APPLICATION OF AC TEST VOLTAGE DURING FACTORY TESTING OF SUPER LONG HVDC CABLES

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Abstract: The transmission of high electric powers by way of DC voltage gains increasing importance. In some cases, HVDC cables with lengths of more than 100 km are used for transmission. To perform partial discharge (PD) tests on joints at the factory, AC voltage is preferred so as to be able to detect any errors reliably. The present paper describes the possibilities for provision of the required test voltage and power, taking into account the high screen resistances of HVDC cables. To this day, generation by way of resonant circuits is compared to the use of VLF generators. The required feeding powers are estimated using typical cable specifications. In addition, the possibilities to reduce the losses in the cable screen by way of appropriate test parameters and connection technologies for the test object (TO) are discussed.

1 INTRODUCTION

Thanks to the technical development of high-voltage electronic components, energy transmission over long distances by way of high-voltage rectifiers is becoming increasingly attractive. An important element of such high-voltage rectifier transmission systems are high-voltage DC cables, referred to as HVDC cables for short.

Today, HVDC cables are produced preferably for submarine applications as a result of which the complete cable length may exceed 100 km. Depending on the main insulation between conductor and cable screen, mass-impregnated, oil-paper insulated and extruded cables are differentiated; this study will focus on extruded cables [1].

Normally single manufacturing lengths of extruded HVDC cables are 10-40 km long. For longer cables, several manufactured lengths must be connected to each other by way of special joints. The production process is evaluated in detailed tests on samples from the start end of each manufactured length. The quality of joints is checked directly on the joint by way of PD measurement using sensors. Since the PD activity is very low when a DC test voltage is used, no reliable assessment of the quality is possible for the joint. For this reason, the target is to test these joints with AC voltage [6].

In the case of extremely long extruded HVDC cables, testing with AC voltage results in test currents up to several 100 A due to the large capacitance. In connection with the high test voltages, extremely powerful AC generators are required for testing. In addition, the screen of HVDC cables displays a relatively small cross-section, resulting in turn in a significantly higher screen resistance than with HVAC cables. This property becomes a problem in AC testing, as the high test currents in the cable screen may result in losses in the range of several megawatts. Because the cables are wound on large turn tables during the factory tests, there is the risk of thermal overload.

For cost reasons, reinforcement of the cable screen merely for AC testing is not desirable. Therefore, methods are to be found to reduce the losses in the cable screen by way of appropriate test parameters and connection techniques.

2 AC TEST VOLTAGE GENERATION

2.1 Resonant test systems with variable frequency

Series-resonant circuits are normally used for the HVAC testing of high-capacitance TOs. The one-side grounding of the capacitance C together with a resonant reactor L with fixed or variable frequency constitutes a resonant circuit. Its natural frequency f_0 is calculated using the following equation (1):

$$f_0 = \frac{1}{2\pi\sqrt{L \cdot C}} \qquad (1)$$

The required excitation power is supplied from a exciter transformer T. If the frequency of the excitation voltage is equal to the resonant frequency f_0 of the resonant circuit, its impedance is reduced to a minimum, and the energy in the circuit only oscillates between the capacitance and the inductivity. In this case, only active power covering the losses in the resonant circuit is transferred via the exciter transformer. The amount of the active power only ranges between 0.5 … 2% of the apparent test power, depending on the losses in the components. If a test is performed at mains frequency, the reactor L is fitted with an adjustable core so as to be able to match the resonant circuit exactly to 50 or 60Hz according to the TO capacitance. If, however, the reactor is fitted with a fixed core without adjustment possibility, the frequency of the excitation voltage must be adapted to the resulting high-voltage circuit resonant frequency.

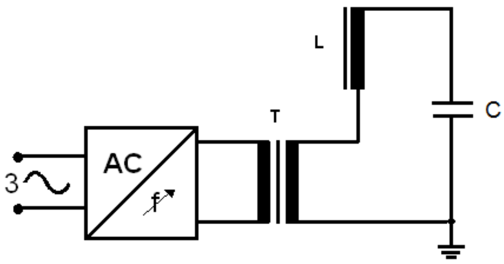

Fig. 1: Series resonant circuit with variable frequency

The excitation frequency for the on-site testing of extruded HVAC cables lies in the range 20…300 Hz [3], [4]. For the testing of super-long cables, several test systems can be combined in series or parallel connection [2].

Fig. 2: Test of a HVDC submarine cable with two resonant reactors in series

2.2 Very low frequency generators

Very low frequency generators, referred to as VLF generators for short, have been used for the testing of medium-voltage cables for many years. They are used to generate an AC voltage with a very low frequency of 0.1 Hz, or in some cases even 0.01 Hz. The form of the voltage characteristic may be either sinusoidal or nearly square-wave shaped. The latter – also called cosine-square wave voltage – is intended to simulate the voltage variation rate du/dt of a test voltage with mains frequency during polarity change. For an easy comparability of the calculation results all investigations has been done by the assumption of a sinusoidal VLF voltage.

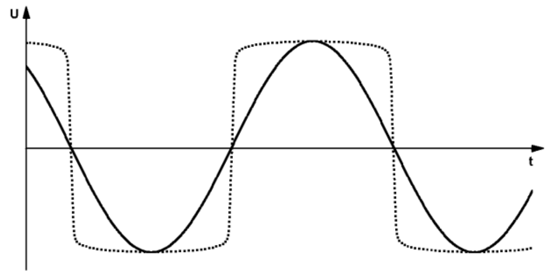

Fig. 3: Typical wave shape of a cosine-square wave (dotted) and sinusoidal VLF voltage

Due to the fact that the frequency deviates greatly from the mains frequency when medium-voltage cables are tested, a test voltage higher than the test voltage at mains frequency by the factor 1.5 is usually used ($3U_0$ instead of $2U_0$ at 50/60 Hz) [5].

The principle of voltage generation is completely different to the resonance principle. The cable is charged periodically with DC voltage of alternating polarity. Each time the polarity is reversed or the cable discharged, the complete energy previously stored in the cable is converted into heat by way of resistors. Therefore, the required feeding power corresponds to at least the apparent test power, and is actually a bit higher still due to the losses in the VLF generator.

Since the losses increase quadratically with the voltage when the cable is discharged, the currently available VLF generators provide only an output voltage up to 200 kV (peak value) and a charging current of approx. 100 mA [7], [8]. This corresponds to an apparent power of approx. 14 kVA; the total weight of the components of such systems is 2…4 t.

3 DETERMINATION OF THE TEST POWER

3.1 Cable specifications

For estimation of the required test power, a typical extruded HVDC cable with a nominal voltage of 500 kV is to be investigated. The following cable data will be used to calculate the test power:

Capacitance:	C = 0.22 µF/km
Conductor resistance:	R_{cond} = 0.009 Ω/km
Screen resistance:	R_{screen} = 0.23 Ω/km
Loss factor @ 50 Hz:	$\tan\delta < 3 \cdot 10^{-4}$

The test power is to be estimated for cables 25, 50, 75 and 100 km in length. The following cable data result for the calculation:

Table 1: Cable data for different lengths

Length [km]	C [μF]	R_{cond} [Ω]	R_{screen} [Ω]
25	5.5	0.23	5.75
50	11.0	0.45	11.5
75	16.5	0.68	17.25
100	22.0	0.90	23.0

3.2 Test parameters

Normally, a test voltage whose r.m.s. value corresponds to the nominal voltage of the cable is used for the AC testing of extruded HVDC cables. For a 500 kV cable, for example, a test voltage of 500 kV is assumed. This test voltage applies for frequencies in the range 10…50 Hz. Similarly to the testing of medium-voltage cables, a test voltage which is higher by the factor 1.5 is used for testing with 0.1 Hz VLF (sinusoidal). The calculations of the feeding power are made for test frequencies of 0.1 Hz (VLF), 5 Hz, 10 Hz and 20 Hz. On the basis of the assumption that the relevant cable properties of a 320 kV cable are similar to a 500 kV cable, the calculations of the feeding power are made for test voltages of 320 kV and 500 kV.

The apparent test power S_{test} can be calculated from the capacitance C, test voltage U_{test} and frequency f:

$$S_{test} = U_{test}^2 \cdot 2\pi \cdot f \cdot C \qquad (2)$$

4 DETERMINATION OF THE REQUIRED FEEDING POWER

4.1 Losses in the cable

The total losses P_{total} and thus the active component of the required feeding power comprise the losses in the cable P_{cable} and the losses in the test system $P_{generator}$:

$$P_{total} = P_{cable} + P_{generator} \qquad (3)$$

The cable losses are assumed to be the total of the ohmic losses in the conductor P_{cond}, in the cable screen P_{screen} and in the insulation P_{diel}:

$$P_{cable} = P_{cond} + P_{screen} + P_{diel} \qquad (4)$$

To calculate the dielectric losses, the model of a resistor connected parallel to the cable capacitance is used. Thus, the dielectric losses are investigated independently of the test frequency and are only dependent on the test voltage. A value of 2.5*10^{-4} at 50 Hz is assumed for the loss factor:

$$P_{diel} = S_{test50} \cdot \tan\delta = U_{test}^2 \cdot 2\pi \cdot 50^{-s} \cdot C \cdot \tan\delta \qquad (5)$$

The screen losses in the cable, in particular, depend on how the power is fed into the cable. If the power is fed at one end only, the current in the cable screen at the remote end will be zero and will increase to the value of the full test current i_{test} in the form of a linear curve towards the fed end. The losses in the screen are thus calculated as follows:

$$P_{screen} = \frac{1}{3} R_{screen} \cdot i_{test}^2 \quad \text{(fed from one end)} \qquad (6)$$

Significant reduction of the screen losses is possible by feeding power into the cable at both ends. This is usually possible if the test is performed at the factory. In this case, the current in the cable screen increases in the form of a linear curve from the centre towards both ends of the cable and reaches half the value of the test current at each end. In this case, the losses in the cable screen amount to only a quarter of the losses with single-end feeding:

$$P_{screen} = \frac{1}{12} R_{screen} \cdot i_{test}^2 \quad \text{(fed from both ends)} \qquad (7)$$

4.2 Losses in the test system

The losses in the test system used depend to a high degree on the function principle. In the case of resonant test systems with variable frequency, it can be assumed that the losses are approx. 1 % of the total apparent test power. The losses occur mainly in the resonant reactors in the form of load losses in the winding. By comparison, the losses in the excitation transformers and static frequency converters play only a subordinate role.

The situation with VLF generators is completely different, due to the function principle of periodic charging/discharging of the cable. When assigning the losses in the required charging/discharging resistors to the losses of the test system, the loss power is equal to the apparent test power. In addition, there are internal losses, e.g. in rectifiers. The losses of a VLF generator are assumed to be 1.1 times the apparent test power.

It can be derived from these considerations that the required feeding power for tests with 0.1 Hz VLF does not differ significantly from the required feeding power used in tests with a resonant test system with variable frequency. It is true that the apparent test power is significantly lower due to the low test current, but instead, the full apparent test power must be provided. Testing at higher frequencies may lead to significantly higher apparent test powers, but the requirement for feeding power is not significantly higher, as resonant test systems with variable frequency only require approx. 1 % of the test power. Assuming that the test voltage must be higher with 0.1 Hz, the power required for a VLF generator is even higher for the same cable to test.

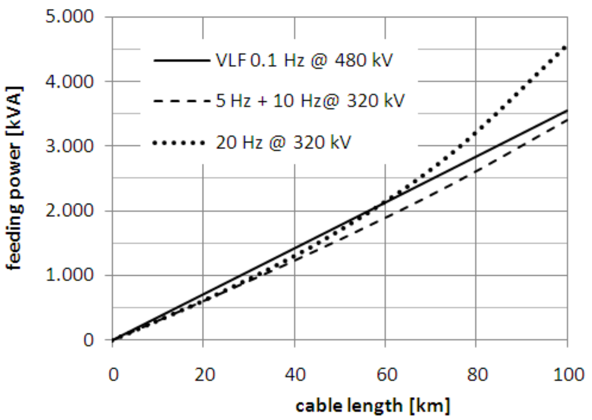

Fig. 4: Required feeding power at a test voltage of 320 kV (480 kV for 0.1 Hz), cable fed from both ends

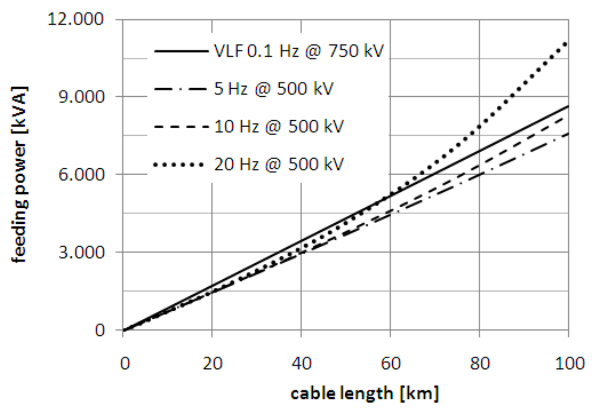

Fig. 5: Required feeding power at a test voltage of 500 kV (750 kV for 0.1 Hz), cable fed from both ends

The results show that the required feeding powers lie in the range of several MVA. Up to a cable length of approx. 60 km, the differences between feeding with 0.1 Hz VLF and feeding from resonant test systems with variable frequency in the range 5…20 Hz are low. Only in the case of lengths >60 km and high test voltages do the losses in the cable screen become increasingly noticeable at higher frequencies and thus also higher test currents.
While the reduction of the test frequency from 20 to 10 Hz, especially with super-long cables and high test voltages, also results in reduction of the feeding power, no significant improvement can be noticed for the investigated length range in the case of further reduction to 5 Hz.

Optimum connection of the cable to the test system gains increasing importance in the case of high test currents. Fig. 6 clearly shows the disproportionate increase of the feeding power when the power is fed on one cable only at higher frequencies.

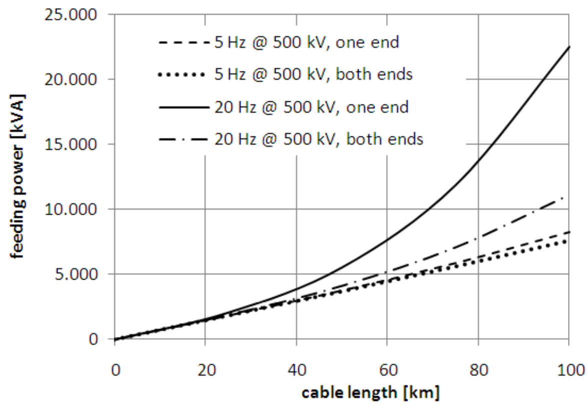

Fig. 6: Required feeding power at a test voltage of 500 kV depending on the cable connection

5 CONCLUSIONS

The investigations show that AC voltage testing on extruded HVDC cables several 10 km in length places high demands on the test equipment and the feeding power to be provided. With the equipment and technology used today for the testing of extruded HVDC cables, AC tests can be performed on HVDC cables up to approx. 80 km in length at 320 kV and up to 35 km at 500 kV. The largest currently available VLF generators are much too small in their power to be able to be used over the investigated voltage and length ranges. Even for testing at 0.01 Hz, only devices with sinusoidal voltage seem to be theoretically suitable. The relatively steep rise of the cosine-square wave voltage when charging/ discharging the cable would require charging currents of several 100 A. Furthermore, it should be asked whether it makes sense to perform PD measurements on the joints at 0.01 Hz, as it is unclear, if PD activity will start at all within the testing time.

To be able to test HVDC cables as long as possible using the currently available technology, the power must be fed into the cable at both ends. This is the only way to reduce the losses in the screen and the resulting feeding power.

An extension of the frequency range to 10 Hz would be helpful with reference to maximum test cable lengths provided the PD measurements on the joints are not significantly impaired.

For testing with extreme lengths, the test procedure must be adapted accordingly. Firstly, segments of several manufactured lengths, each between 80 and 100 km (depending on the voltage level), could be tested with AC voltage. In this case, only the required high-voltage connection of these pieces has to be tested with DC voltage, which would increase the quality of the test significantly compared to DC testing for all joints.

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