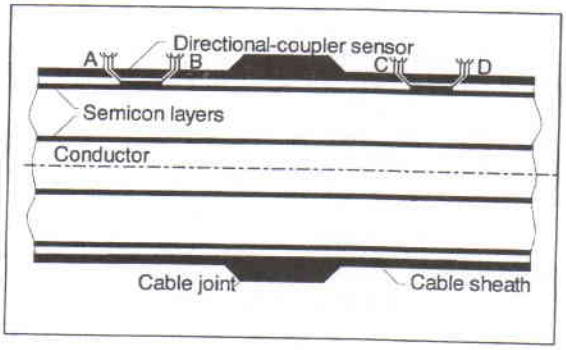
used favourably for commissioning (after-laying) tests on polyethylene cable with test powers up to 35 MVA (on basis of 50 Hz), which corresponds to cable lengths of up to 20 km /13/. Figure 7 shows such a system during testing. Since these on-site tests are generally carried out in industrial environments, a high background noise level is to be reckoned with during partial discharge measurements. The classical methods of partial discharge measurement are also only able to "look" a few kilometres into the cable, since a partial discharge signal is damped during its propagation in the cable. Directional-coupler sensors integrated directly into the joints of a cable system represent a promising future solution, both for partial discharge measurements during on-site testing and for the subsequent partial discharge monitoring /14/. Directional-coupler sensors use a mixed capacitive-inductive signal coupling and gain a high sensitivity (< 1 pC). It is thus possible to localise the point of origin of the partial discharges exactly, e.g. at a cable joint or between two cable joints, see also figure 8.

2.2. High-voltage test equipment for the components of HVDC transmission systems

There is currently an increasing demand for DC test systems, since DC transmission lines, especially submarine cable links but also HVDC back-to-back links, are gaining in significance. Development work is currently concentrated, for example, on transmission voltages of up to ± 500 kV and transmission power of up to 2800 MW for submarine cable links in Japan, in Northern Europe, in the Mediterranean region and in Southeast Asia.

There are currently two new trends for future DC transmission projects:

- the introduction of gas-insulated switchgear (GIS) for DC voltages and
- the use of cross-linked polyethylene (XLPE) in DC cables in order to be able to replace the conventional oil-paper cables.



	A	B	C	D
PD signal from left	X		X	
PD inside the joint		X	X	
PD signal from right		X		X

Fig. 8: Selective recording of partial discharges with directional coupler sensors

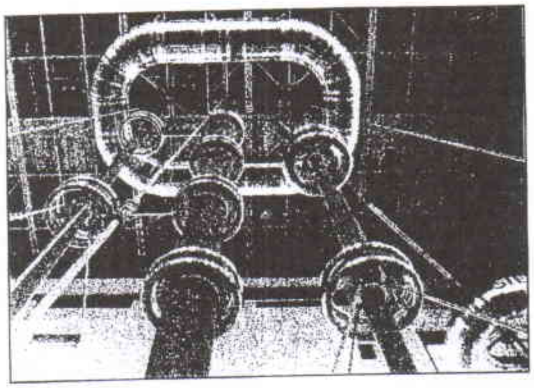


Fig. 9: DC test system 20 mA, 2000 kV with fast polarity reversal

The development work on GIS for DC voltages is concentrated on disturbances of the purely ohmic voltage distribution as present on the spacers of the GIS. Especially surface charges and charged microscopic particles can lead to a significant lowering of the flashover voltage of the spacers, particularly where they are located at the electrode with opposite polarity. These phenomena can be studied favourably using DC test systems with fast polarity reversal, since the surface charges generated at a high-voltage electrode under a certain polarity lead to a significant increase in the field strength at this electrode after polarity reversal. In the case of DC cables with polyethylene insulation, the space charges which can arise around the points of faults play an important role. They at first envelop the point of fault, but can become critical after a polarity switch-over. DC test systems with fast polarity reversal are also well suited for the optimisation of the classical oil-paper insulation of converter transformers.

Figure 9 shows a DC test system with fast polarity reversal produced by the company HIGHVOLT in Dresden in 1995 and supplied to Hitachi in Japan the same year. The test system has a nominal current of 20 mA and a nominal voltage of 2 MV. The polarity can be switched from - 750 kV to + 750 kV and vice versa within a time of less than 200 ms.

The potential distribution and thus the field-strength stressing in the coaxial insulation of an AC voltage cable is a capacitive one and can be calculated as an electrostatic field using the known methods of field calculation, such as charge simulation method (CSM) or finite element methods. Since the dielectric coefficient of common insulation materials is effectively independent of the temperature, the temperature gradient which arises from the operating current in the cable is of practically no influence for the potential and field strength distribution in the cable, i.e. the greatest field strength occurs as expected at the inner conductor. The potential and field strength distribution in a DC voltage cable is determined on the other hand by the flow field. When "cold" the flow field of a DC cable is nearly identical to the electrostatic field, i.e. the equipotential lines of the two fields practically coincident. As soon as a temperature gradient builds up on account of the operating current flowing through the inner conductor of the cable, the specific resistance of the insulation is also changed in line with the local temperature, i.e. the field strength diminishes in the warmer areas of the cable inner conductor, and thus increases in the colder outer areas. This may even lead to the greatest field strength occurring at the cable sheath. In order to be able simulate these conditions realistically for type testing, it is necessary to heat up DC voltage cables with a direct current of several thousand amperes. A DC heating system is shown in figure 10. A second cable is set up alongside the cable to be tested simultaneously with a high DC voltage (e.g. 1200 kV) and a heating current. A high AC current is induced in the inner conductor of this second cable by means of a conductor heating transformer, subsequently rectified to high-voltage potential with the aid of a rectifier bridge and passed to the cable to be tested.

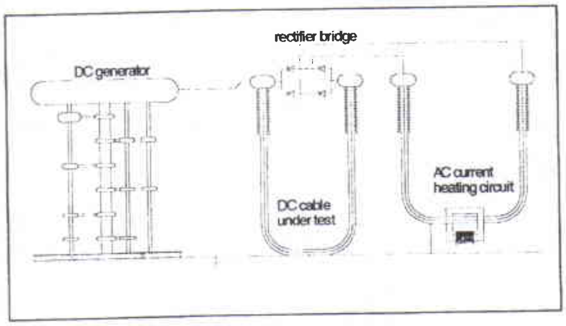


Fig. 10: DC heating system for DC voltage cables

3. Summary

New developments in power engineering demand further developed components for power generation, transmission and distribution, e.g. extra-high-voltage cables for AC and DC voltages and gas-insulated DC switchgear. This also results in new methods for the corresponding high-voltage tests, which must then be backed up by appropriate high-voltage test equipment. This paper gives a brief overview of the historical development of high-voltage test equipment, as well as describing two examples of new developments in high-voltage testing, namely on-site test systems for high-voltage cables and DC test equipment for the components of HVDC transmission systems.

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