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Testing of Extruded HVDC Cables – Challenges and Experiences

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Abstract

The increasing integration of extruded HVDC cables into the power transmission system raises new questions regarding transient fault voltage waveforms and their simulation in the laboratory. This paper gives an overview of the challenges to high-voltage test laboratories that have come up with the increasing use of extruded HVDC cables. Besides the request to test longer cable lengths, laboratories are faced with the demand for testing non-conventional waveforms, which are the result of numerical calculations of failures in HVDC grids. Experiences with generating such waveforms are presented as well.

Keywords: Extruded Cable, HVDC, Testing, Transient Overvoltage

1. Introduction

The transition towards renewable energy is spreading all over the world and is very much linked to the capability to transmit and dispatch energy from one place where the clean energy is produced to another place where the energy is consumed. New challenges thereby arise in the power grid, such as renewable energy source remoteness and increased power flow fluctuations. The focus of these new systems is on using DC for transmission because of its advantages, such as:

- No need to compensate for reactive power
- Coupling of parts of the grids which are not synchronous
- No skin effect, no eddy current

The development of reliable and durable HVDC cable systems thereby plays an important role in future electrification efforts. As proof of this, the number of HVDC interconnectors in the construction stage is larger than ever before. Also, there are many projects in progress at various preliminary stages (planning, studies etc), and these interconnections are typically very long and with higher power ratings, thus pushing voltages to new levels with new cable technologies.

The cable market is one of the hot sectors in the clean energy transition, as demand for products such as submarine HV lines leads to order backlogs of 2 to 5 years for cable manufacturer portfolios.

The integration and management of intermittent renewable sources but also the reliability of supply and the integration of electricity markets are asking for bidirectional interconnection systems, this is the reason why utilities are requesting a polarity reversal endurance test.

Furthermore, network operators and utilities recently highlighted the occurrence of Transient Over Voltages (TOV), which may occur during the cable operation in point-to-point connections comprising VSC converter technologies (preferred for extruded cables)[1,2]. While the CIGRÉ Technical Brochure on the numerical simulation of such over voltages has not yet been published, there are already requests to the laboratory to carry out tests on extruded cables.

These requests are addressed to the test laboratory to test already installed cable loops additionally with special waveforms as described in CIGRÉ TB 852[3] and TB 853[4].

This paper presents challenges and experiences with the testing of HVDC cables that typically occur in high-voltage test laboratories.

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2. Challenges

2.1 Testing of Long HVDC Cables

Typically, cable loops for impulse tests on HVAC cables are of a length in the range of 30 meters, as described in IEC 62067[5]. Such cable length can easily be handled in a high-voltage laboratory since the load capacitance for the impulse generator is in the range between 6 nF and 10 nF.

Requirements from clients for pre-qualification tests of extruded HVDC cable systems specify carrying out the impulse tests on the complete loop including accessories. If this loop includes different laying conditions such as tunnels, ducts, etc. the cable length might exceed 200 meters and the load capacitance might exceed 40 nF which results in low efficiency of the impulse generator, see[6].

2.2 Testing with New Waveshapes

New requirements due to TOV are based on the results of numerical simulations of HVDC grids[1,2]. The length of extruded HVDC cables is strongly increasing, in Germany mainly due to the projects SuedLink and SuedOstLink which have been initiated to transport electrical energy from offshore wind parks in Northern Germany to the industrial areas in South Germany. But also new projects as the Xlinks Morocco-UK Power Project set new benchmarks in terms of the length of the cable.

Simulations revealed that a transient overvoltage stress to the cable can occur. In the case of an earth fault in one polarity the voltage in the other polarity may rise to a value of 1.7 to 2.0 p.u. and is over the regular voltage for a time such as 200 ms or longer. Figure 1 shows an example of such a voltage in the red curve. The faulted pole is meanwhile discharged with an oscillating waveform as shown in Figure 1 in the grey curve.

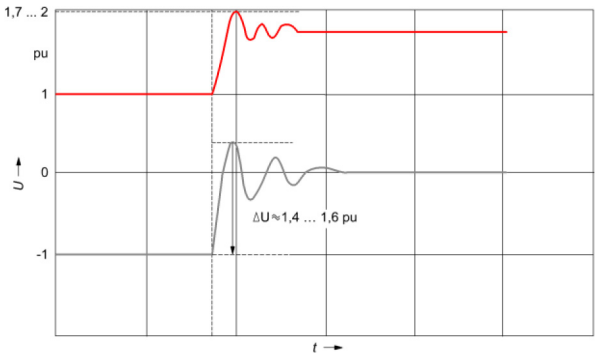


Figure 1. The typical waveshape of the voltage of the faulty pole (grey curve) and the healthy pole (red curve) in case of a single pole fault in an SMP configuration (1, redrawn).

In general, the cable system is subjected to a damp discharge in the faulty pole and a slow superimposed impulse in the healthy pole. Therefore, the request to the laboratory was to generate waveforms as close as possible to the simulated curves to introduce this stress as an additional evaluation test in the future.

Currently, such waveshapes as shown in Figure 1 are not yet part of IEC 62895[7]. Since November 2021 CIGRÉ TB 852[3] indicates such waveshapes. As shown in Figure 1, two general waveshapes are described, an oscillating discharge and a superimposed impulse, which has the same polarity as the DC voltage on the cable. This superimposed voltage may also be chopped after the peak to simulate the grounding of the cable in a grid after a pole-to-earth fault.

The CIGRÉ TB 852[3] gives a wide range of peak and time parameters. In many cases, additional notes indicate that these values are based on the restrictions of laboratory equipment. Besides the experiences in our laboratory, presented in[8], most publications[9,10] mentioned problems in generating wave shapes as the red curve in Figure 1.

The client's specifications do not consider such restrictions. So, our laboratory was contacted to provide the following waveforms on a 525 kV cable loop with a length typical for a type test:

1. Oscillating discharge test from U_0 with a high frequency of between 5700 Hz and 8000 Hz and at least 14 oscillations and with a low frequency of below 400 Hz and at least 5 oscillations
2. Very slow front impulse test (same polarity) after a pre-charge with U_0, a peak voltage of 1.6 U_0 and a time to peak between 7 ms and 10 ms and a plateau time from 1.6 U_0 to 1.5 U_0 between 100 ms and 200 ms
3. Fast front impulse test (opposite polarity) after a pre-charge with U_0, a peak voltage of -0.6 U_0 a time to peak of 60 µs +/- 20% and a plateau time between 100 ms and 200 ms

To carry out these tests on a real cable system loop, a type test loop, consisting of 2 outdoor terminations, 2 joints and the extruded DC cable has been installed by Prysmian Italy in the HVDC test hall of KEMA Labs in Mannheim. After a pre-stress with a type test, it was intended to carry out the first Transient Overvoltage Test (TOV) on a 525 kV HVDC cable.

3. Experiences

3.1 Testing of Long HVDC Cables

The testing of long HVDC cables is no problem if only DC needs to be supplied. In case of polarity reversal tests

a discharge, a switch might be needed to discharge the cable in an acceptable time.

As soon as the capacitive component is part of the test, the testing becomes more difficult. This is the case for the impulse testing of extruded HVDC cables, which is described in IEC 62895[7] and IEC 60230[11]. This test must be carried out as a superimposed impulse test, i.e. the impulse voltage is superimposed to the voltage on the pre-charged cable[7]. IEC 60230[11] proposes two different options to superimpose this voltage: The use of a sphere gap for coupling or the use of a coupling capacitor. Both options have advantages and disadvantages.

A coupling capacitor provides a good reproduction of the required waveshapes but besides its physical size, it additionally reduces the efficiency of the test circuit according to[6], since this capacitor builds a voltage divider together with the test object. Therefore, such a coupling capacitor shall have a capacitance of at least 5 to 10 times the capacitance of the test object. In our laboratory, a coupling capacitor of 400 nF is used for testing objects up to 240 m in length.

Using a sphere gap is possible and does not affect the efficiency of the impulse generator. However, as shown in[12], it is essential to use a sphere gap which is triggered on both sides. Otherwise, it might happen that the sphere gap does not ignite in case of the same polarity of the impulse and the DC pre-charge on the cable. Additionally, using a sphere gap will not reproduce the waveshape as shown in[7] but will always end with a discharged test object while the standard waveshape ends always with the test object back on the DC pre-charge.

3.2 Testing of Transient Over Voltages

The priority during the evaluation of the laboratory capabilities was to use as much of the already existing equipment. At least a DC generator and an impulse generator might be installed in an HV test laboratory.

Furthermore, it was assumed that the tests should be carried out on a typical test loop which shall have a capacitance of approximately 15 nF in the case of XLPE cable. The reason to choose a type test length is that these TOV tests are seen as special requests concerning the design of the cable system and therefore the tests should be done in conjunction with the type tests. This saves efforts for the installation of a separate test loop. While the oscillating discharge was carried out as the first test, the Transient Overvoltage Test was done following this test.

3.3.1 *Oscillating Discharge Test*

The general test circuit is shown in Figure 2.

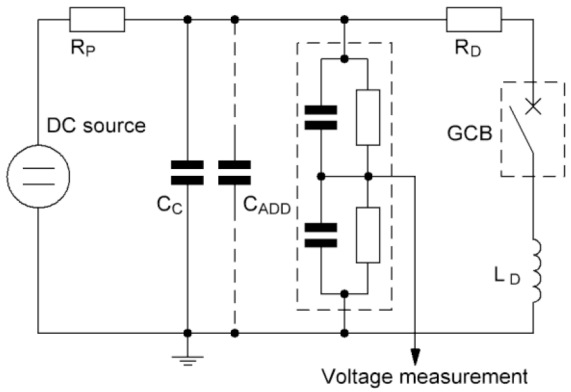


Figure 2. General test circuit for the zero-crossing damped temporary overvoltage test.

The cable capacitance C_C needs to be discharged by an inductor L_D. The damping can be adjusted using a series resistor R_D. The cable was pre-charged by a DC source and then discharged by closing a circuit breaker (GCB) that was available in the laboratory. As shown in[3], a spark gap might be used also, to switch the inductor. To adjust the lower frequency an additional capacitor C_{ADD} was installed, using several capacitors of the impulse generator in a series circuit. The protection resistor R_P was used to avoid an over-current trip-out of the DC generator during the discharge of the capacitance C_C

Two fixed-value air-core reactors are available at the laboratory to be used as L_D. For the high frequency, a value of 65 mH was installed, while for the low frequency, a 1000 mH inductor was used. A numerical simulation revealed that with the available equipment, all requested parameters could be realized. Therefore, the circuit was built up in the laboratory and the test was carried out with full-scale DC voltage. The voltage was recorded with a transient recorder.

The test itself was carried out as follows: The load was pre-charged with U_0 for a time of at least 10 hours. After this, a C-t-O operation was done by closing and opening the circuit-breaker GCB. The time t was not exactly kept constant but simply done with a manually controlled C-t-O operation.

Figure 3 shows the recorded voltage for the high-frequency discharge while Figure 4 shows the recorded voltage for the low-frequency discharge.

The damping caused by the air core reactor is low. To reduce the number of oscillations, damping resistors R_D in the range of 50 Ohm were inserted.

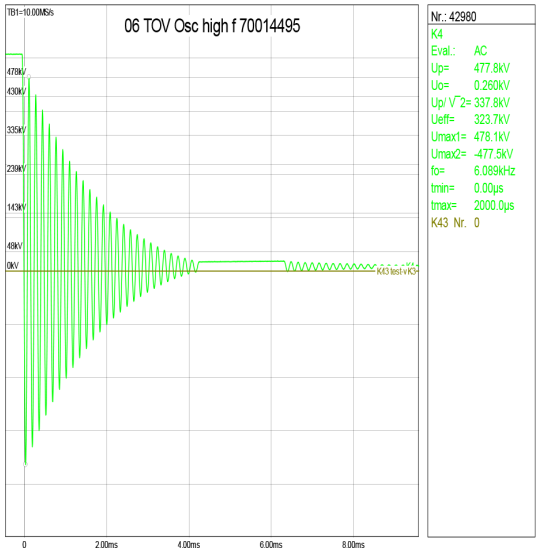


Figure 3. Recorded waveform during the oscillating discharge test with high-frequency f_0 = 6089 Hz.

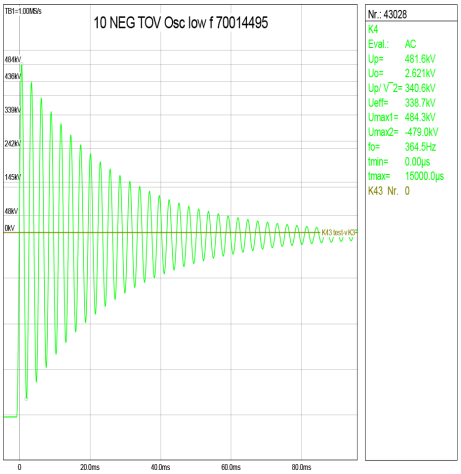


Figure 4. Recorded waveform during the oscillating discharge test with low-frequency f_0 = 364.5 Hz.

The requirements of the specification were fulfilled. However, it can be noticed that there is a DC offset overlaid to oscillation. Figures 3 and 4 show that the offset's polarity was the same as the DC pre-charge. Communication with another laboratory revealed that they observed an offset in opposite polarity compared to U_0. The reason for this offset is not yet clear. It might be supposed that it is caused by the low-voltage branch of the universal voltage divider. Another explanation is that the cable is still charged by DC even with GCB closed since the DC generator is not disconnected. This problem needs deeper investigation and might be solved by an update of the evaluation software to remove this offset by calculation or by a different configuration of the test set-up as shown in Figure 5.

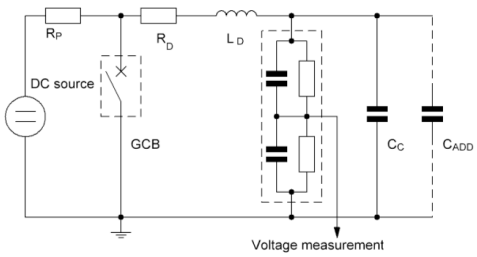


Figure 5. Alternative test circuit for the zero-crossing damped temporary overvoltage test.

3.3.2 *Transient Overvoltage Test*

If the required test voltage is evaluated, it becomes clear that the parameters may be fulfilled by a double-exponential function voltage as it is delivered by an impulse generator, and which is superimposed to the pre-charged DC voltage of the load. The general function is well known and is in general identical to a superimposed impulse test as described in[7].

This theoretical approach does not completely reflect the reality inside the high-voltage laboratory as already discussed in[8]. To overcome these problems, it was decided to upscale the set-up with a rectifier, which has already been proposed in[8]. A rectifier does not need an ignition, and it seems to be clear that a standard impulse generator can be used without big additional effort, only an additional external damping resistor is possibly needed. A simulation confirmed that the insertion of a rectifier dramatically increases the discharge time constantly after the peak of the voltage. Figure 6 shows the general test circuit.

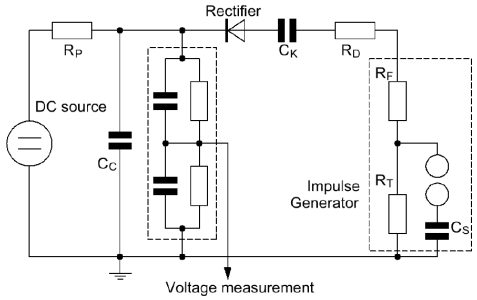


Figure 6. General test circuit for the temporary overvoltage test.

To reach a steep front as described above, a selenium rectifier could not be used due to its high internal resistance. Therefore, a new rectifier has been purchased and used for this test.

The cable capacitance C_C is pre-charged to U_0 by the DC generator. The impulse from the impulse generator is coupled by a capacitor C_K as described in IEC 60230[11] but the cable will be charged or discharged by the impulse only

as long as the current flows in the right direction through the rectifier. As soon as the output voltage of the impulse generator is smaller than the voltage of the cable, the current will change its direction. This means the impedance of the rectifier changes to the value determined by the voltage grading resistors, a value exceeding 500 M Ohm.

Therefore, the discharge time constant increases dramatically, and will be determined mainly by the branch resistors of the voltage divider and the protection resistor R_P. The time to peak depends mainly on the capacitors C_S, C_K and C_C and the resistors R_F and R_D and can be therefore adjusted in a wide range.

A silicon-based rectifier providing a high forward peak current and a low forward resistance was used. The additional damping resistor R_D was adjusted to approximately 400 kOhm for slow charging of the cable to reach the time-to-peak as specified. This resistor works for the front time but also for the tail time, therefore the impulse generators' tail resistors could be adjusted to 20 kOhm per stage. This value was used to avoid a too-quick discharge of the surge capacitors. The impulse generator consists of 15 stages with 200 kV each and a total energy of 300 kJ. The coupling capacitor had a capacitance of 100 nF.

Figures 7 and 8 show examples of the measured test voltage on the cable. As Figure 7 proves, the peak was 7.536 ms, which is approximately a factor of 30 compared to a standard switching impulse voltage. This long peak is mainly caused by the high additional resistor value of R_D. The time for the reduction from 1.6 p.u. to 1.5 p.u. is close to 200 ms, which is also far more than with a standard switching impulse layout. Therefore, it can be concluded that the timing limits in CIGRÉ TB 852[3] can be exceeded with limited efforts.

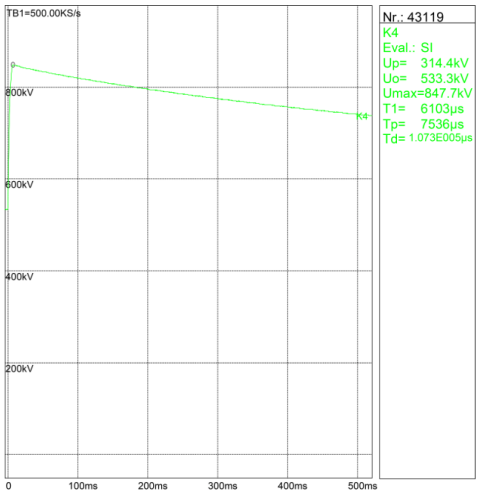


Figure 7. Measured transient overvoltage during the full-scale test with the same polarity as U_0.

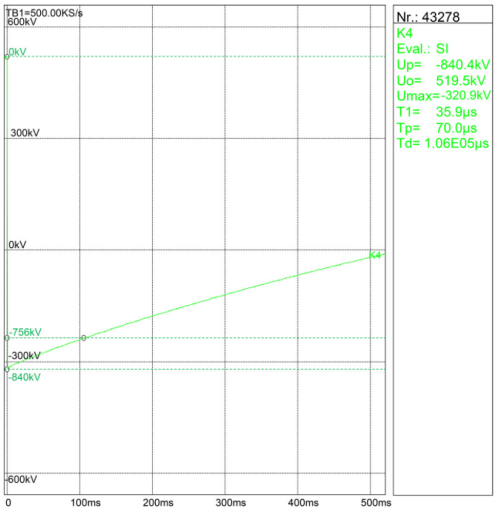


Figure 8. Measured transient overvoltage during the full-scale test with opposite polarity as U_0.

Anyway, during the test it was found that the resulting efficiency of the test circuit is as low as 25% if the charging voltage is compared to the impulse part of the voltage across the test object. This means the high-voltage impulse generator must provide adequate energy and voltage levels. The Mannheim laboratory was upgraded, adding a stage to perform the test fulfilling all the requirements. The original impulse generator consists of 15 stages and 14 of them were used in a 7s2p-configuration. With two additional capacitors, this configuration was extended to an 8s2p configuration.

It should be noted that not all the HV laboratories could be properly equipped to generate such voltage level and time to peak since the impulse generator is working close to its limit. The reason for the reduced efficiency is that the output voltage of the impulse generator must exceed the DC pre-charging voltage U_0 on the cable before the rectifier can carry current from the impulse generator to the test object. After the peak, the charge cannot flow back to the impulse generator and therefore, the discharge is very slow. If the circuit is analyzed, the coupling capacitor could be removed for the same polarity impulses, which increases the efficiency a little bit. Since after this test, the same circuit was used also for opposite polarity impulses, where the capacitor C_K is essential, it was installed also for the same polarity test.

Does this test prove that a rectifier is a perfect solution? The rectifier is an element which must be understood in its function. In a regular superimposed impulse voltage test with a coupling capacitor and without a rectifier all adjustments for the waveshapes can be done with reduced voltages, e.g.

at 30% to 50% of the test voltage level. Therefore, the test object is not overstressed. After increasing the values, the time parameters will still be the same, only the measured voltages will change.

If a rectifier is in the circuit and a test with the same polarity between the impulse and the DC pre-charge is carried out, the parameters of the superimposed impulse change with the charging voltage, see Figure 9. Therefore, the laboratory must know very well the behaviour of this non-linear element to understand how it should be used.

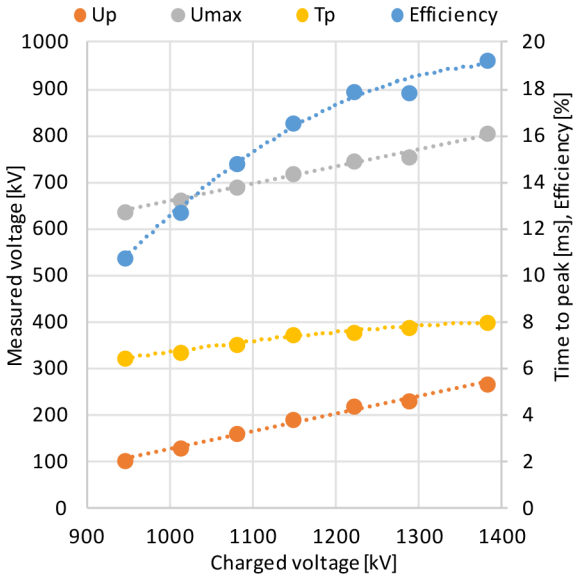


Figure 9. Waveshape parameters as a function of the charging voltage at a constant DC pre-charging voltage of U_0 = 525 kV (Up – peak voltage of the impulse part, Umax – the total peak of the voltage on the test object, Tp – time to peak, Efficiency – Up related to the charging voltage).

The reason is that only this part of the impulse voltage is transferred to the test object, which exceeds the DC pre-charge voltage. Therefore, a numerical simulation of the circuit can be helpful to find the appropriate values for the resistors in the circuit. To reach this goal, the rectifier needs to be investigated to find the correct parameters for the numerical simulation. The rectifier which was used in the test had the following nominal values:

- Nominal forward current 20 A
- Peak forward the current 1000 A
- Nominal reverse voltage 1000 kV
- Reverse peak voltage 1300 kV

The numerical simulation revealed that the calculated waveshape is close to the waveshape as measured in the full-scale test in the laboratory. Figure 10 gives an impression of the set-up in the laboratory.

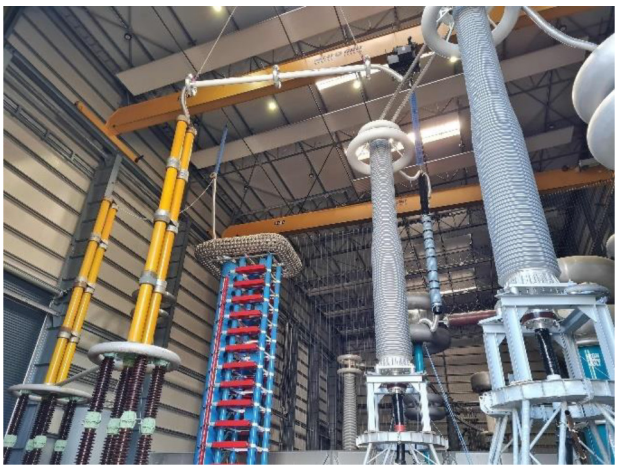


Figure 10. Test set-up for the full-scale test in the HVDC laboratory of KEMA Labs in Mannheim.

In conclusion, the requested test parameters as described in the client's specification (see above) were reached. Therefore, it is clear, that the limits of laboratories, listed in clause 12.2 of CIGRÉ TB 852[3] may maybe be estimated too conservative. A standard test laboratory shall be able to reach a plateau time of > 100 ms without a big effort when a rectifier is used. Concerning the time to peak it might be challenging to reach a value exceeding 3 ms. It is worth mentioning that this kind of test may require much space to fit all the equipment needed inside a test bay. This could translate into a reduction of test capability for the laboratory performing different tests at the same time.

4. Conclusion

In a changing electrical market, driven by renewable energies, the target is to get wind or solar energy to the consumption centres, transporting energy over thousands of kilometres. Interconnectors using HVAC cables are currently limited to lengths of approx. 100 km, with established technologies, HVDC solutions are more and more preferred not only for submarine cables but also for land applications, especially for long distances.

To have higher thermal and electrical performance, the TSOs sought a new class of extruded cables; in particular, the German TSOs were looking for the first group of cable manufacturers capable of supplying extruded cable systems at 525 kV DC.

Recently, an increase in requirements coming either from equipment manufacturers or from grid operators is observed. These requests are addressed to verify the possibility of reversing the flow of energy circulation in the event of varying needs of adjacent markets, and withstand electrical transients, giving higher confidence for all transient phenomena occurring in HVDC schemes such as during pole-to-ground fault, pole-to-pole fault, faults on AC side etc.

Consequently, KEMA Labs Mannheim laboratory was requested to perform a feasibility study on the possibilities of setting up test circuits that could enable laboratory testing of full-scale HVDC cable systems up to 525 kV according to the above-mentioned TOV. The aim was to verify the performance of the HVDC cable system to withstand these stresses, which are of a non-standard nature[13].

After the positive indications received during the preliminary tests, at the request of an important manufacturer, tests were carried out on a 525kV DC system immediately after a Type Test.

In April 2022, a new important goal for the HVDC Cable Sector has been reached in our KEMA Labs Mannheim HVDC Laboratories. The first TOV (Transient Over Voltage) test has been carried out on a 525kV DC Cable System Loop consisting of 2 External Terminations, 2 joints and the DC cable.

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