Surge and extended overvoltage testing of HVDC cable systems

JWG B4/B1/C4.73

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ABSTRACT

In this contribution a short status update of the Cigré JWG B4/B1/C4.73 is presented. The focus of joint working group is to investigate the surge and extended overvoltage testing of HVDC cable systems, since standard test levels for HVDC are at present not available. In this paper, a historic overview of the standardization status for HVDC cable systems is presented. This is followed by summarizing some findings and trends from data of the HVDC project collection, which are used for prioritization of the work tasks. Moreover, preliminary simulation results on the topic are presented. Since the JWG B4/B1/C4.73 is still in operation mode no firm conclusions on standardization should yet be drawn by the investigations presented here. Instead the relating brochure and/or Electra publication should be awaited.

KEYWORDS

High Voltage Cables, HVDC Transmission systems, Temporary overvoltages in HVDC systems, Symmetric Monopole, Bipole, Asymmetric monopole.

INTRODUCTION

CiGRE JWG B4/B1/C4.73 held its kick-off meeting in March 2016. It has the task of looking into surges and extended over-voltages testing for HVDC cable systems. More specifically, the goal is to reconsider temporary overvoltages experienced by the cable within HVDC transmission systems, given various converter configurations, respectively system topologies, i.e. monopole, symmetrical monopole, bipole etc. Furthermore, a method for lightning impulse (LI) level determination in mixed OHL-cable systems based on project specific parameters should be considered. Based on these studies recommendations on testing schemes and levels for HVDC cable systems shall be concluded. Beyond point-to-point, multi-terminal and DC/AC mixed grids could also lead to new types of overvoltage shapes, and should, if possible, be considered by the JWG. However, since this topic might not be relevant in the immediate future, it is considered as optional. The driver for these requests has been the way temporary overvoltages are defined in today's standards and recommendations, where specific test levels are not provided, but left for customer-supplier negotiations. Moreover, the switching impulse (SI) wave shape has been more and more challenged in recent discussions. Instead, impulses on longer timescales have been considered relevant, motivated by changes in converter configurations compared to earlier standardization work.

In this paper the status of the ongoing work is shared. This is done by providing a summary on today's practise as well as drawing some conclusions from the market development by looking on commissioned and to be commissioned projects. A major focus for the work of this JWG are simulation HVDC system tools, as respective data is rare. Therefore, preliminary simulation results are summarized.

TECHNOLOGY STATUS AND TODAYS PRACTICE

Present Practice for Impulse test on HVDC Cables

Nowadays the main reference adopted for testing an HVDC cable system for electrical purpose are the following. Electra 189 (2000) "Recommendations for tests of power transmission dc cables for a rated voltage up to 800kV", and relevant addendum from TF B1-16. The document is a revision of the previous Electra 72 (1980) "Recommendations for tests of power transmission DC cables for rated voltage up to 600kV". Electra 189 applies to cables and accessories, either submarine cables or land cables, and is intended for use in DC power system transmission systems with rated voltages up to 800kV. The recommendations are applicable to paper insulated cables (mass impregnated, oil filled, gas pressure and lapped insulation e.g. PPL) and cover routine tests, type tests and after laying tests. There is no indication regarding the HVDC schemes considered, but taking into account the year of publication, it is assumable that the recommendations are applicable to HVDC system with LCC schemes. The other main reference is TB 496 (2012) "Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV". The document is a revision of the previous TB 219 (2003) "Recommendations for DC extruded cable systems for power transmission at a rated voltage up to 250 kV". TB 496 applies to HVDC extruded cable systems for land or submarine application and includes recommendations for electrical testing of HVDC system for long duration testing (PQ test), type testing, sample testing routine testing, and tests after installation of HV and return cables. The test program proposed in TB 496 follows the same principles as in TB 219 and includes testing programs for VSC and LCC application.

Considering the impulse test, publication Electra 189 includes a test program with switching and lightning impulse superimposed to DC voltage of the opposite polarity. Other overvoltages of short duration and relatively lower amplitude are omitted with reference to results of JWG 33/21/14-16 (1994). A test factor of 1.15 for impulse amplitude (peak value) is suggested with reference to JWG 15/21/33. The following parameters apply for switching impulse wave shapes: a time to crest of 250 μs ± 20% and a time to half value of 2500 μs ± 60%. For lightning Impulse the time to crest is 1÷5 μs and the time to half value: 50 ± 10 μs. Values come from IEC 230 (1966) "Impulse test on cables and their accessories" which is a very old standard and is today under revision. This standard contains conditions and procedure for carrying out impulse tests on cables and their accessories. This standard applies solely to the methods of carrying out the tests as such, independently of the problem of selecting the test levels to be specified. Testing programs proposed in TB 496 are somewhat different between LCC and VSC application. Specifically, for the case or transient overvoltages relevant in this paper, the wave shapes suggested for LCC in Electra 189, are applied in a similar way to VSC, However, additionally switching impulses superimposed to DC voltage U_0 of the same polarity are foreseen and required for VSC application. The required wave shapes for impulse tests suggested in TB 496 are shown in Figure 1. TB 496 does not include technical explanations regarding the typologies of switching impulses to be applied for VSC and LCC scheme; the following note is reported at paragraph 1.5.3. "*[…] Due to the constraints within the DC system design $U_{P2,S}$ does not necessarily equal $U_{P2,O}$, i.e. the same polarity impulse is limited by surge arresters, but the opposite polarity impulse may be limited by the converter".* TB 496 and 219 do not deal with the evaluation or characterization of this overvoltage.

As for lightning impulse TB 496 does not differentiate between VSC and LCC: LI impulses superimposed to DC voltage with opposite polarity must be applied. TB 496 suggests a test factor of 1.15 for impulse peak value (type test), this is based on previous works in light of the good experience gained in the past (explanation in Appendix A of TB 496). TB 496 refers to the same procedure given in Electra 189 for application of superimposed impulse voltage (same wave shapes and number of impulses for each series).

Beside Cigré publications, there is a new standard for HVDC cable testing: IEC 62895 (2017) "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". This International Standard specifies test methods and requirements for transmission power cable systems, cables with extruded insulation and their accessories for fixed land installations, for rated voltages up to and including 320 kV. Requirements for impulse tests follow in general the recommendations of TB496, as for wave shapes, number and type of impulses and test factors.

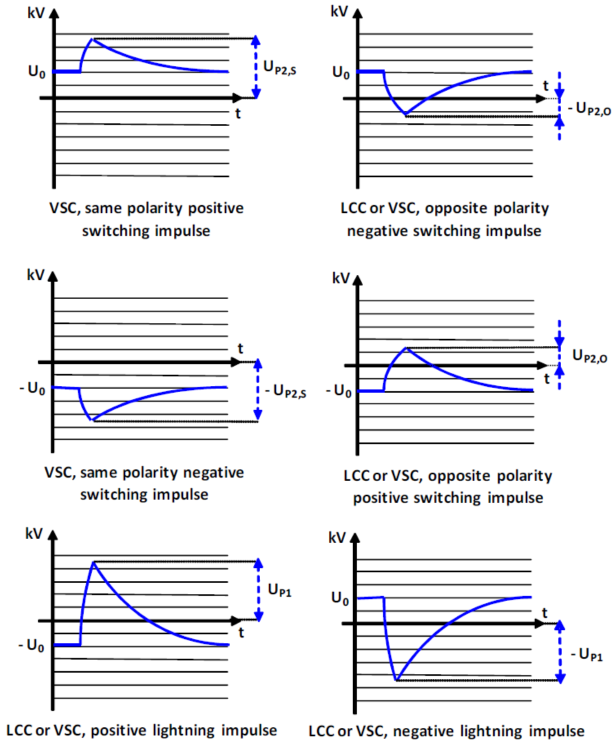

Figure 1: Required wave shapes for impulse tests for VSC and LCC systems suggested in TB 496.

Table 1 summarizes the references for HVDC cable testing; it should be noted that for paper insulated cable intended for HVDC-VSC application there is no specific document.

Table 1: Reference for HVDC cable testing.

	HVDC-LCC	HVDC-VSC
Paper insulated cables	Electra 189	?
Extruded insulated cables	TB496 / IEC62895	TB496 / IEC62895

Apart from the recommendation for testing there is a Cigré document, which deals with overvoltage in HVDC cables: TB No. 86 (1994) "Overvoltage on HVDC cables" (JWG 33/21/14-16). The focus of the JWG 33/21/14-16 was to evaluate the influence of transient overvoltages on DC cable insulation, compare the overvoltages with the DC cable test voltages and investigate the applicability of overvoltage limiting device. The work deals with paper cables (MI and Oil filled) and HVDC-LCC system. Typical topics addressed in TB No. 86 are a collection of data and type test information for DC cables in operation/planning stage, analysis of the insulation capability of DC cables (MI and Oil filled), analysis of internal and external overvoltages occurring on DC cable schemes, means of reduction of overvoltages, determination of typical values for withstanding of lightning overvoltages, internal over-voltages and long duration overvoltages, suggestion for safety margins between protective level and insulation withstand. However, discussion on alternatives for cable tests have not been addressed from JWG 33/21/14-16 but suggested for a future special WG.

Technologies and statistics from projects

In the following, a summary deduced from collection of HVDC projects in operation and tendering phase is given. Preliminary priorities for the work in the JWG are defined based on the analysis on existing HDVC projects.

About 100 HVDC cable systems are in operation or planned worldwide. The first modern HVDC transmission systems were installed in the 1950s. These systems are based on LCC technology (Line-Commutated Converter). Working on the principle of bridge rectifiers, early LCC converters used mercury arc valves. A significant technical advance was made in the 1970s with the introduction of thyristor valves. At the beginning of the 21st century, VSC technology (Voltage-Source Converter) was introduced, thanks to the development of higher rated valves, such as IGBTs (Insulated-Gate Bipolar Transistors). MMC converters (Modular Multilevel Converters) then appeared as the most cost effective VSC converter concept, as these topologies practically eliminate filtering needs. Today, the number of VSC systems has almost reached the number of LCC systems, and the amount of cumulated kilometers of cables connected to VSC systems will soon reach parity to LCC systems (cf. figure 2).

HVDC cables are mostly used for submarine applications, but they are also used for land applications. The two main technologies available today are mass impregnated (MI) cables and extruded cables mostly with XLPE as the main insulating material. In *mass impregnated cables* conductors are insulated by paper layers, which are impregnated with a high viscosity fluid. MI cables have proven to be highly reliable in service and are qualified up to 500 kV. Recent developments introduced 600 kV cables and potentially higher using Polypropylene Laminated Paper (PPLP) insulation. MI cables are today widely used in LCC systems as they are less sensitive to polarity reversal than polymeric cables. Polymeric *Extruded cables* nowadays are mainly XLPE based. The development of VSC converters, which allows to reverse the power flow without polarity reversal, encouraged the use of polymeric cables. XLPE cables have been into service at voltages up to 320 kV with a project also being awarded at 400kV. Although service experience is still limited, the rated voltage of extruded cables in service is expected to increase in near future up to 525 kV, whereby potentially higher voltages might be available. Figure 3 shows the length of installed (and to be installed) cumulative cable lengths related to insulation technology. Recent development suggests that there is no clear separation of converter technologies and cable insulation technologies. It is envisaged that a considerable part of VSC links will be operated with MI cables. This is visualized in Figure 4, which summarizes the amount of cable in kilometers, installed or to be installed in near future, related to converter technology in combination with cable insulation technology. As a conclusion, if one considers MI-LCC as historical basis, VSC-XLPE is the major technology at the moment from the HVDC transmission systems. However, there is also a considerable amount of cable lengths in MI-VSC systems to be considered in near future.

From the system perspective, there are basically three converter station topologies: asymmetric monopole, symmetric monopole, and bipolar configurations. In Figure 4 their evolution in power with time is shown, indicating also the amount of realizations in time. The *Asymmetric mono-*

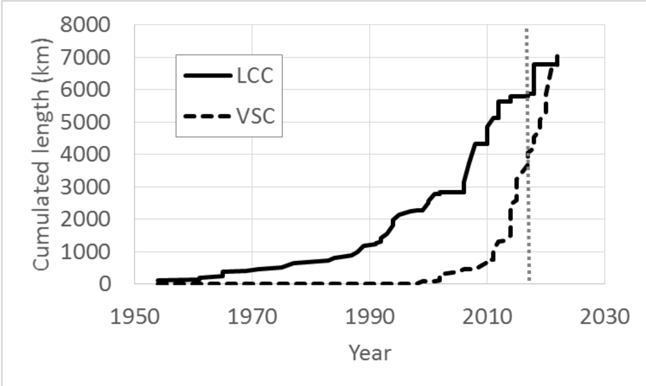

Figure 2: Cumulated length of HVDC cables world wide relating to converter technology. Numbers beyond 2017 include also tendering phase project, which might change in the future.

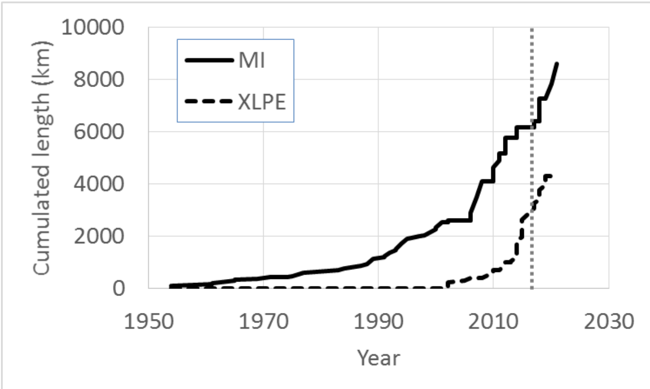

Figure 3: Cumulated length of HVDC cables relating to insulation technology. Numbers beyond 2017 include also tendering phase project, which might change in the future.

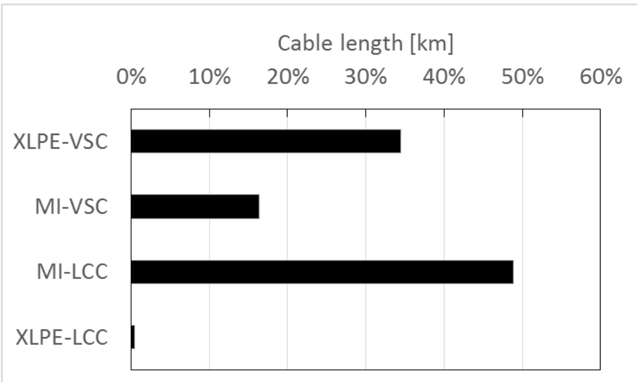

Figure 4: Cumulated length of HVDC cables relating to converter technology. Numbers beyond 2017 on a tendering phase are included, but add uncertainty to this figure

pole configuration requires only one HV cable. The current returns through a neutral cable (rated for the load current but only lightly insulated) or through the ground. Asymmetrical monopoles represent roughly 30% of the links, but they are not considered as the preferred choice for future links. In Figure 4 this is reflected by very little project realized and planned in the recent years. For the *symmetric monopole* configuration two HV cables are required. Compared to an asymmetric monopole, no DC stress is imposed on the converter transformer. Symmetric monopoles are uncommon for LCC systems, but have found wide acceptance for VSC systems. They represent more than 50% of all links. The *bipolar* configuration can be seen as two asymmetric monopoles connected in series on the DC side and in parallel on the AC side. The benefit of a bipole is that the loss of any major element leads only to the loss of half of the transmission capacity. Bi-poles are used when high power is sought, cf. Figure 5. They represent about 20% of the links.

Based on those considerations and the assumption that MI-LCC systems are the historic basis on which todays standards are based the JWG has decided on prioritizing VSC systems with XLPE an MI cable technology in symmetric monopole configurations for intermediate power levels and todays 320 kV voltage level. For the highest power however the focus will be shifted towards bipolar configurations.

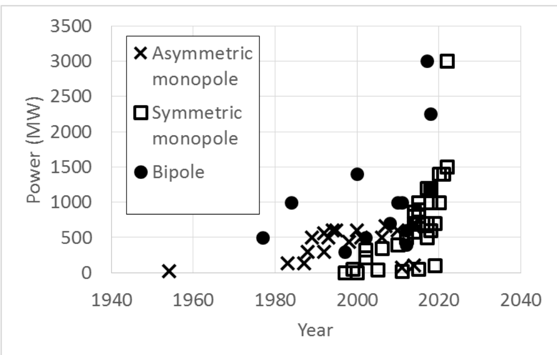

Figure 5: Evolution of the power for the different system configurations.

SIMULATIVE EVALUATION APPROACH

In this section a first glimpse of our work is shown by representing first calculation results on overvoltage type that differs considerably from those described in the summarized past standardization activities in a 320 kV symmetric monopole configuration.

As of today, the highest share of high voltage DC projects is realized in symmetrical monopolar configuration utilizing state-of-the-art modular multilevel converter topologies (MMC-HVDC). Simulations presented within this chapter highlight results to obtain characteristic overvoltage shapes and verify these in different EMT software tools. Finally, selected parametric sensitivities supplement initial investigations.

System Parameters and Modelling

Following the framework provided by previous working groups [1] an exemplary MMC-HVDC point-to-point connection based on half-bridge technology has been determined, see Table 2. The transmission corridor has a length of 300 km, is realized with an extruded dc cable, and is modeled using a frequency dependent model. The pre-fault power flow at the point of common-coupling of MMC 1 is +1 *GW* ac in-feed and +300 *MVAR*. The control strategy considers an active/reactive power flow control on MMC-1 and a DC voltage/reactive power control on MMC-2. Control system details are reported in [1].

Table 2: Half-bridge MMC-HVDC system specification

Description	Parameter	Value
Rated power	P^r	$1\ GW$
Nominal DC voltage (pole-to-ground)	V_{dc}^r	$\pm 320\ kV$
Nominal AC voltages (converter-/grid-side)	v_{ac}^r	$330\ kV$, $400\ kV$
AC short circuit level	SCL	45 GVA
Line frequency	f	$50\ Hz$
Number of submodules per arm	N_{SM}	320
Arm sum capacitor voltage (each arm)	$\sum v_{C,i}$	$640\ kV$
Arm inductance	L_{arm}	$70\ mH$
Average submodule voltage	$v_{C,i,avg}$	$2\ kV$
Submodul capacitor size	C_{SM}	$8.1\ mF$
Converter control sample time	t_s	$50\ \mu s$
Protection system delay	t_p	manually triggered
Protection level surge arrester	V_p	$1.7\ pu$ @ $3\ kA$

Impact of Simulation Environment

In order to obtain typical overvoltage levels of MMC-HVDC a large number of time domain simulations needs to be carried out considering related system layout and relevant fault locations. Besides these project specific parameters, the impact of state-of-the-art commercially used EMTP-software on obtained overvoltage levels needs to be addressed and quantified first. A comparison of occurring transients subsequent to common faults is performed using two exemplary EMTP-programs, namely EMTP-RV [2] and PSCAD/EMTDC [3]. Therefore, the first task is to validate and benchmark both models used for this working group. A symmetrical monopolar MMC-HVDC link is set up in both EMT-programs, considering identical system parameters, as stated in Table 2 and Figure 6. The implemented half-bridge submodule stacks are classified as a *Type 4* model according to [3] in the PSCAD/EMTDC and EMT-program.

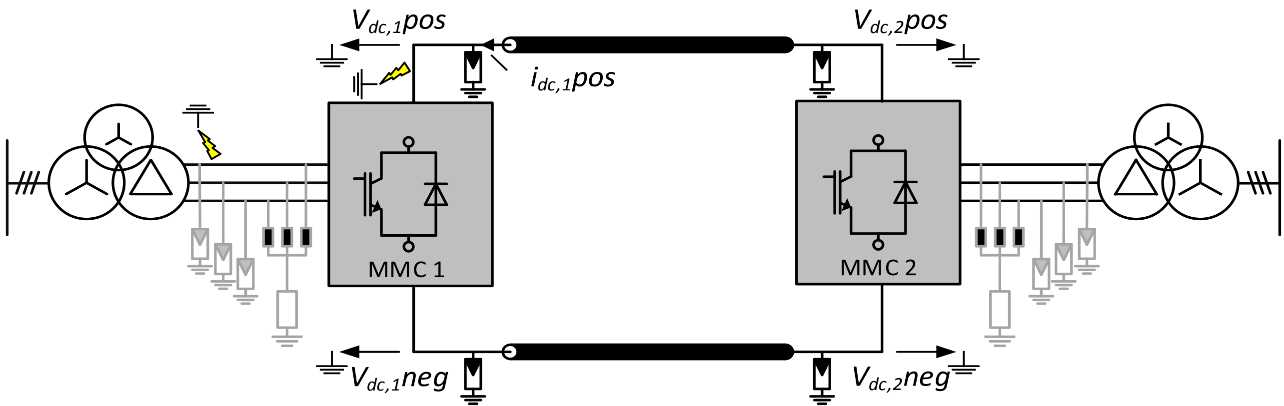

Figure 6: Schematic overview of investigated monopolar MMC-HVDC link including relevant quantities as well as fault positions.

A first benchmark between the two EMT-programs is performed for a positive pole to ground fault at MMC 1 (Figure 6). The obtained transients are depicted in Figure 7. Apparently, there are some minor differences in the voltage curve, whereby the absolute peak value of the pole to ground voltage at the healthy (negative) pole as well as the rise time of the voltage are close (Figure 7(b) and (d)). The pole to ground voltage at the faulted pole shows a damped oscillation due to reflections and negative pole discharge, see Figure 7 (c). Investigations have shown that the differences in the obtained voltage oscillations at the faulted pole are mainly due to different damping properties of the underlying cable representation in EMTP and PSCAD. Nevertheless, differences in modelling of ideal branches, e.g. very low impedance faults, as well as representation of power electronic devices in both EMT-tools can also have impact on these discrepancies.

A second benchmark is given in Figure 8 for a phase to ground fault at the transformer of MMC 1 (converter side). The pole to ground voltage at the dc side shows the typical characteristic due to the converter operating as a diode rectifier after submodule blocking. Again, it can be observed that almost similar system behaviour in both EMT-programs does occur.

Even though slight differences exist between the results obtained using EMTP-RV and PSCAD/EMTDC models, the general system behaviour and overvoltage levels are in a good agreement. Therefore, it is concluded to consider the achieved accuracy as sufficient and to proceed with a detailed parametric sensitivity study to deal with varying converter design parameters as well as different transmission system configurations.

Parametric Sensitivity

To address the impact of project specific parameters such as cable length and ac short circuit level on overvoltage shapes, a brief parametric sensitivity study is shown within this section.

First, the cable length is varied between 200 km and 50 km. Presented results within this section are performed using EMTP-RV. However similar results are expected with the PSCAD/EMTDC model. The system behaviour after a phase to ground fault at the converter transformer (Figure 6) and after a pole to ground fault at the DC side of MMC1, this time on the negative pole, including two different cable lengths, are depicted in Figure 9. The red curves are for a HVDC system with a cable length of 200 km while the blue dotted curves are with a cable length of 50 km. It can be seen in Figure 9(a), that for the phase to ground fault at the converter transformer, the rise time of positive pole to ground voltage, as well as the voltage level after current interruption through ac circuit breaker, is of major difference for the different cable lengths. Similar variation can be also observed for a negative pole to ground fault, see Figure 9(b) and (c).

As another example in a parameter sensitivity analysis, the short-circuit level (SCL) of the AC network has been varied. Overvoltage results for both faults of Figure 6, i.e. one phase to ground fault on the converter transformer and one pole to ground faults, negative pole, with the variation of the SCL are depicted in Figure 10. For this specific test case, it can be noticed in Figure 10(a) that for a one-phase-to-ground fault at the converter transformer the varying SCL has an impact on the overvoltage shape. However, for the negative pole to ground fault, Figure 10(b), the impact of the SCL variation on the occurring overvoltage (on the healthy pole) is minor.

It should be noted that these results are based on the generic HVDC-MMC model of the working groups [1]. Therefore, depending on the circuit configuration, the wave shape of these over voltages can differ and it remains the task of the JWG to agree on the most severe type relevant for the cable performance.

SUMMARY AND OUTLOOK

In this paper we presented a status summary of ongoing work in Cigré JWG B4/B1/C4.73. We summarized the todays practice and elaborated on the limited guidance of today's testing recommendations for temporary overvoltages of HVDC cable systems. By evaluating data based on installed and to be installed projects we prioritized VSC systems with XLPE and MI cable technology in symmetric monopole configurations for intermediate power levels up to todays 320 kV voltage level. For the highest power however the focus is shifted towards bipolar topologies. Moreover we compared simulation tools to be used as a fundamental part for reaching conclusions in the JWG. A demonstration of a temporary overvoltage on the 320 kV on symmetric mono-

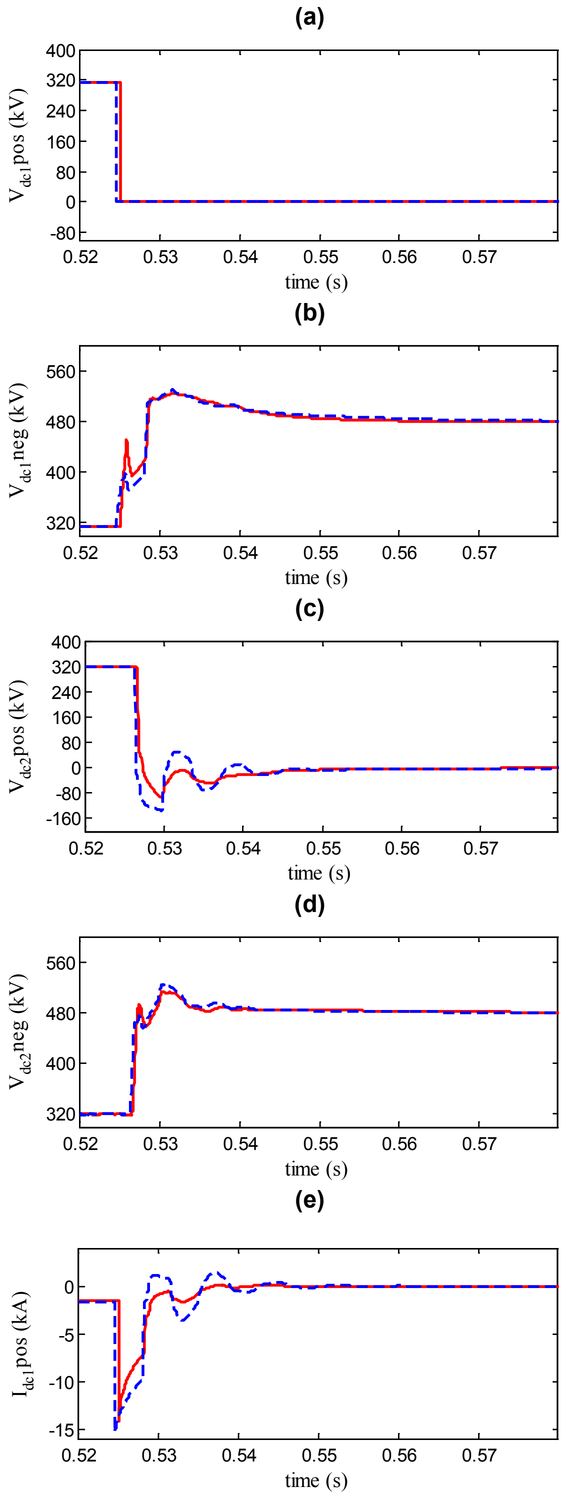

Figure 7: Selected transients subsequent to a positive pole to ground fault at MMC 1 obtained using EMTDC (blue) and EMTP (red) software.

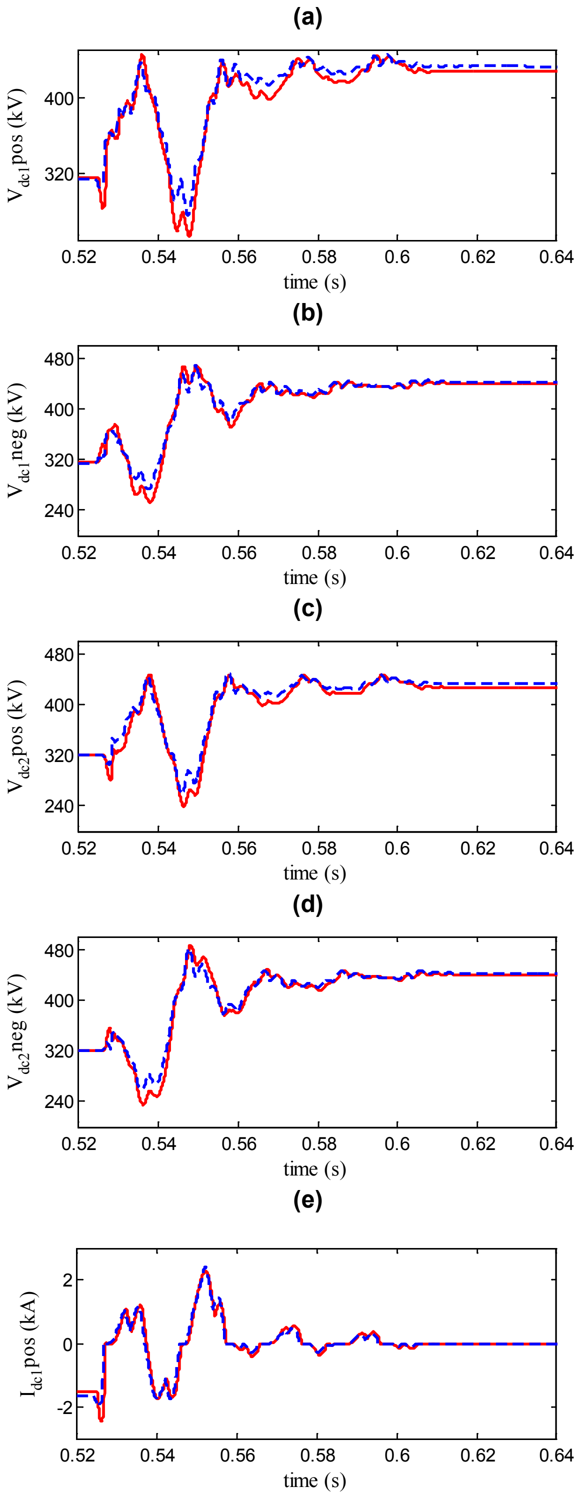

Figure 8: Selected transients subsequent to a phase a to ground fault at the converter transformer of MMC 1 obtained using EMTDC (blue) and EMTP (red) software.

Close and Return

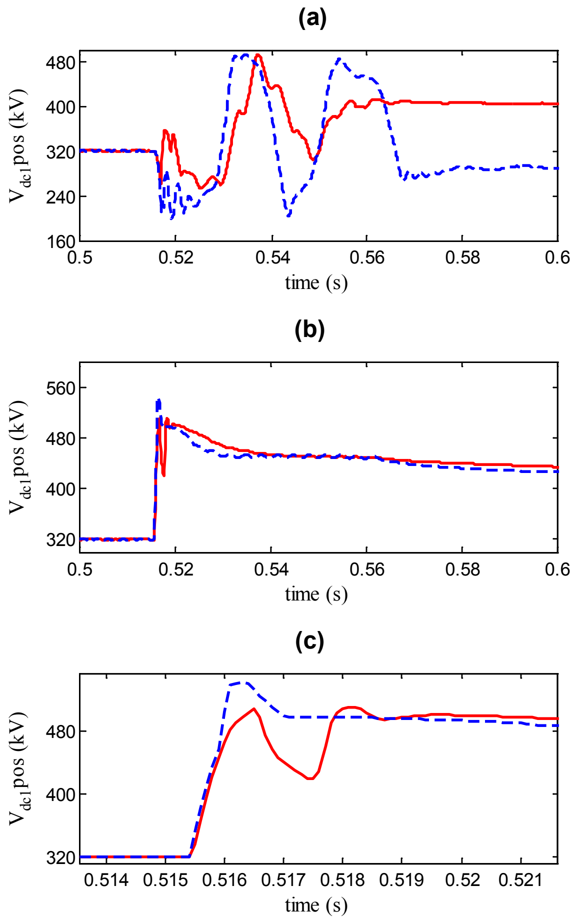

Figure 9: Sensitivity with respect to two cable lengths (red=200 km, blue=50 km) in EMTP on voltage transients subsequent to: (a) phase a to ground fault at the converter transformer of MMC 1, (b) negative pole to ground fault at MMC 1, (c) Zoomed waveform of negative pole to ground fault at MMC 1

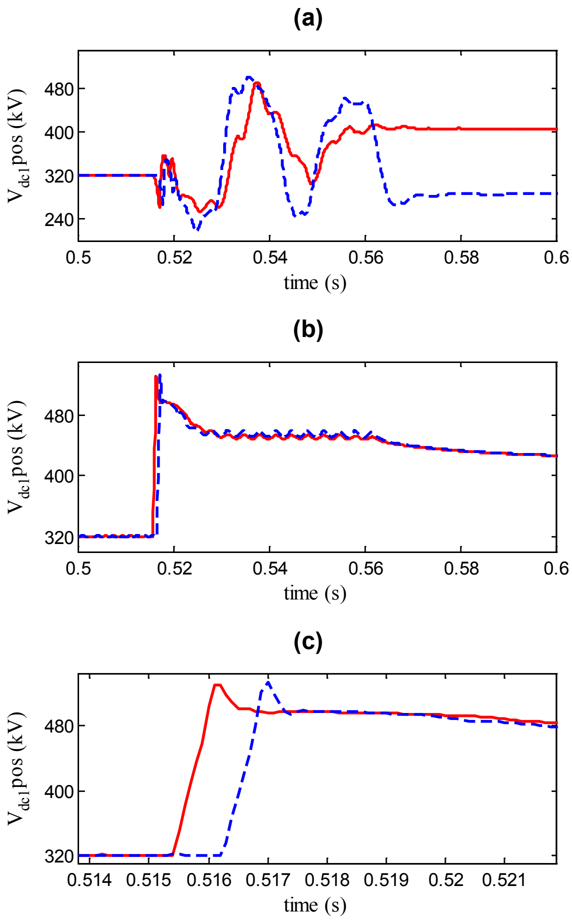

Figure 10: Sensitivity with respect to two AC short circuit levely, red=3 GVA, and blue= 50 GVA, on the overvoltage transients subsequent to: (a) phase to ground fault at the converter transformer of MMC 1, (b) negative pole to ground fault at MMC 1, (c) zoomed waveform of pole to ground fault at MMC 1

pole configuration was presented and parameter evaluation was exemplified. No conclusions on worst case scenarios or severity on temporary overvoltages are to be made yet as these are ongoing discussions in the JWG. The further objective of the JWG should then go beyond the simulative evaluation approach and also give a guidance whether extended testing of HVDC cable systems is recommended, i.e. the response of the cables insulation system should also be considered. Based on necessity and if possible first direction of testing schemes shall be mentioned.

Moreover, it is a task of the JWG to evaluate mixed OHL-cable systems and recommend an approach for determining LI testing levels based on project specific paramters.

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