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HV AC TESTING OF SUPER-LONG CABLES

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ABSTRACT

The AC high-voltage testing of super-long cables requires a test power of up to 100 MVA. The different possibilities for supplying this large test power are discussed. It is shown how the necessary feeding power and losses can be reduced by choosing a low, but physically meaningful test frequency. An optimum test circuit arrangement is discussed.

KEYWORDS

- high-voltage AC withstand test
- on-site tests on long cables
- high-voltage resonant test
- partial discharge test

REQUIRED TEST POWER

The growing length and transmission voltage of extruded XLPE-cables cause an increase in the requirements for the power of proper test systems (Fig. 1). The requirements of test voltage and frequency for on-site tests of complete cable test systems are defined in the IEC-Standard IEC 62067.

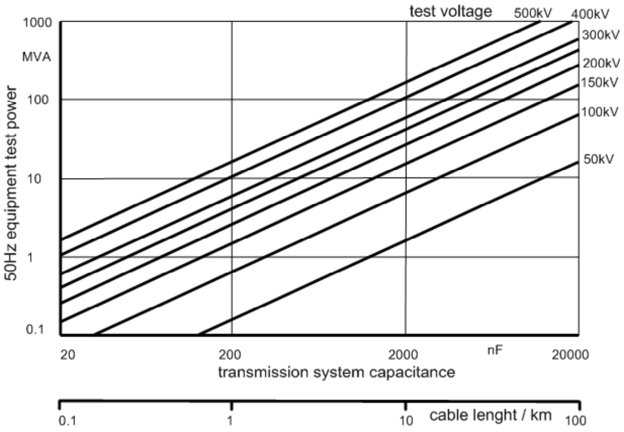

Figure 1: Required AC test power depending on cable capacitance and length respectively

The demand for reactive power is linearly dependent on the frequency when the test voltage is constant. If the test frequency is reduced from 50 Hz to 20 Hz then the demand for test power decreases to 40%. For this reason it is more suitable to substitute the classification “super-long” by the term “required test power”. The limit is drawn at a 50-Hz-equivalence-power (S_{50}) of about 35 MVA for a single test system [1].

Besides the testing of very long extruded cables for AC voltage supply networks, the AC voltage testing is also applied successfully for the testing of super-long extruded XLPE-cables for DC voltage. The HV AC testing allows a fast and easy recognition of failures inside the insulation [2]. These kinds of cables can be manufactured in one piece with lengths of up to 100 km and are used - for example - to connect off-shore oil platforms with the mainland.

SELECTION OF SUITED HV TEST SYSTEM

In general, there are three different solutions to provide the necessary AC test voltage off-line:

- compensated test transformer
- resonant circuit with variable inductance
- resonant circuit with variable frequency.

AC tests with systems based on compensated HV transformers and operated with power frequency are limited to a cable length of some 100 meters with respect to the very high apparent power.

Series resonant circuits are more suitable for the test of very long cables. Such a resonant circuit consists mainly of three parts: feeding source, inductance L (resonant reactor) and capacitance C (cable). While the high reactive power oscillates between inductance and capacitance of the HV circuit, the power source has to supply the losses (active power) only. Depending on the design of the test system components and the test object itself, these losses amount to typically 0.5 ... 2% of the test power. To operate at resonance the impedances of L and C have to be equal. This is given at a certain frequency f, the resonant frequency.

$$f = \frac{1}{2\pi\,\sqrt{L \cdot C}} \qquad [1]$$

This equation can be fulfilled in two ways:

- The product of L and C is adapted to a fixed frequency f (power frequency, 50 or 60 Hz). Because the capacitance C is determined by the test object, the inductance L has to be adjustable. This solution is an inductance-tuned resonant test system (ACRL).
- The frequency of the feeding source is adapted to the resonant frequency f, which is determined by the capacitance C and a resonant reactor with a fixed inductivity L. It is a frequency-tuned resonant test system (ACRF).

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Depending on the type of test each solution has advantages. For the testing of fabrication lengths in cable plants usually ACRL systems are used. The capacitance variation caused by different cable types and fabrication length can be compensated by a tunable reactor with a typical regulation range of 1:20. The necessary feeding power is available by the power grid and the weight-to-power ratio is not critical for a fixed installation.

For on-site testing or factory tests of very long cables ACRF systems are more useful. Because the resonant frequency is proportional to 1/√C, a variation of the feeding frequency of 1:15 (20 ... 300 Hz) leads to a possible capacitance range of 1:225 at a constant inductivity. To extend the flexibility of the test system regarding the load range or test voltage, two or more of smaller reactor units can be combined in parallel or series connection instead of one larger reactor. This is very simple, since the reactors do not contain moveable parts [3].

Important for testing of very long cables, mainly on-site, is the necessary feeding power from the grid. In case of resonance the power demand is equal to the losses in the circuit. They are determined by the losses in the test system itself (reactor, exciter transformer) and the losses in the test object. The losses in the test system are caused mainly by the resistance of the reactor winding but also by losses in the iron core. The latter can be influenced by the design of the core. Because a multi-gap-core is used for a reactor with a fixed inductivity, the losses in the core are smaller compared to a tunable reactor with adjustable gaps. The losses in the cable are the losses in the insulation (tanδ) and the ohmic losses in the inner and outer cable conductor.

DESIGN OF ACRF TEST SYSTEM

Every ACRF system consists of a resonant reactor with a fixed inductivity, an exciter transformer, a frequency inverter unit and a capacitive voltage divider. The power inverter is part of the control and feeding unit, which contains amongst the inverter all necessary sub-circuits for voltage regulation, test control and safety functions. The exciter transformer adapts the output voltage of the frequency inverter to the necessary input voltage for the resonant circuit, usual some kV. Since the test voltage depends on the quality factor of the resonant circuit (ratio between test power and losses), the exciter transformer has different output taps. This enables an optimum working range for the frequency inverter for each test voltage and different quality factors. The exact value of the test voltage is controlled by the pulse width of the inverter.

The testing of super-long XLPE cables requires a very powerful test system (Fig. 2). Since the maximum size and weight of a resonant reactor is limited with respect to an easy transportation without special permissions, high-power tests require usually a combination of two or more reactors in series or parallel connection. The following example describes a test set, which is used for testing super-long extruded submarine DC cables up to a length of approx. 80 km [2].

To get a maximum flexible design, two resonant reactors (110 kV / 194 A each, (5)) in an oil-filled steal tank are used. They can be connected in series for higher voltages and lower frequencies or in parallel for lower voltages and very large capacitances.

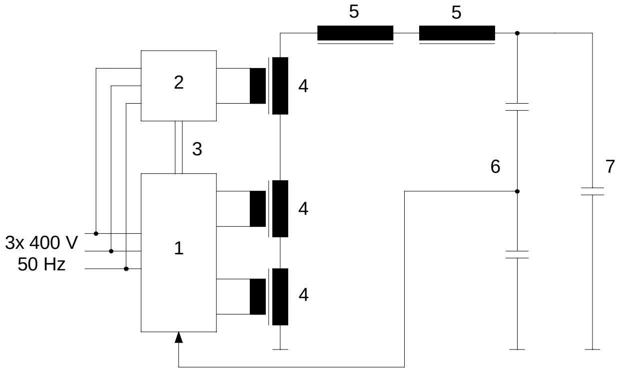

Figure 2: Principle design of ACRF system

To compensate the high losses in the cable (7), the power inverter is realized by two control and feeding units, one (1) for 400 kVA and a second (2) for 200 kVA output power. Both work in a master-slave mode and are coupled by fiber optic links (3). Each control and feeding unit is built in a separate control container. The voltage divider (6) is connected to the master unit and enables the measurement of the test voltage, automatic search of resonant point and breakdown detection. The output power of the inverter units is coupled with three identical exciter transformers (4). This flexible design allows a separation in two independent test systems by adding an additional voltage divider only.
The following test cases were realized with this test set (Table 1):

Test voltage [kV]	Length [km]	Cable capacitance [µF]	Frequency [Hz]
160	52	8.1	25.9
92	74	18.0	16.6

Table 1: Examples of performed tests on DC cables

LIMITATIONS CAUSED BY LOSSES

The consideration of the possible test cases ignores the losses in the HV circuit. Whether a particular test can be performed, depends not only on the limitation of voltage and current caused by the HV components but also on the capability of the feeding source to compensate all losses. Otherwise the test voltage can not be reached.

The power to be supplied by the power inverter has to cover all losses occurring in the test circuit during a resonance case. These losses consist of the ones occurring inside the components of the test system, the ones inside the test object and the additional parasitic losses (e.g. connection technology, water end terminations).

The losses of the test system are mainly caused by load losses (copper loss) and no-load losses (iron loss) inside the resonant reactor. The design of these reactors is a compromise regarding minimum losses on the one hand and minimum weight on the other hand. A further reduction of the reactor losses would lead to a disproportionate increase of weight and volume. This makes the on-site operation very difficult or even impossible.

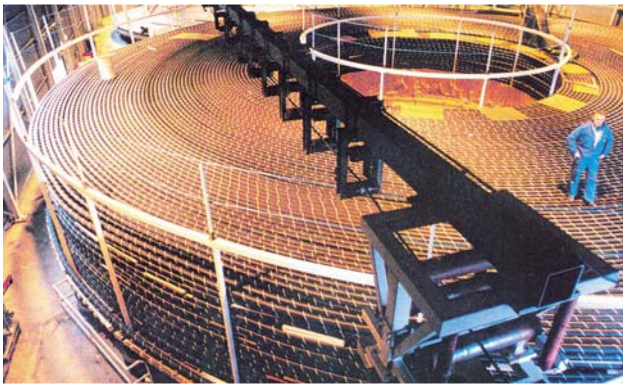

Figure 3: Submarine cable on a turntable (Photo: courtesy of ABB Karlskrona)

The losses inside the test object (cable) are typically less than the ones inside the test system components. The loss factor of modern XLPE cables and their accessories is extremely low so that for super-long cables the dielectric losses are also respectively small. The cross-sections of inner and outer conductors used in AC high-voltage power cables are quite large so that the thereby caused ohmic losses are comparatively small.

The described test system can compensate losses up to 600 kW. The special design of submarine cables for DC leads to a different situation with respect to the cable losses. Due to the reduced cross section of outer conductor (cable screen) its resistance is significantly higher than for AC power cables. It results again in a higher loss which can lead

- to overload the feeding components of test system and/or
- to overheat the cable under test.

The overheating can happen because a cable fabricating length of some 10 km is wound on a big turntable as a large coil (Fig. 3). Consequently the natural cooling of the inner turns is remarkable reduced and the large testing current heats the cable up.

The reduction of cable losses by a suitable test setup can be done in two ways. On the one hand the test current can be reduced by a lower test frequency (Fig. 4). On the other hand the losses can be reduced by an optimized coupling between cable and test set. If one end (conductor and screen) of the cable is connected with the system, the capacitive current in the cable conductors decreases from a maximum value I_{max} at the feeding side linear along the cable to zero at the far end (Fig. 5). By contrast a very long cable on a turntable in the factory can be energized from both sides, because both ends are available at the same location. In this case the current on both ends is 0.5 I_{max} only and it decreases from both sides to become zero in the middle of the cable.

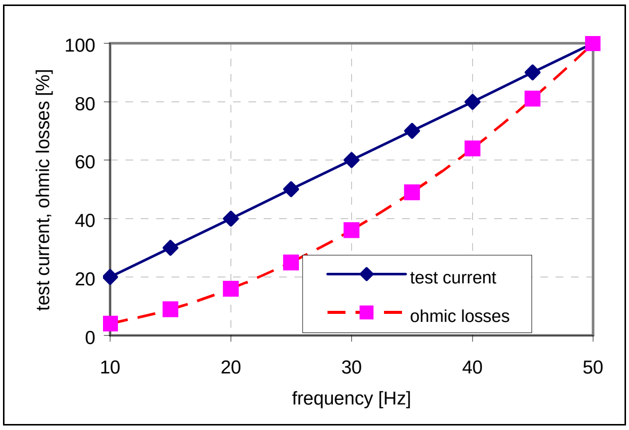

Figure 4: Test current and ohmic losses vs. test frequency

For the realization of the second test case shown in Table 1 both aforesaid methods for the reduction of losses were used. By connecting both reactors in series, the test frequency was lowered to 17 Hz and the cable has been fed from both ends. The low frequency could be accepted because the cable to be tested was an XLPE-cable for DC voltage. At the time there exists no standard for the AC voltage testing of such cables [2]. In addition, the physical effects inside the insulation do not significantly deviate from the ones at 20 Hz [4].

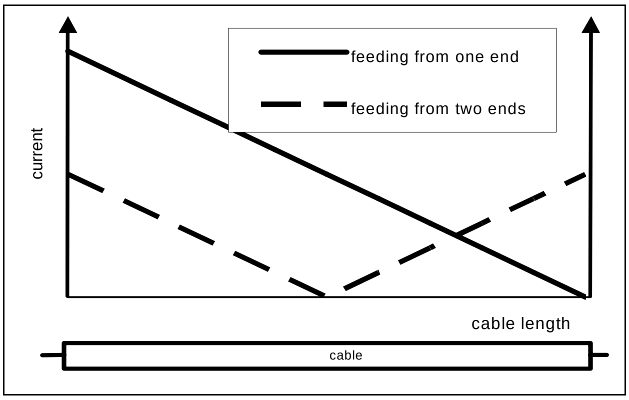

Figure 5: Current distribution in cable depending on feeding from one or two sides

GENERAL PROBLEMS OF TESTING SUPER-LONG CABLES

Apart from the special application for factory tests of submarine cables described before, these kinds of tests are mainly performed on-site. Hence, one faces the problem to provide the necessary feeding power. The demand can reach values of over 500 kVA despite the usual circuit quality of > 100. Only in very rare cases the power can be withdrawn from a 400 V three-phase supply network. Normally, one or more diesel generators supply the required power.

The large cable capacitance in connection with high test voltages leads to a considerable storage of energy in the cable. In case of an insulating defect the energy is completely discharged at the failure location. Especially in cases where the cable is connected to gas-insulated switchgear, substantial damages can occur when the cable capacitance is de-energized inside the GIS.

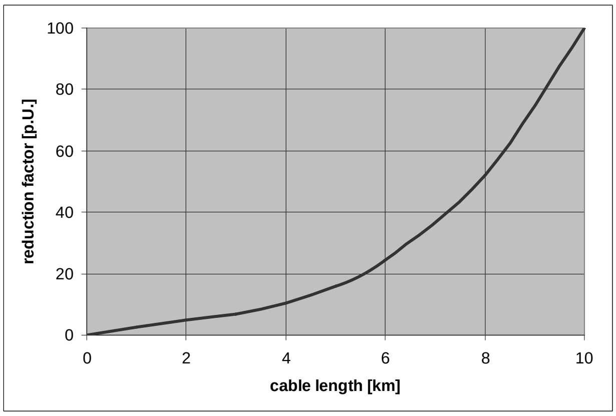

Figure 6: Damping of PD pulses depending on the cable length

The voltage tests on HV and EHV cables are often combined with PD measurements. PD measurements on cable ends according IEC-Standard 60270 seem to be inappropriate, especially when testing super-long cables.

Although the function principle of HIGHVOLT inverters supports sensitive PD measurements, the measuring sensitivity is limited by the PD background noise level, which is typically very high on-site. Due to the damping of the PD signals passing the cables from the failure location to the end of the cable, only a fraction of the signal reaches the measuring sensor at the end of the cable [5]. PD signals are already damped by the factor 25 at a failure distance of only 6 km from the cable end (Fig. 6). Therefore the PD measuring is typically performed on cable joints and cable end terminations only and hereby unconventional PD measuring procedures are applied. At the moment these methods are non-compliant to the standards but have a clearly better significance as the PD measuring according IEC 60270.

EXTRACT OF IMPORTANT ON-SITE TESTS

The outstanding appropriateness of ACRF test systems described above is pointed out by some important testing examples of long XLPE insulated AC power cables in the range of 400 kV (Table 2). Because of the functionally different test voltage frequencies case by case, the 50-Hz-equivalence-power (S_{50}) is calculated for better comparability.

A test arrangement with an interconnection of 4 HV reactors (two in series and two in parallel) is shown in Fig. 7 (see also case 4 of table 2).

Figure 7: Test of a 380 kV cable in Jeddah / Saudi-Arabia

Location	Year	Length [km]	Test voltage [kV]	Frequency [Hz]	S_{50} [MVA]	PD measurement
Berlin	1998	6.5	400	26.1	58	sensors in accessories
Madrid	2004	13	260	32.0	62	at crossbonding
London	2005	20	280	31.2	106	sensors in accessories
Jeddah	2005	9	260	40.9	40	at crossbonding

Table 2: Examples of high power on-site tests

CONCLUSION

Today resonant test systems with variable frequency are used successfully for the AC HV testing of super-long cables. Thereby the systems are designed for operation at the lower frequency limits around 20 Hz to minimize the necessary testing power. The special construction of the HV reactor leads to an overall quality factor of the complete resonance circuit quite better than 100. It reduces the feeding power required on-site to a value easily to provide. This kind of testing technology is also well suited for AC

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testing of extremely long DC submarine cables.

The ACRF cable test systems are designed for modular applications. Small and light-weight test system components can be connected in series and/or parallel to supply the enormous power demand. Companies which are doing HV tests with ACRF equipment frequently, use their own specialized test systems adapted to their needs and with an average power. But at the same time they are also in the position to offer large test powers by cooperation or lending of additional test systems.

The long cables require adapted technologies for the PD measurement. The common measuring method according IEC 60270 does not declare about the cable quality over the whole cable length, neither in factory nor on-site.

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