15. Symposium Energieinnovation, 14. bis 16. Februar 2018, Technische Universität Graz, www.EnInnov.TUGraz.at
ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

Superimposed Impulse Voltage Testing on extruded DC-Cables according IEC 62895

Andreas Voß*, Michael Gamlin

Haefely Test AG, Birsstrasse 300, 4052 Basel, Schweiz, Tel.: +41 61 373 4313,
Fax: +41 61 373 4912, avoss@haefely.com, www.haefely-hipotronics.com

Abstract: The European energy supply system is currently undergoing massive changes due to the change from a fossil based to a renewable based power generation. This transition, however, is not only limited to power generation itself but at the same time also affects the whole energy system. In particular, the structure of transmission and distribution grids changes massively and thousands of kilometers of new lines need to be built. This also involves the combination of high voltage alternating current (HVAC) grids with single high voltage direct current (HVDC) point-to-point connections or even an overlay HVDC grid. Whereas HVAC components are well known and established in power transmission and distribution for decades, there is a large development in HVDC components always aiming for higher transmission voltages of currently up to 1100 kV DC. These developments, however, also come with the same requirements on safety and reliability which makes a proper and accurate testing of these components imperative.

One example for such a development as well as the need for accurate testing are cables used for HVDC links. Since cable failures can easily result in down times of years, there is a strong need for an appropriate testing of these cables as well as their accessories. Since extruded cables using cross-linked polyethylene (XLPE) insulations are state of the art for this application, the newly created IEC 62895 ("High Voltage Direct Current (HVDC) power transmission - Cables with extruded insulation and their accessories for rated voltages up to 320 kV for land applications – Test methods and requirements") defines the testing procedures for such cables. The type and prequalification tests on HVDC cable systems include the superimposed impulse voltage test, during which several switching and lightning impulses are applied on the HVDC cable which has been energized for multiple hours by a DC voltage. The DC voltage shall be maintained during the application of the impulse voltage. This test condition poses a technical challenge to the test setup, since the DC source and the impulse voltage generator have to be protected from each other. Neither must the DC voltage be present at the impulse voltage generator nor must the impulse voltage have any influence on the DC voltage generator. The superimposed impulse voltage test on HVDC cables is a composite test according to IEC 60060-1 Ed. 3.0 which requires suitable coupling and protection elements in combination with suitable converting devices and recording instruments. For the impulse side, the coupling and protection is possible with either a spark gap or a capacitor. For the DC side, the coupling and protection is realized by a damping resistor.

The pros and cons as well as the design aspects of the coupling and protection devices are introduced. A possible smart solution for the capacitive coupling by using spare capacitor stages of the impulse voltage generator is discussed. Additionally, the revision of IEC 60230 Ed. 2.0 "Impulse tests on cables and their accessories" is commented with respect to the proposed test setups and the measuring system for the superimposed impulse voltage test.

Keywords: Superimposed Impulse Voltage Test, DC-Cables, High-Voltage Testing

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

1 Introduction

The changes in the energy supply system, which happened over the past two decades, demand technical solutions fundamentally different from before. There is an ever growing demand for energy transmission over increasing distances and with increasing power. Due to its typical cost structure, which shows higher fixed costs but lower costs per length, DC transmission lines become more cost efficient than AC technologies above a certain break even distance. The increasing power demand of these connections additionally calls for higher transmission voltages. This altogether gives a strong need for HVDC transmission cables, which can e.g. be used for connecting offshore wind farms to the grid or to interconnect different grids.

These needs led to technological developments of HVDC cables with extruded insulation for up to 600 kV and of mass impregnated cables for even up to 700 kV [1]. However, the recent history with project delays due to cable problems also illustrates the increased technical demands of such cables [2]. Therefore, there exists an equally strong need for accurate testing of HVDC cables in order to ensure a safe operation which is mandatory for a reliable energy supply.

2 Superimposed Impulse Voltage Test

The test standard for HVDC cables with extruded insulation considers multiple tests such as the heating cycle voltage, the polarity reversal and the superimposed impulse voltage test [3]. Of these tests, especially the superimposed impulse voltage test, which superimposes a DC voltage with occasional impulses, poses technical challenges to the testing equipment. The test is a composite test according to IEC 60060-1 Ed. 3.0 [4] which means the different voltages are applied to the same test object, implicating the test equipment generating the voltages also has to withstand the superimposed stress. In order to achieve this, additional elements in between the test equipment and the test object have to be used, which serve as a coupling for the generated voltage but at the same time as a blocking element for the other, superimposed voltage form.

2.1 Test Setup

For the test setup, IEC 60230 Ed. 2.0 gives two different possibilities:

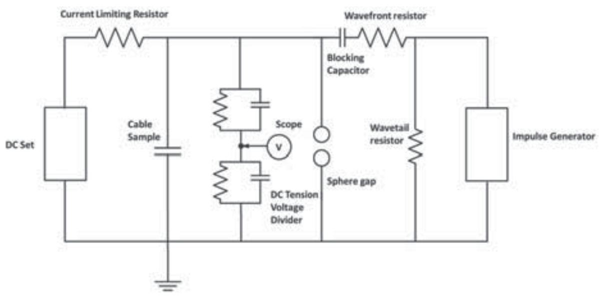

Figure 1.1: Superimposed impulse test arrangement with a blocking capacitor

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

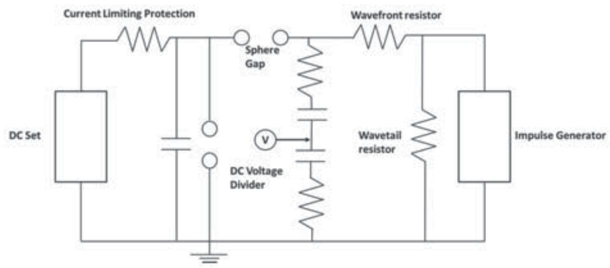

Figure 1.2: Superimposed impulse test arrangement with a sphere gap

Figure 1: Test setups for superimposed impulse voltage test [5].

In both setups, a current limiting resistor is used to protect the DC voltage generator from the impulse voltage. This resistor needs to be sufficiently large in order to neglect the impulse voltage's influence on the DC Set and avoid any harm.

For the protection of the impulse voltage generator, there exist two possible setups. In the first option, the impulse circuit is permanently connected to the test object via a capacitor. The capacitor presents an open circuit to the DC voltage thereby decoupling it from the impulse circuit. On the other hand, the capacitor presents a sufficiently small impedance to the fast impulse voltages, so that it has no major influence and the impulse is "pushed through" the capacitor to the test object.

In the second option, the impulse circuit is disconnected from the test object by a sphere gap. In that way, the impulse generator is only connected to the test object when the impulse is applied and the sphere gap fires. During the rest of the test procedure, the impulse circuit is not connected to the test object.

Figure 1 also shows different possibilities for connecting the measuring system. For composite voltage tests in general, there are three possible spots for the connection of the measurement: At the DC Set, at the impulse voltage generator or at the test object. Figure 1.1 shows the measurement at the test object whereas Figure 1.2 shows the voltage measurement at the impulse voltage generator which is decoupled from the DC Set and the test object by a sphere gap. In accordance with IEC 60060-1 Ed. 3.0, the voltage measurements at the sources should only be used for voltage adjustments and the composite voltage should always be measured at the test object, as depicted in Figure 1.1.

2.2 Voltage waveshapes

The following composite voltage waveshapes are given in the IEC standard for the superimposed impulse voltage tests of HVDC cables:

15. Symposium Energieinnovation, 14. bis 16. Februar 2018, Technische Universität Graz, www.EnInnov.TUGraz.at
ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

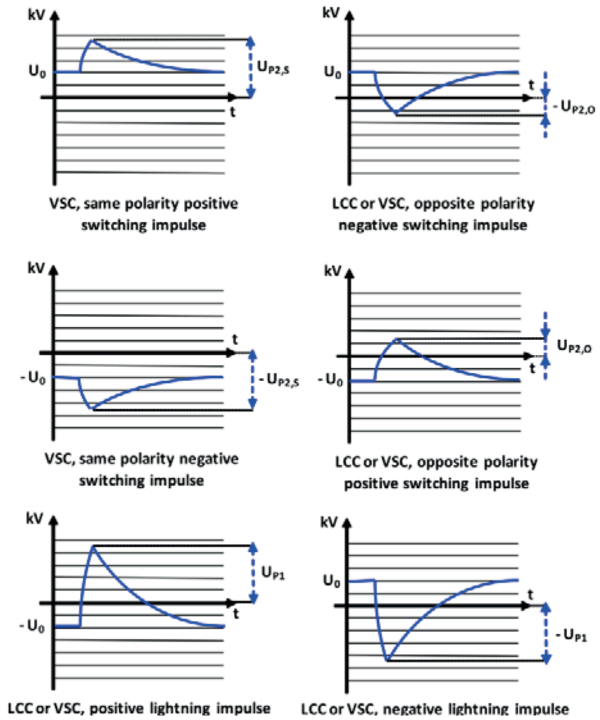

Figure 2: Voltage waveshapes for the superimposed impulse voltage tests [3].

As shown in Figure 2, there exist six different voltage waveshapes. The DC voltage is superimposed with a switching impulse of either the same or the opposite polarity or with a lightning impulse of the opposite polarity. These tests are performed for both DC polarities.

The composite voltage is defined as the “maximum absolute value measured at the test object” [4] so for the aforementioned cases, there are three different composite voltage levels:

- $U_{P2,S}$ defines the composite voltage when the switching impulse is applied at the same polarity as the DC voltage (U_0).
- $U_{P2,O}$ defines the composite voltage when the switching impulse is applied at the opposite polarity as the DC voltage (U_0). $U_{P2,O}$ is given as 1.2 U_0.
- U_{P1} defines the composite voltage when the lightning impulse is applied at the opposite polarity as the DC voltage (U_0). U_{P1} is given as 2.1 U_0.

3 Coupling and protection elements

After the description of the framework given by the different IEC standards, this paragraph focuses on the optimal design of the coupling and protection elements as well as the analysis of the different test setups.

3.1 DC Coupling

The current limiting resistor is the coupling and protection element used for connecting the DC generator to the test object. It is a key part used in both setups given in Figure 1 and therefore a mandatory part in the superimposed impulse voltage test setup.

In order to entirely block the impulse voltages from the DC set, the resistance needs to be sufficiently high so that the impulse capacitors are discharged via the test object and the

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

waveshaping resistors but not via the DC set. On the other hand, the resistor also determines the time constant $\tau = R * C_{DUT}$, by which the test object is charged with the DC voltage, and forms a resistive voltage divider together with the measuring system, which reduces the DC Set's efficiency (s. Figure 1.1). Therefore, the resistance must not be excessively high either to allow for a fast DC charging of the test object and a reasonable efficiency of the DC source.

As described above, the design of the DC coupling resistor depends heavily on the other components of the test setup as the DC Set, the test object and the voltage divider. For the voltage levels however, which the analyzed IEC 62895 is referring to, a resistance in the range of 10 – 100 MΩ was found suitable to fulfill all the aforementioned criteria. A lower resistance allows for a faster charging of the test object and a better DC efficiency but puts more stress on the DC Set. The same applies for a larger resistance vice versa.

The design of the DC coupling resistor however is not only limited to the electrical resistance but also to the mechanical dimensions. These are strongly determined by the different composite voltages which were described in section 2.2:

- $U_{P2,S}$ and U_{P1} define the maximum switching and lightning impulse voltage levels at the test object and the resistor. They are the relevant voltages for the field strength design of the resistor.
- $U_{P2,O}$ and U_{P1} define the maximum switching and lightning voltage drops across the resistor. They are the relevant voltages for the design of the resistor's length.

The exact mechanical design of the resistor depends heavily on the DC voltage level of the test object and the according composite voltages. However, it is crucial, to keep the different stresses of the composite test on the resistor in mind and design it accordingly.

3.2 Impulse Coupling

Whereas the coupling resistor is mandatory for connecting the DC Set to the test object, there are two different options for the impulse voltage generator connection: A blocking capacitor or a sphere gap. Whereas a sphere gap only connects the impulse generator during the impulse, when it is necessary, a blocking capacitor presents a steady connection which however is only possible for the impulse voltage to pass. It is a main incentive of this paper to present the advantages and disadvantages of the two solutions and to identify the superior.

3.2.1 Sphere Gap

The first possibility of connecting the impulse voltage generator to the test object is by using a sphere gap. It disconnects the impulse voltage generator from the DC voltage when no impulse is applied and it fires during the impulse thereby connecting the impulse voltage to the test object. In order for that test setup to work properly, it is essential to control the sphere gap so it is conducting during the whole impulse and insulating during all other times.

First of all, the sphere diameter and the distance between the spheres have to be chosen in that way, that the sphere gap can permanently and safely withstand the applied DC voltage U_{DC}. Additionally, the voltage across the sphere gap U_{SG} has to increase during the impulse by at least an amount ΔU, so that the voltage across the gap is higher than the breakdown voltage U_{BD} and the gap is triggered according to IEC 60052. The voltage drop across the sphere gap can be calculated according to Figure 3 by:

15. Symposium Energieinnovation, 14. bis 16. Februar 2018, Technische Universität Graz, www.EnInnov.TUGraz.at
ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

$$U_{SG} = U_{DC} - U_{IMP} \tag{1}$$

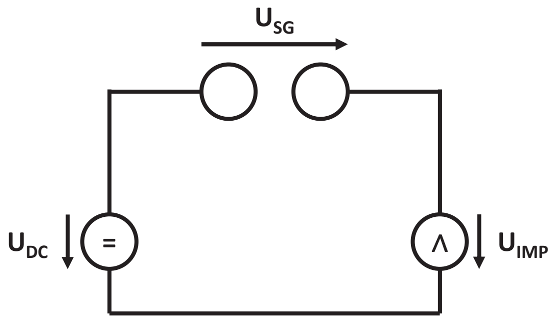

Figure 3: Voltage drop across sphere gap

In order for the sphere gap to trigger, the absolute voltage across the sphere gap has to be bigger than the breakdown voltage:

$$|U_{SG}| = |\ U_{DC} - U_{IMP}| > U_{BD} = U_{DC} + \Delta U \tag{2}$$

This gives two conditions, depending on if the impulse has the same or the opposite polarity as the DC voltage:

$$U_{IMP,O} < -\ \Delta U \tag{3}$$

$$U_{IMP,S} > 2\ U_{DC} + \Delta U \tag{4}$$

Equations 3 and 4 clearly show that the sphere gap is far easier to trigger for opposing impulse polarities, since this increases the voltage drop across the sphere gap. If the impulse has the same polarity as the DC voltage, it has to be at least twice as high as the DC voltage plus an additional increment ΔU to safely trigger the gap. If this requirement is not fulfilled, an artificial triggering, which is synchronized to the firing of the impulse generator, will be necessary.

However, the reliable triggering is not the only challenge for the sphere gap operation. The sphere gap also has to stay conducting during the whole impulse. In order to achieve this, a certain minimal voltage gradient dU_{SG}/dt is always required. For fast lightning impulses, this does not pose too much of a challenge whereas for slower switching impulses, this circumstance might not always be fulfilled. Especially during the switching impulse's peak, the voltage gradient is rather small and the sphere gap might extinguish. If this is happening, the cable is charged to the switching impulse peak voltage but due to the disconnected impulse generator, it cannot discharge via the tail resistors, leading to an almost constant voltage plateau after the impulse's peak. Since the impulse voltage generator discharges regularly via the tail resistors, the voltage drop across the sphere gap will increase over time and a refiring of the sphere gap during the impulse's tail occurs. At that time however, the impulse voltage generator is already that far discharged, that the voltage drops strongly and the resulting waveshape is no longer a switching impulse. Figure 4 shows the resulting voltage across the test object.

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

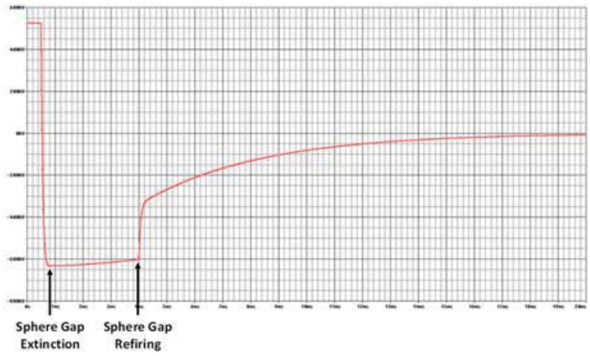

Figure 3: Sphere gap extinction during switching impulse tail

The sphere gap's extinction however is just one disadvantage of this arrangement, which has to be controlled. A second problem is the cable's discharge for opposing impulses, which occurs when the sphere gap stays conducting during the whole impulse, which is desirable as described above. During that time, the test object is charged as usual by the DC Set with a time constant $\tau_{DC} = R_{Coup} * C_{DUT}$ but the test object is also discharged via the front and tail resistors of the impulse volt-age generator with a second time constant $\tau_{IMP} = (R_{Front} + R_{Tail}) * C_{DUT}$, which can be deduced from Figure 1.2. Since the impulse time constant will be in the range of the impulse's duration, a considerable part of the energy, which is stored in the test object, will be discharged via the impulse resistors causing the voltage to not recover to the full original level. At the same time, the DC time constant is far bigger than the impulse duration so that the DC Set will not be able to recharge the cable. The resulting voltage waveshape is shown in Figure 5.

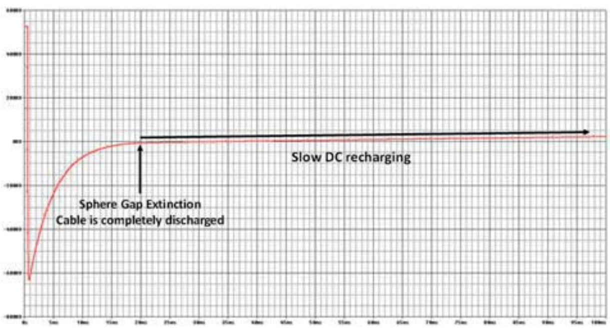

Figure 4: Test object discharge during opposing impulses

Summarizing, the advantage of the sphere gap is the relatively easy to implement setup, as long as the triggering conditions are fulfilled. The clear disadvantages however are the possible extinction of the sphere gap during times of low voltage gradients and the test object's discharge during the impulse. Therefore, it is not possible with this test setup to generate a clean superposition of a DC voltage with an impulse voltage.

3.2.2 Coupling Capacitor

The second possibility to operate this test is via a coupling capacitor between the impulse voltage generator and the test object. This capacitor works as an open circuit to the DC voltage thereby decoupling the impulse voltage generator from the DC source even though there is a permanent connection. That requires the capacitor to being able to withstand the full DC voltage. On the other hand, the coupling capacitor forms a capacitive voltage divider together with the test object during the impulse. That requires the coupling capacitor to have a much larger

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

capacitance than the test object in order to not overly decrease the impulse voltage generator's efficiency. However, if these criteria are fulfilled, this solution offers the possibility for a clean superposition of the two different voltages for all described composite test voltages. The results for that are shown in the following figure.

Figure 5: Superimposed voltage waveshapes using a coupling capacitor

The clear advantage of this test setup is the achievement of the desired composite voltage waveshape, which was not possible with the sphere gap setup. The disadvantage however is the practical implementation, since the coupling capacitor has to not only withstand the full DC voltage and have a high capacitance in the range of a few hundred microfarads, but it also has to be placed on high voltage potential on both terminals. This implementation however is easily possible by extending the impulse voltage generator to more stages, than would be necessary for the impulse generation, and use the spare impulse capacitors as DC coupling capacitor. This possibility presents a smart solution for realizing the test setup without the need for additional elements. This configuration is shown in Figure 7.

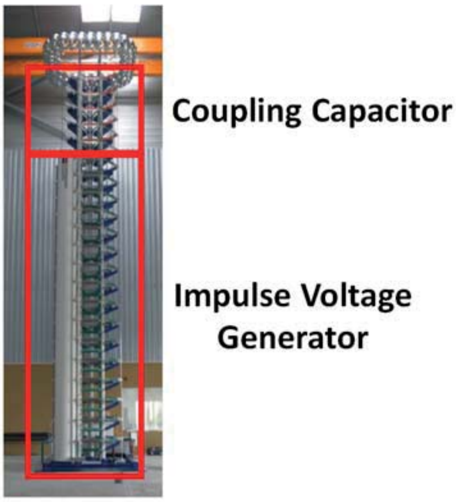

Figure 6: Superimposed impulse voltage generator using spare stages as capacitive coupling

Due to the superior results and the possibility, to avoid the disadvantages of this solution by smartly using the impulse capacitors as coupling elements, this option clearly forms the better way of conducting superimposed impulse voltage test for HVDC equipment.

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

4 Measuring System

Whereas the previous paragraph focused on the test setup to perform the test properly, this section will describe the requirements for an appropriate measuring system. According to IEC 60060-1, there are generally three different measurement locations for composite voltage tests: At each of the sources or at the test object. However, since the coupling elements are designed in a way to only allow the generated voltage to pass and to block the opposing voltage, the measurements at the sources can solely be used for the voltage source adjustment to properly generate the desired voltage level and shape. Therefore, an appropriate composite voltage measurement always has to be taken at the test object.

Since for the superimposed impulse voltage test, a DC and an impulse voltage are superimposed, only a universal voltage divider is suitable for this application. This divider consists of a high resistive column, which is suitable for DC measurements, and a damped capacitive column, which is suitable for impulse voltage measurements [6]. However, not only the divider type is important for an appropriate composite measurement. The different voltages also demand adaption by the recording system. During the superimposed impulse voltage test cycle, the cable is first heated by the DC voltage for at least ten hours [3]. During this period, the DC voltage has to be recorded by the measuring system with a low sampling rate such as 1 Hz in order to not exceed the memory depth of the system. Since there are no fast voltage changes during the sole DC application, this is acceptable.

After the heating of the cable, the impulses are applied and during this period, the sampling rate of the recording system needs to change. During the impulses, the sampling rate needs to increase to at least a couple of 10 MHz, to properly record the exact impulse shapes. In between the impulses, the sampling rates needs to reduce to the DC level though, in order to not exceed the memory depth. This adaption is called a dynamic sampling rate and is a key point for the successful measurement of composite voltages [7].

5 Conclusions

With the increasing demand for HVDC transmission cables and the recent technical problems herewith, there is a strong need for the reliable testing of these components. One part of this testing is the superimposed impulse voltage test according to recent IEC standards 60230 and 62895. These drafts consider two possible test setups. A thorough analysis has shown that only one of these setups presents a suitable solution for this test in order to be performed properly. It should be strongly preferred to connect the impulse generator by a coupling capacitor to the test object. A possible smart solution for this is to extend the impulse voltage generator by additional stages and use the spare impulse capacitors for this coupling. The recommended setup is shown in Figure 8.

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

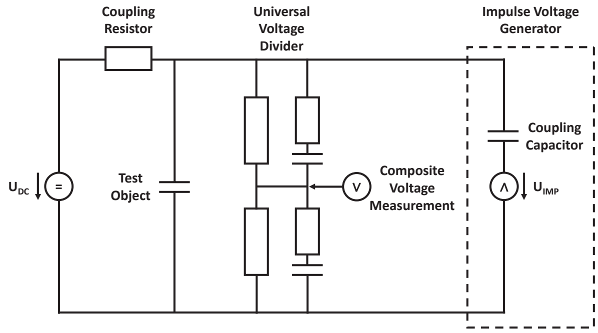

Figure 7: Recommended test setup for superimposed impulse voltage test

This test setup however is only suitable for the superposition of DC and impulse voltages. The coupling capacitor does not work for the superposition of AC with impulse voltages so for other superimposed application, a coupling via a sphere gap might be the only technical choice.

The analysis has furthermore shown the need for a composite measuring system. This system consists of a universal voltage divider to measure the different voltages at the test object and a recording system, which has the ability to adapt the sampling rate according to the test voltage. This also poses a key requirement for an appropriate superimposed testing.

6 References

[1] Prysmian Group. Double technology milestone in the field of power transmission. URL: https://www.prysmiangroup.com/en/en_2016_HVDC.html, last ac-cessed: February 05, 2018.

[2] S. Emrich. ABB hat Probleme mit Windpark, July 2016. URL: http://www.srf.ch/news/wirtschaft/abb-hat-probleme-mit-windpark, last accessed: February 05, 2018.

[3] IEC 62895 Ed.1.0, “High Voltage Direct Current (HVDC) power transmission cables with extruded insulation and their accessories for rated voltages up to 320 kV for land applications – Test methods and requirements”, 2017.

[4] IEC 60060-1:2010, “High-voltage test techniques - Part 1: General definitions and test requirements”, 2010.

[5] IEC 60230 Ed.2.0, “Impulse tests on cables and their accessories”, 2018.

[6] M. Modrusan, “Hochspannungsteiler: Typen, Messeigenschaften und Einsatz”, Bull. ASE/UCD 74 (1983) S. 1030-1037.

[7] Haefely Hipotronics. Hias 744 Product Brochure, April 2017. URL: https://hubbell-cdn.com/brochure/HAEFELY_LL_HiAS744_170821_BROCHURE.pdf, last accessed: February 05, 2018.