Overvoltage Characteristics in Symmetrical Monopole HB MMC-HVDC Configuration comprising Long Cable Systems

M. Goertz, S. Wenig, C. Hirsching, K. M. Schäfer, S. Beckler, J. Reisbeck, M. Kahl, M. Suriyah, T. Leibfried

Abstract—**This contribution focuses on high voltage direct current (HVDC) transmission systems comprising modular multilevel converters (MMC) equipped with half-bridge (HB) submodules and analyses cable stresses during various station internal as well as dc side faults. In order to examine relevant overvoltage characteristics affecting HVDC cable systems, a systematic approach to evaluate overvoltage stresses is presented and an extensive set of time-domain simulations has been carried out. Obtained results are relevant for considerations on insulation co-ordination of HVDC cable systems.**

Keywords—**Extruded dc cable system, half-bridge, HVDC, insulation co-ordination, OHL-cable mixed system.**

I. Introduction

THE number of installed HVDC projects in symmetrical monopole (SMP) configuration based on HB MMC technology is emerging at a fast pace [1]. In line with the gathered project and operational experiences, several articles have covered the aspects of overvoltage stresses in SMP configuration caused by station internal or dc side faults. The general system behaviour under dc side faults is discussed in [2]. Studies concerning insulation co-ordination of converter stations or focusing on cable overvoltages are conducted in [3] and [4]–[6], respectively. With regard to offshore projects [7] gives an insight into the gained experience and presents measuring results of a fault recorder during a cable fault. Moreover, recent research focuses on the laboratory imitation of the occurring overvoltage shape during dc side faults in SMP configuration [8], [9]. However, since standardized test levels for HVDC cable systems with extruded insulation are not yet available [10], [11], preliminary insulation co-ordination studies are still of essential importance to provide a reliable cable system design. This contribution analyses overvoltages affecting the cable system in case of very long land cable systems and gives an indication of the impact of systems comprising mixed overhead lines (OHL) and cable sections. The scope of this research is motivated by the designated embedded interconnectors in Germany.

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II. System Description and Modelling

A schematic of the considered SMP configuration is depicted in Fig. 1 and underlying equipment design is stated in Tab. I. Converter equipment as well as cable terminations are protected by surge arresters (SA). The non-linear voltage-current characteristic of the SAs is approximated by piecewise linear resistances. Converter arm inductances are located on the dc side. Investigated transmission system configurations are shown in Fig. 2. In order to evaluate the impact of very long land cable systems, two different transmission system configurations comprising either 200 km or 700 km onshore cable with extruded insulation are investigated. Then, results are extended to an OHL-cable mixed system with a total length of 700 km. Along the cable system, a solid cable shield grounding is assumed every 5 km taking into account a grounding resistance of $R_{\mathrm{SJ}} = 5\Omega$ and $R_{\mathrm{S}} = 0.1\Omega$ at joints and cable terminations, respectively. Cable and OHL sections are modelled by frequency-dependent line models in accordance with the theory given in [12]. The submodule stacks of the MMCs are represented through a *Type 4* detailed equivalent circuit model according to [13]. Time-domain simulations are carried out using PSCAD/EMTDC. An adequate solution time step of 5μs is considered.

A. Control and Protection

Station 1 operates in an active/reactive power control mode, station 2 acts as a dc voltage/reactive power controlled station. The protection system of each converter station consists

TABLE I
Selected Parameters of Symmetrical Monopole Configuration

Parameter	Value
rated power P_{r}	1 GW
nominal dc voltage (pole-to-ground) U_0	± 320 kV
nominal ac voltage (valve-/ grid side)	330 kV / 400 kV
line frequency f	50 Hz
short circuit level ac grid	45 GVA
X/R ratio ac grid	10
transformer configuration	wye-delta
number of submodules per arm N	256
average arm sum voltage	640 kV
average submodule voltage	2.5 kV
submodule capacitor C_{S}	8.5 mF
arm inductance L_{arm}	50 mH
clearing time ac circuit breakers T_{C}	80 ms
switching impulse protective level of arresters	1.7 p.u. @ 3 kA

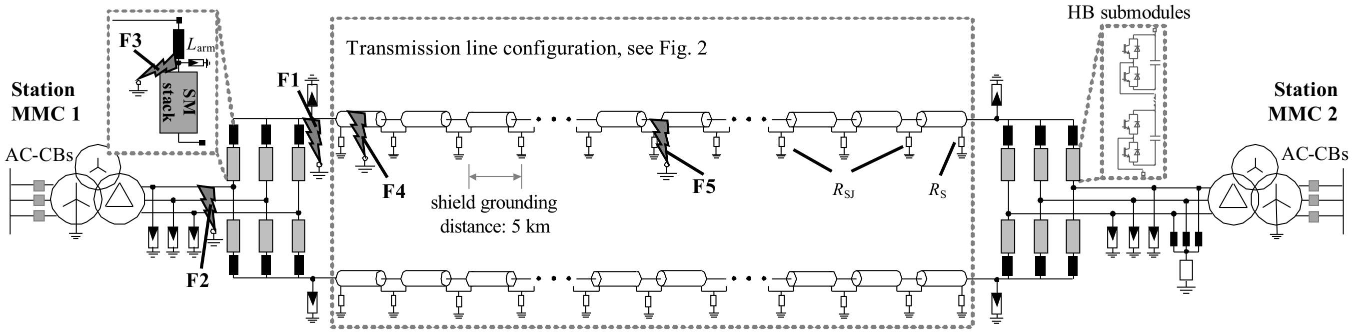

Fig. 1. Schematic of symmetrical monopole configuration.

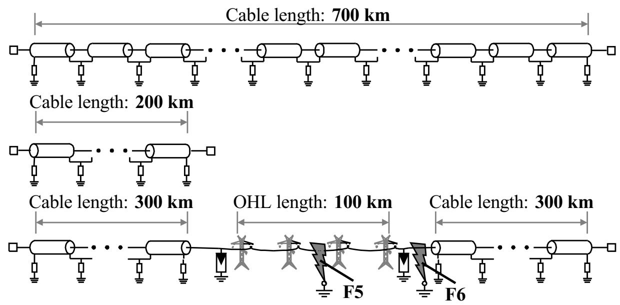

Fig. 2. Single pole diagram of investigated transmission system configurations: 700 km cable, 200 km cable and 700 km OHL-cable mixed system.

of valve overcurrent, submodule under-/overvoltage loops as well as a dc pole-to-ground voltage imbalance criterion. The protection loops comprise artificial delays in order to address delays due to data acquisition and processing. After protection tripping, all IGBTs of the affected converter are blocked and an opening order is sent to the ac circuit breakers (AC-CBs). Protection thresholds and controller parameters are held constant for all investigated transmission system configurations.

B. Parametric Study Framework

With regard to voltage stresses affecting the cable system, a broad range of station internal as well as dc line faults are considered, as stated in Tab. II. In order to ensure that overvoltages are derived in consideration of worst-case conditions, different pre-fault converter operation modes and various fault instants are taken into account.

III. Systematic Approach to Evaluate Overvoltages

In order to assess occurring voltage stresses affecting the cable system, a systematic approach for calculating overvoltage parameter is developed. First, a parametric study is performed by means of EMT-software. Then, obtained data are evaluated during post-processing by numerical computing software. Along the cable system, voltage measuring points are placed in equidistant sections with a length of 5 percent of total transmission length. For each run of the parametric study all voltage measuring points along the cable are taken into consideration for post-processing. This measure allows to

TABLE II
Parametric Study Framework

	Description	Configuration
1.	power set point at station 1	a) $+P_{\mathrm{r}}$ (ac in-feed), $+Q_{\mathrm{r}}$ (cap.) b) $-P_{\mathrm{r}}$ (ac export), $+Q_{\mathrm{r}}$ (cap.) c) 0GW (zero load), $+Q_{\mathrm{r}}$ (cap.)
2.	fault type	F1: positive dc pole-to-ground fault at cable termination F2: phase a-to-ground fault at transformer valve-side F3: positive arm $p1$-to-ground fault F4: positive dc cable core-to-screen-to-ground fault at 1km distance from station 1 F5: positive dc cable core-to-screen-to-ground fault at 50% of transmission length F6: positive dc pole-to-ground fault at OHL-cable transition station (mixed line)
3.	fault resistance	0.1Ω, 10Ω
4.	fault synchronisation	a) zero crossing of phase a-to-ground voltage at transformer valve-side b) zero crossing of ac current in phase a at transformer valve-side
5.	fault instant	a) $\omega \cdot t = 0°$, b) $\omega \cdot t = 45°$ c) $\omega \cdot t = 90°$, d) $\omega \cdot t = 225°$ e) $\omega \cdot t = 270°$ after zero crossing

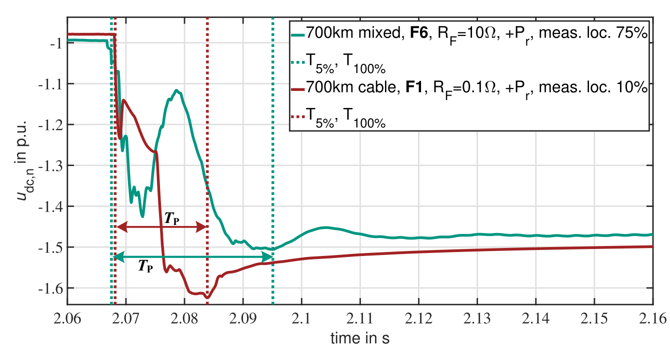

Fig. 3. Determination of time-to-peak value.

characterise the voltage shape at each point along the cable. Besides the absolute maximum overvoltage levels at each measuring point, time-to-peak values and maximum voltage gradients are calculated. Here, the time-to-peak value T_{P} is

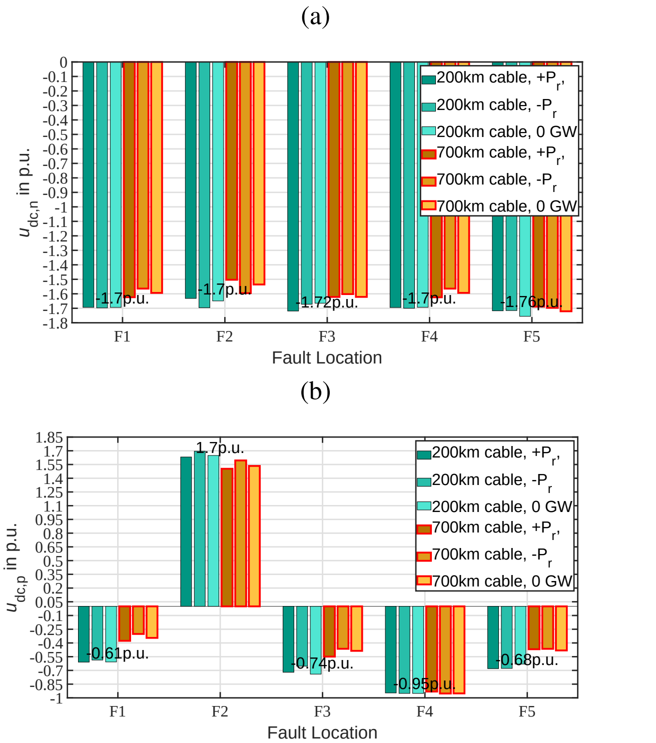

Fig. 4. Absolute maximum overvoltages or polarity reversals along the cable system as a function of fault type F1 - F5, power set point and cable length: (a) voltage stresses along negative dc pole, (b) voltage stresses along positive dc pole.

defined as the time interval between $\pm 5\%$ of rated dc voltage U_0 and the point in time of absolute maximum overvoltage. It is important to mention that this definition is not in line with the time to crest defined in [14] for impulse voltage test. The front of the overvoltage might consist of superimposed voltage oscillations or travelling wave phenomena, as exemplified in Fig. 3. This issue has to be kept in mind when evaluating time-to-peak values. During the time-to-peak, absolute maximum voltage gradients are determined. In order to avoid that numerical oscillations might distort the obtained gradient, an average voltage gradient along five solution time steps is calculated.

IV. Impact of very Long Cable Systems

Within this section, results of the 200 km as well as 700 km cable system are presented and the impact of long cable systems on voltage stresses affecting the cable system is discussed. Obtained results are classified in overvoltages with same polarity as dc operating voltage and overvoltages with opposite polarity to dc operating voltage. An overvoltage with opposite polarity to dc operating voltage might occur at the faulted dc pole during the cable discharge process.

A. Absolute Maximum Overvoltage Levels

For each run of the parametric study absolute maximum voltage levels of all voltage measuring points along the cable are determined during post-processing. Then, absolute maximum voltage levels of all runs of the parametric study related to the same fault type and the same power set point are identified. Results are depicted in Fig. 4 (a)-(b) in per unit (p. u.) of rated dc voltage U_0. All investigated dc side faults (F1, F3, F4, F5) are located along the positive dc pole. Hence, a polarity reversal and an overvoltage with same polarity as operating voltage can be observed at the positive and negative dc pole, respectively. For both cable lengths, absolute maximum overvoltage levels occur during a cable fault at 50% cable length (F5) at zero load operation (0 GW). Absolute maximum overvoltage levels are 1.76 p. u. and 1.72 p. u. for 200 km cable length and 700 km cable length, respectively. Occurring overvoltage levels reach higher values in the 200 km system than in the 700 km system for all investigated fault types.

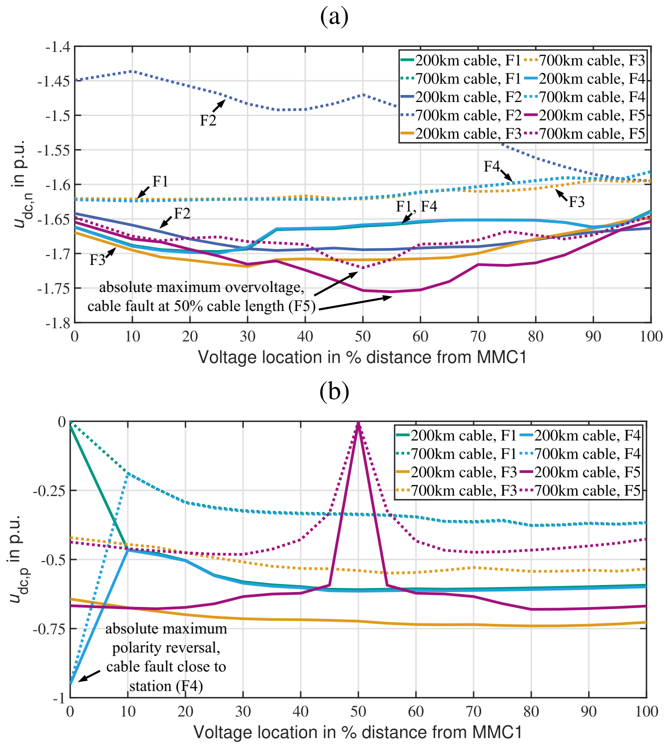

Fig. 5. Worst case voltage profiles along the cable system as a function of fault type F1 - F5 and cable length: (a) negative dc pole, (b) positive dc pole.

B. Voltage Profiles along the Cable System

A worst-case voltage profile along the cable for each fault type is shown in Fig. 5 (a)-(b). Within this study, a worst-case is defined as absolute maximum overvoltage or polarity reversal at each voltage measuring point along the cable for all simulation runs related to the same fault type. Hence, a voltage profile of the same fault type might consist of different simulation runs. As can be seen, highest overvoltage levels occur in the middle of the cable of the healthy dc pole during F5. This finding is also achieved in [5]. At the faulted cable, the absolute maximum polarity reversal can be observed subsequent to a cable fault in the vicinity of the converter station (F4). The absolute maximum polarity reversal occurs at the cable termination adjacent to the faulted cable section. The occurring polarity reversal is below 1 p. u. and is independent of total cable system length. As shown in [4], [15], the voltage reversal at the faulted cable is caused by the intrinsic discharge process of the cable through the fault impedance. As converters have only limited impact on the cable discharge and thus on occurring polarity reversal, the following sections focus on the overvoltage along the cable of the healthy dc pole.

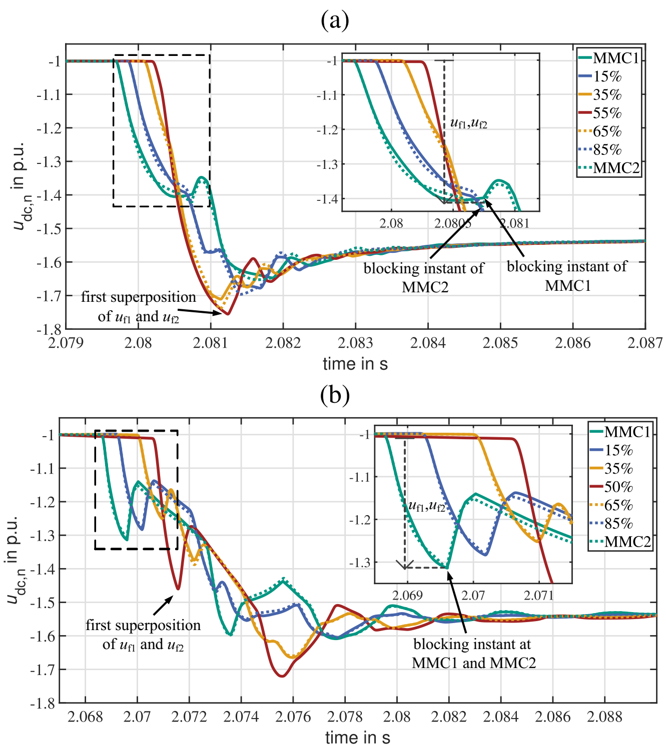

Fig. 6. Overvoltage build-up along the dc cable of the negative pole during a cable fault at the positive pole (F5): (a) cable length 200 km, (b) cable length 700 km.

C. Overvoltage Build-up during Cable Fault F5

This section describes the voltage build-up along the cable during the worst-case fault F5. Figure 6 presents the cable core-to-ground voltage $u_{\mathrm{dc,n}}$ at different voltage measuring points along the cable for both considered system lengths during the worst-case run of F5. As can be seen in the zoomed part of Fig. 6 (b), both converters block their IGBTs at the same time instant (green curve). For the 200 km system, blocking instants of both converters are slightly different. At the instant of IGBT blocking $t_{\mathrm{b}y}$, the voltage $u_{\mathrm{dc,n}}$ at the respective converter station $y \in \{1, 2\}$ consists of an impulse voltage $u_{\mathrm{f}y}$ superimposed on dc operating voltage, as depicted in Fig. 6. The impulse voltages u_{f1} and u_{f2} represent forward travelling waves that propagate from both converter stations into the cable. In case both converters block at the same time instant, a first superposition of u_{f1} and u_{f2} occurs in the middle of the cable. Otherwise, the location of the first superposition might deviate from the middle of the cable. Thus, the voltage at the point of superposition x_0 can be written as the sum of both travelling waves superimposed on dc operating voltage:

$$u(x_0, t) = U_0 + u_{\mathrm{f1}} \cdot e^{-\alpha \cdot l_1} + u_{\mathrm{f2}} \cdot e^{-\alpha \cdot l_2}. \qquad (1)$$

The exponential parts in (1) describe the attenuation of the travelling wave along the cable distance l_y. For simplicity, dispersion effects are neglected. The attenuation constant α is frequency-dependent and is $\alpha(10\mathrm{Hz} \ldots 1\mathrm{kHz}) \approx 0.36 \times 10^{-3} \frac{1}{\mathrm{km}} \ldots 1.6 \times 10^{-3} \frac{1}{\mathrm{km}}$ for the considered cable design. Applying (1), the superposition of both travelling waves can be estimated based on the assumption that α is constant. In the 200 km system, the absolute maximum overvoltage along the cable is caused by the first superposition of u_{f1} and u_{f2}. In the 700 km system, the superposition of u_{f1} and u_{f2} leads to a peak during the front of the overvoltage, but not to the absolute peak voltage, see Fig. 6 (b). This is due to following reasons: *i)* for very long cable systems the cable self attenuation effect mitigates the impulse voltages propagating along the cable, *ii)* the initial impulse voltage at the converter stations $u_{\mathrm{f}y}$ as well as the voltage gradient prior to blocking decreases for very long cable sections. However, it should be kept in mind that system behaviour is affected by considered protections thresholds and blocking delays as well as converter control prior to blocking.

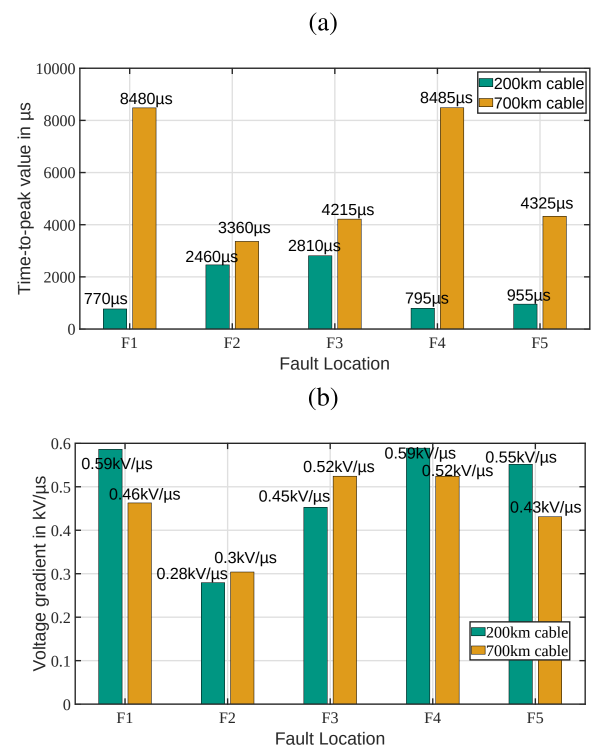

Fig. 7. Impact of cable length on overvoltage characteristics: (a) fastest time-to-peak values, (b) absolute maximum voltage gradients.

D. Overvoltage Characteristics

Fastest time-to-peak values and absolute maximum voltage gradients of all voltage measuring points along the cable of the healthy pole under consideration of all runs are depicted in Figure 7 (a)-(b). In the 200 km system, fastest time-to-peak values T_{P} are in the range of $700\mu s$ and occur during a fault at the cable termination (F1). In the 700 km system, fastest time-to-peak values are in the range of several milliseconds. Moreover, voltage gradients during the front of the overvoltage take on smaller values with increasing cable length. Figure 8 shows a distribution of all calculated time-to-peak values. For long cable systems, a wider range of time-to-peak values exists. It should be noted that a phase-to-ground fault at

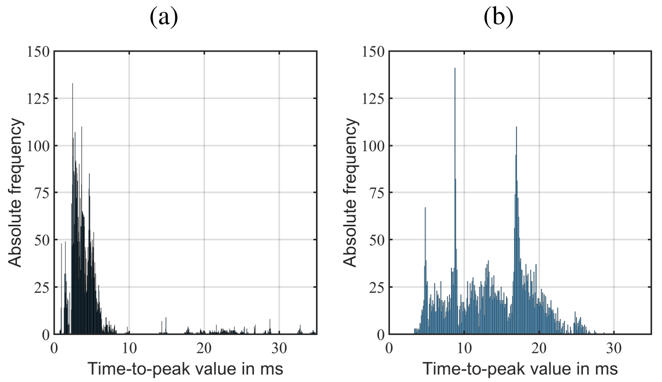

Fig. 8. Histogram of all occurring time-to-peak values: (a) cable length 200 km, (b) cable length 700 km.

transformer valve-side (F2) might evoke an overvoltage on the dc side where the peak value is reached only after several half-cycles of ac voltage. Therefore, certain T_P values are between 20 ms to 30 ms for both system lengths.

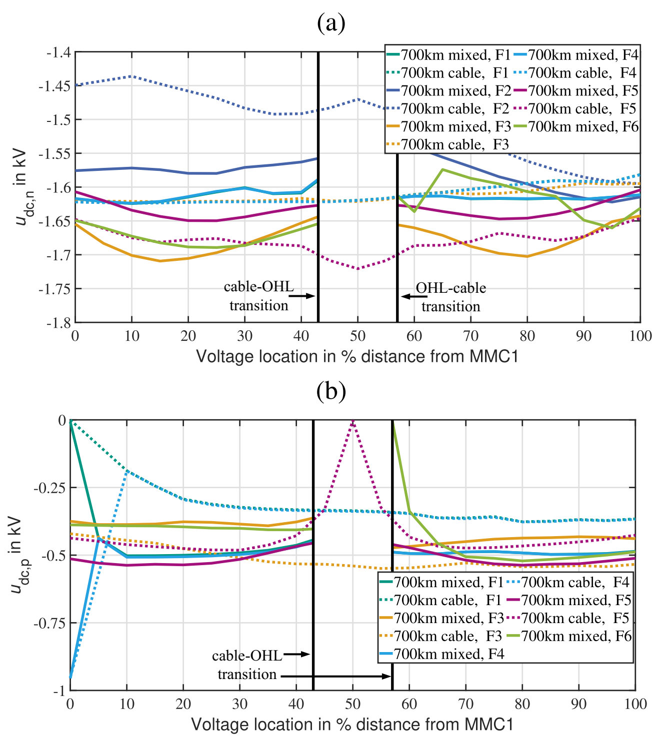

Fig. 9. Worst case voltage profiles along the cable system as a function of fault type F1 - F6 and transmission line configuration. Considered system length 700 km: (a) negative dc pole, (b) positive dc pole.

V. Impact of OHL-cable mixed systems

This section focuses on a transmission length of 700 km and extends results to mixed transmission systems. As introduced in Fig. 2, the mixed system comprises a 100 km OHL section embedded between two cable sections, each with a length of 300 km. The mixed system is compared to the 700 km system comprising solely cable sections. The worst-case voltage profiles under consideration of all investigated fault types are depicted in Fig. 9. As can be seen in Fig. 9 (a), absolute maximum overvoltages along the cable of the healthy pole reach similar levels in both systems. However, the voltage profiles in the mixed system show a strong location dependency along the cable. This is due to the fact that the embedded OHL represents a discontinuity in surge impedance at the cable transition stations. Hence, the OHL-cable transitions lead to additional travelling wave reflections. Fastest time-to-peak values and absolute maximum voltage gradients of the cable overvoltage at the healthy pole are shown in Fig. 10. The mixed system shows faster time-to-peak values and significant steeper voltage gradients than the system comprising solely cable sections. Especially, faults at the OHL-cable transition station (F6) lead to shortest front times and steepest voltage gradients of all investigated fault types.

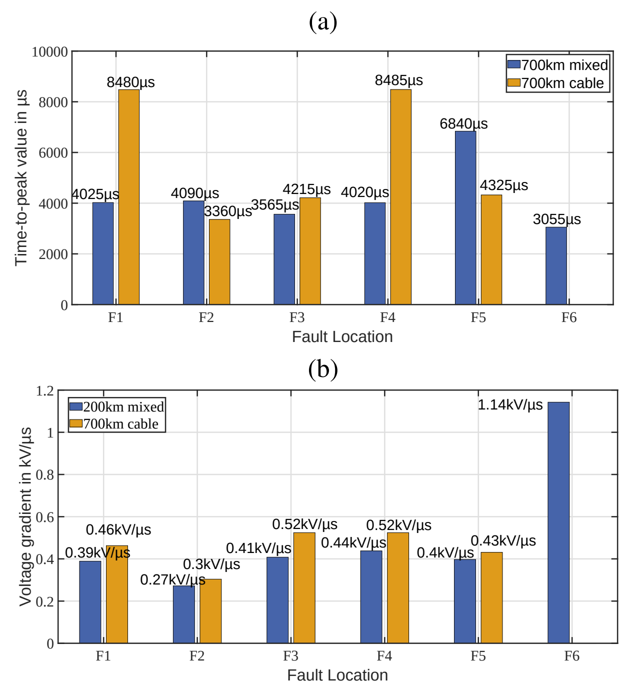

Fig. 10. Impact of transmission line configuration on overvoltage characteristics. Considered system length 700 km: (a) fastest time-to-peak values, (b) absolute maximum voltage gradients.

VI. Characteristic Voltage Shapes

The voltage curves at the location of absolute maximum overvoltage during a fault at 50% system length (F5) and a phase-to-ground fault at transformer valve-side (F2) are shown in Fig. 11. For F5, differences exist between the considered transmission system configurations during the overvoltage front. The voltage shape during F5 consists of a voltage increase up to a peak value followed by a temporary overvoltage (TOV) at a decreased level. The TOV level depends on considered SA characteristic and is approximately 1.5 p. u. for all investigated systems. The TOV persists until the cable is discharged through intrinsic shunt or stray impedances to ground or auxiliary earthing breakers are applied, see [4] for further explanation. During F2, voltage oscillations can be observed at the cable system until AC-CBs have cleared the fault. The amplitude of the voltage oscillation increases with decreasing cable length as well as for mixed systems.

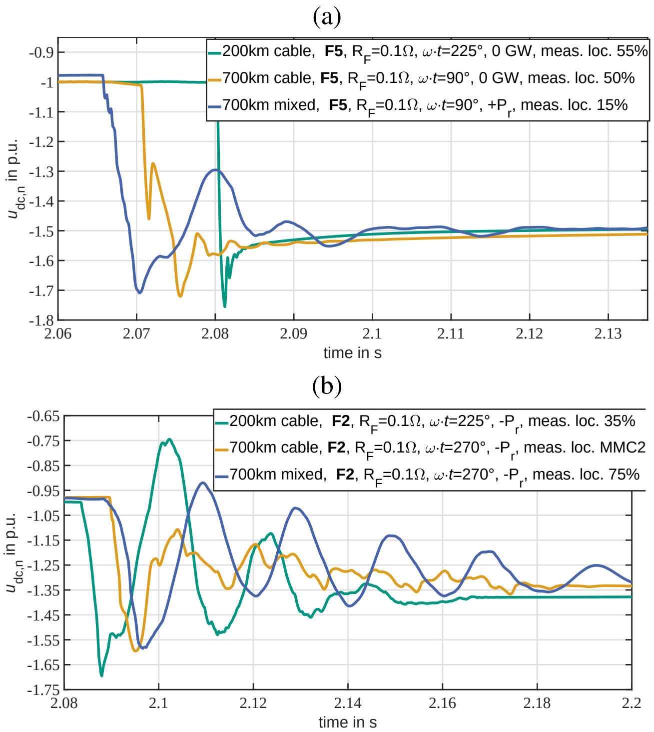

Fig. 11. Worst case voltage curves at the location of absolute maximum overvoltage: (a) fault at 50% transmission length (F5), (b) phase-to-ground fault at transformer valve-side (F2).

VII. Conclusion

In order to assess relevant overvoltage characteristics affecting HVDC cable systems in SMP configuration based on HB MMC technology, a detailed parametric study has been carried out and a systematic approach to evaluate overvoltages is presented within this paper. The following list provides an overview of the main findings:

- A decrease of absolute maximum overvoltage level can be observed for very long cable system lengths. This statement is proven only for the considered cable system lengths of 200 km and 700 km.
- An increasing cable system length leads to slower time-to-peak values and lower voltage gradients.
- Time-to-peak values have to be evaluated carefully as the overvoltage front might consist of superimposed voltage oscillations.
- In the considered systems, fastest time-to-peak values and absolute maximum overvoltage levels occur not at the same measuring location. Therefore, a combination of fastest time-to-peak value and highest overvoltage level for testing purposes might result in unrealistic cable stresses.
- In mixed OHL-cable systems, faster time-to-peak values and significant steeper voltages gradients occur compared to systems comprising solely cable sections. For the considered systems absolute maximum overvoltage levels are similar.
- The authors expect that short cable sections embedded between OHL segments might lead to multiple superpositions of travelling waves for certain fault locations and result in severe overvoltages. Therefore, overvoltage stresses affecting the cable system in OHL-cable mixed systems are difficult to predict as system behaviour depends on projects specific parameters.

For the sake of completeness, it should be mentioned that further project specific parameters such as converter station design or the transformer vector group might impact on overvoltages [3], [7]. Future research is required in order to examine if the analysed parameters such as overvoltage level, front time and voltage gradient might be critical stresses for the cable insulation. It is worth mentioning that besides the investigated overvoltage characteristics, other parameters such as duration of TOV appear relevant for cable system design. However, results provided within this paper represent a profound starting point for further work on insulation-coordination of HVDC cable systems. Therefore, obtained results are of importance with regard to upcoming projects in symmetrical monopole HB MMC-HVDC configuration.

References

[1] M. Saltzer et. al., "Surge and extended overvoltages testing of HVDC cable systems," *Int. Conf. on Insulated Power Cables (Jicable'17)*, Dunkerque, France, Nov. 2017.

[2] F. B. Ajaei and R. Iravani, "Cable Surge Arrester Operation Due to Transient Overvoltages Under DC-Side Faults in the MMC-HVDC Link," *IEEE Trans. Power Del.*, vol. 31, no. 3, pp. 1213–1222, June 2016.

[3] H. Saad, P. Rault, S. Dennetière, "Study on Transient overvoltages in the Converter Station of HVDC-MMC links," *Int. Conf. on Power System Transients (IPST'17)*, no. IPST17-185, Seoul, Republic of Korea, June 2017.

[4] S. Dennetière, H. Saad, A. Naud, P. Honda, "Transients on DC cables connected to VSC converters," *Int. Conf. on Insulated Power Cables (Jicable'15)*, Versailles, France, June 2015.

[5] S. Mukherjee, M. Saltzer, Y.- J. Häfner, S. Nyberg, "Cable Overvoltages for MMC based VSC HVDC Systems: Interactions with Converters," *Int. Colloquium on H.V. Insulated Cables, CIGRE Study Committee B1*, New Delhi, India, Oct. 2017.

[6] M. Goertz et. al., "Analysis of Overvoltage Levels in the Rigid Bipolar MMC-HVDC Configuration," *15th IET Int. Conf. on AC and DC Power Trans. (ACDC 2018)*, Coventry, UK, Feb. 2019.

[7] M. Greve, M. Koochack Zadeh, T. Rendel, A. Menze, "Behaviour of the HVDC links with MMC technology during DC cable faults," *CIGRE Winnipeg 2017 Colloquium, Study Committees A3, B4 & D1*, Winnipeg, Canada, Sept. 2017.

[8] C. Freye, S. Wenig, M. Goertz, T. Leibfried, F. Jenau, "Transient Voltage Stresses in MMC-HVDC links - Impulse Analysis and Novel Proposals for Synthetic Laboratory Generation," *IET High Voltage*, vol. 3, no. 2, pp. 115–125, June 2018.

[9] T. Karmokar, M. Saltzer, S. Nyberg, S. Mukherjee, P. Lundberg, "Evaluation of 320 kV extruded DC cable system for temporary overvoltages by testing with very long impulse waveforms," *CIGRE General Meeting*, Paris, France, Aug. 2018.

[10] "Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500 kV," *CIGRE Tech. Rep. 496 (WG B1.31)*, 2012.

[11] "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," *IEC 62895:2017*.

[12] A. Morched, B. Gustavsen and M. Tartibi, "A universal model for accurate calculation of electromagnetic transients on overhead lines and underground cables," *IEEE Trans. Power Del.*, vol. 14, no. 3, pp. 1032–1038, July 1999.

[13] "Guide for the development of models for HVDC converters in a HVDC grid," *CIGRE Tech. Rep. 604 (WG B4.57)*, 2014.

[14] "High-voltage test techniques - Part 1: General definitions and test requirements," *IEC 60060-1:2010*.

[15] M. Goertz, S. Wenig, S. Suriyah, and T. Leibfried, "Determination of transient overvoltages in a bipolar MMC-HVDC link with metallic return," *Proc. Power Sys. Computation Conf.*, Dublin, Ireland, June 2018.