Lightning Overvoltages in a HVDC Transmission System comprising Mixed Overhead-Cable Lines

M. Goertz, S. Wenig, S. Gorges, M. Kahl, S. Beckler, J. Christian, M. Suriyah, T. Leibfried

***Abstract*—This paper analyses the lightning behaviour of a high-voltage direct current (HVDC) transmission link comprising overhead line (OHL) and cable sections. Maximum lightning overvoltages due to shielding failures and backflashovers are calculated along the cable and are evaluated for different OHL to cable ratios. Moreover, this paper introduces and distinguishes between different cable sheath grounding conditions feasible for HVDC applications. Detailed models consisting of frequency dependent line models, multiconductor tower models and a leader progression model are presented. Time-domain simulations have been carried out using PSCAD EMTDC.**

***Keywords*—backflashover, cable-OHL mixed line, extruded cables, HVDC, lightning overvoltages, shielding failure;**

I. Introduction

TRIGGERED by energy transition towards sustainability, the German network development plan specifies the use of high-voltage direct current (HVDC) transmission corridors to increase transmission capacity between the northern part of Germany, which is rich in wind power, and to the major centers of consumption in the south of the country. Due to poor public acceptance for overhead line (OHL) expansions, the federal government of Germany has specified a general underground cable priority for HVDC projects. Nonetheless, OHL sections may be the preferred choice for forested areas or when soil protection is of high importance. This leads to a transmission system, which may consists of short OHL sections embedded between long cable sections. In such systems the cable is indirectly exposed to lightning strokes. The lightning surge initiated by a lightning incidence in the OHL-part propagates towards the cable and is reflected at the cable-OHL transition. In systems comprising short sections, multiple reflections and superpositions can occur in a short period of time and cause severe overvoltages.

The lightning behaviour of mixed OHL-cable lines for HVAC has already been elaborated by other authors [1]–[3]. For HVDC transmission systems lightning incidences have to be evaluated with regard to impulse voltage level and polarity reversal of the cable system. Relevant test recommendations for extruded dc cables do not specify voltage levels for lightning impulse withstand tests related to the rated system voltage [4]. Instead, [4] recommends to perform lightning impulse tests with an impulse voltage of 1.15 times the maximum absolute peak value of the lightning impulse voltage, which the cable can experience, but only if the cable is exposed to lightning strikes. However, lightning overvoltages in HVDC systems consisting of mixed OHL-cable sections are dependent on project specific parameters such as OHL tower configuration and tower grounding conditions, as shown in [5].

The paper investigates transient system response to a lightning stroke into a +/- 525 kV bipolar HVDC transmission system with metallic return. Direct lightning strokes to conductor as well as backflashovers are considered. The scope of the study is to determine transient overvoltages in a bipolar HVDC transmission link for different cable to overhead line ratios. Furthermore, the impact of cable sheath grounding conditions is discussed. Simulations are carried out in PSCAD EMTDC.

II. System description

The HVDC transmission system consists of two pole conductors with a rated voltage of +/- 525 kV and a third conductor (metallic return) with a rated voltage of 90 kV that is used in asymmetric operation of the transmission system to avoid permanent earth currents. The power transmission capability of the single point grounded bipolar link is 1 GW per pole.

A. Cable Line

The dc cable is composed of a copper conductor with a cross-section of 3000 mm^2, inner semi-conductive layer, main insulation made of XLPE dc polymer, outer semi conductive layer, metallic screen and outer sheath. A major issue of dc cable system design is bonding and grounding of the system [6]. The bonding and grounding strategy of the cable system has to be designed depending on the occurring transient overvoltages in the system. An improper insulation coordination strategy may lead to a failure of cable main insulation or may cause sheath damage during transient overvoltages. In the considered scenario, the cable shield is solidly grounded every 2.5 km. Pole conductors and metallic return are buried at a depth of 1.5 m with a conductor spacing of 0.4 m.

B. Overhead Line

The OHL sections are designed with lattice suspension towers and line spans of 400 m. The investigated tower design, depicted in Fig. 2, consists of three conductors and two ground wires. The height of the two horizontally arranged pole conductors is 34 m, the metallic return is located 25 m above the ground. Both pole conductors and metallic return

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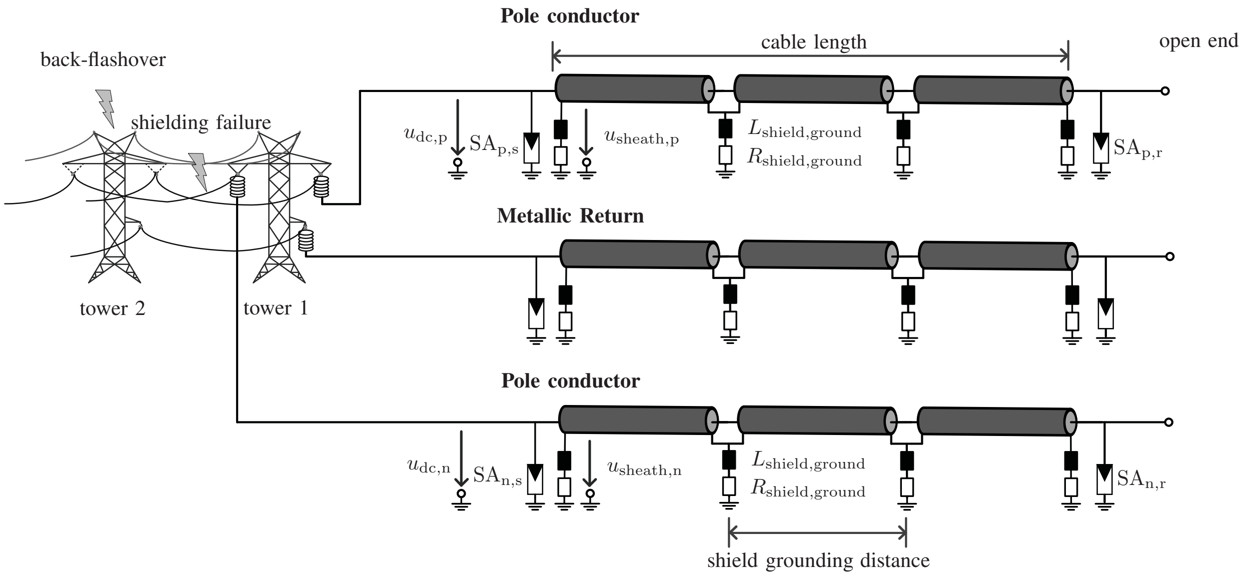

Fig. 1. Cable-OHL scenario

are equipped with a quad bundle of ACSR conductors and V-insulator strings. The line insulators of the metallic return are designed with the same insulation level as the pole conductors. Flashover distances of approximately 6.5 m are chosen for all line insulators.

C. Lightning Performance

Overvoltages caused by lightning incidences can be classified as overvoltages caused by backflashovers and overvoltages due to shielding failures. Overvoltages due to backflashovers (BFO) can occur when the lightning stroke hits the shield wire or the tower top and the magnitude of the lightning stroke current is high enough to cause a tower-to-conductor flashover. In case of BFO's, the dc pole operating voltage of the opposite polarity as the lightning stroke is superimposed with the lightning surge voltage. In the investigated 525-kV-system BFO's occur only for considerably high lightning crest currents and improper tower grounding conditions.

Overvoltages due to shielding failures (SFO) occur when the lightning stroke bypasses the shield wire and hits directly the dc pole conductor. As the lightning current increases, the protection effect of the shield wires improves and thus the probability of shielding failure decreases.

Direct lightning strokes can hit the dc pole with the same polarity as the lightning current. This leads to a constructive superposition of the dc pole operating voltage and the imposed lightning surge voltage which may cause severe overvoltages even for low lightning stroke current magnitudes. Direct lightning strokes onto the dc pole conductor with the opposite polarity as the lightning current lead to a destructive superposition of the dc operating voltage and the imposed lightning surge voltage. This may yield to a polarity reversal for high lightning currents.

The shielding effectiveness of the ground wires is evaluated on the basis of an electrogeometrical model of the investigated line. The critical magnitude of lightning stroke current where a SFO can still occur, is in the range of 7 - 31 kA depending on different parameters used to calculate the striking distance, as stated in [7]–[9]. For further investigations, the striking distances are calculated using the parameters according to [10], which leads to a maximum shielding failure current of around 20 kA. For this lightning current amplitude no insulator flashover occurs.

III. System Modeling

The investigated mixed OHL-cable transmission link is depicted in Fig. 1. A dc cable with an open end is series-connected to an OHL section. The reflection coefficient at the open end is $\Gamma = 1$. This corresponds to a worst case estimation of common reflection coefficients at cable to OHL transitions, which lay in the range of 0.8 to 0.9 for the investigated transmission link. To avoid reflections from the left end of the OHL section, the OHL length is chosen so that the propagation time along the OHL section exceeds the considered time interval after the lightning stroke. The cable is protected by surge arresters (SA) at both ends. The protective level of all arresters is 1.8 pu at 1 kA arrester current ($8/20\ \mu s$). The protective characteristic of the dc pole surge arresters is stated in the Appendix. The voltage-current characteristic of the SA is modelled through a peace-wise linear resistance. Additional inductances due to connection leads have been included ($5\ \mu H$). The model considers the first five towers of the OHL from the left side of the cable entrance. For SFO analysis, the point of incidence of the lightning stroke is between tower 1 and tower 2, see Fig. 1. For BFO analysis the lightning stroke hits tower 2.

A. Tower Model

The towers are modelled through a multiconductor vertical line model, as shown in Fig. 2. Equivalent surge impedances $Z_{T,n}, n \in (1, 2, 3)$ of the multiconductor system are calculated based on [11]. The calculated surge impedances listed from top to bottom are: $Z_{T,n} = 123\ \Omega, 118\ \Omega, 90\ \Omega$. Each equivalent conductor is implemented as a lossless transmission line

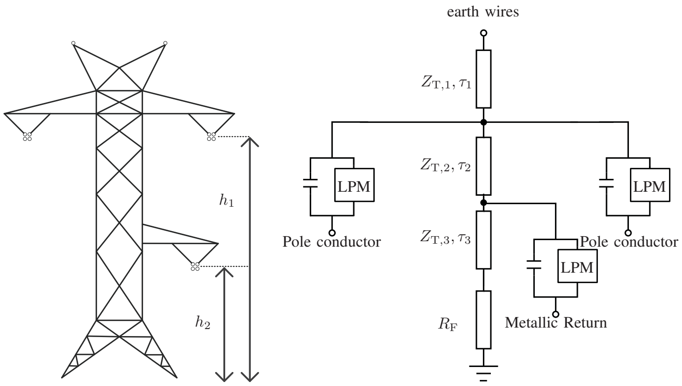

Fig. 2. Tower model

characterised by its surge impedance and its corresponding length using the Bergeron model. The tower footing resistance R_F was conservatively chosen as constant $R_\mathrm{F} = 65\,\Omega$. Due to the neglection of soil ionisation as well as the high footing resistance, the tower grounding condition represents a worst-case scenario. Line insulator flashover is calculated by a leader progression model (LPM), as presented in [12].

B. Transmission Lines

An accurate representation of OHL and cable line is achieved using the frequency dependent phase model [13]. Attenuation of the lightning surge impulse propagating along the OHL due to corona losses is neglected.

Cable sheath grounding has been simulated as lumped R-L elements, as depicted in Fig. 1. The sheath grounding inductance $L_\mathrm{shield,ground} = 5\,\mu\mathrm{H}$ and resistance $R_\mathrm{shield,ground} = 10\,\Omega$ is held constant for all simulations.

C. Lightning Stroke

The concave surge waveform compliant with CIGRE is used [14]. The corresponding lightning stroke parameter are stated in Tab. I. For SFO as well as BFO a lightning current impulse of negative polarity is performed.

IV. Case Study Results

A. Determination of Maximum Overvoltages along the Cable

At any position x along the cable the voltage $u(x,t)$ can be written as the sum of a forward u_f and a backward u_b travelling wave, as depicted in Fig. 3. Due to the discharge current through the SA located at the receiving end, resulting from an impinging lightning surge, the maxima of the forward propagating wave $u_\mathrm{f}(x=0,t)$ and the backward propagating wave $u_\mathrm{b}(x = 0,t)$ do not occur simultaneously at the receiving end of the cable. In case of negligible discharge currents through the SA at the open end, the ratio between backward and forward travelling wave at the receiving end $u_\mathrm{b}(x=0,t)/u_\mathrm{f}(x=0,t)$ corresponds to one and thus the maximum overvoltage along the cable occurs at the receiving end. With increasing discharge current through the SA, the ratio between backward and forward travelling wave at the receiving end decreases. This phenomenon is shown in Fig. 4 for a cable length of 2 km and a lightning surge caused by BFO. Since the maxima of $u_\mathrm{f}(x=0,t)$ and of $u_\mathrm{b}(x=0,t)$ do not appear simultaneously at the receiving end, the corresponding voltage at the receiving end $u(x = 0,t)$ is less than the sum of both maxima. The overall maximum voltage along the cable can therefore be found in distance $x = l$ from the receiving end. The locations of maximum overvoltages along the cable are calculated based on the approach described in [15]. Assuming a constant characteristic impedance of the cable, forward and backward propagating waves at the receiving end can be determined from the arrester current $i_\mathrm{SAp,r}$ and the pole-to-ground voltage $u(x = 0,t)$. Voltage measurements are placed in the vicinity of the calculated location of the maximum voltage to validate the results.

TABLE I
Lightning Stroke Parameter for Backflashover (BFO) and Shielding Failure (SFO) Analysis

	Peak current amplitude [kA]	Polarity –	Steepness [kA/µs]	Wavefront time [µs]	Wavetail time [µs]
BFO	150	neg.	65	8	200
SFO	20	neg.	48	2.5	77.5

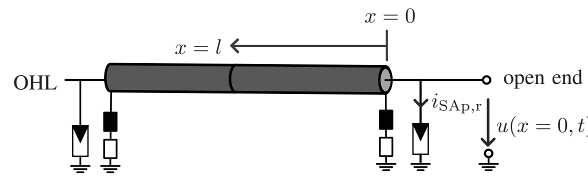

Fig. 3. Determination of maximum voltage along the cable

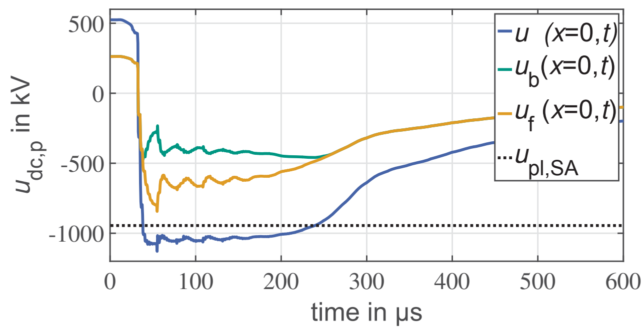

Fig. 4. Pole-to-ground voltage $u(x=0,t)$, calculated forward $u_\mathrm{f}(x=0,t)$ and backward $u_\mathrm{b}(x=0,t)$ propagating wave at the receiving end. Cable length: 2 km, overvoltage caused by BFO. Protective level of surge arrester: $u_\mathrm{pl,SA}$.

B. Influence of Cable Length

The case study is performed for three different cable lengths l_C of 50 km, 15 km and 2 km. The peak value of the pole-to-ground voltage at the cable entrance (sending end) and the peak voltage at the cable open end (receiving end) as well as the absolute peak voltage along the cable are stated in Table II. The pole-to-ground voltages at the locations of the absolute maximum voltage along the cable are shown in Fig. 5.

1) Backflashover (BFO): The BFO occurs between the stricken tower and the dc pole conductor with opposite polarity as the lightning current. This results in a polarity reversal at the cable system. Even for the long cable length of 50 km the BFO leads to a polarity reversal of 2.34 p.u. of the rated voltage of the cable system. Maximum voltage along the cable increases when cable length decreases (Tab. II). For the short cable length of 2 km, the maximum voltage along the cable differs by up to 300 kV compared to the maxima at sending respective receiving end. It should be kept in mind, that the BFO analysis was performed for extremely rare lightning impulse currents (150 kA) and worse-case tower grounding conditions. When considering a typical tower earthing, BFO is likely to be fully avoided in the investigated 525-kV-system.

2) Shielding Failure on Positive Pole (SFO): Direct lightning strokes onto the pole conductor with the opposite polarity as the lightning current lead to a destructive superposition of dc operating voltage and the imposed lightning surge voltage. This destructive superposition leads to a small polarity reversal of 0.28 p.u. of the rated voltage for the long cable length of 50 km, see Fig. 5b. Due to the long propagation time of the travelling wave along the cable compared to the tail time of the lightning impulse, superposition of reflections occurring at the cable ends appear after the lightning impulse has subsided. For the cable length of 50 km and 15 km, the pole-to-ground voltages at the cable ends are below the arrester protective level. Thus the maximum voltage along the cable is located at the cable end ($x = 0$ m). Decreasing cable length and thus decreasing propagation time along the cable leads to a superposition of multiple reflections within a short period of time. This can be seen especially for the cable length of 2 km in Fig. 5b. For short cable lengths, the occurring polarity reversal of the cable system resulting from a direct lightning stroke to the pole conductor with opposite polarity as the lightning stroke is comparable with the system behaviour resulting from a BFO.

3) Shielding Failure on Negative Pole (SFO): A direct lightning stroke onto the negative dc pole conductor causes a constructive superposition of the negative dc operating voltage and the negative lightning surge voltage, see Fig. 5c. The impact of the cable length on the maximum voltage along the cable is considerable small (e.g. -1021 kV @ 50 km, -1127 @ 2km). With decreasing cable length the absorbed energy of the SAs rises strongly (Tab. III). This effect is mainly due to the reflections that occur in a smaller period of time for shorter cable lengths.

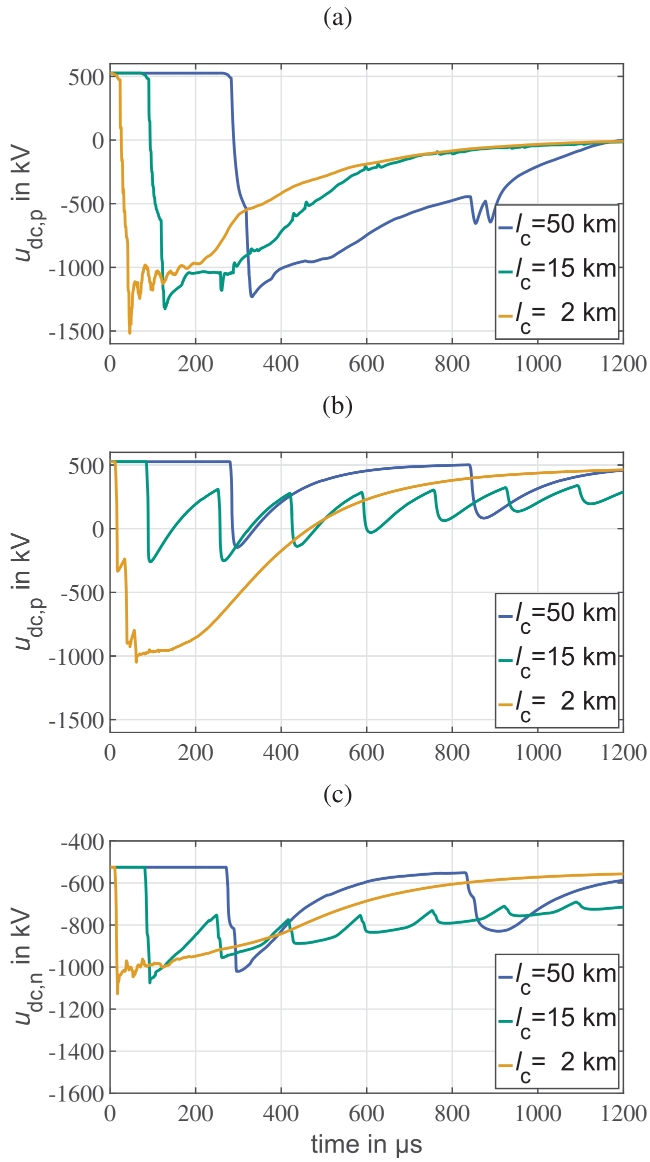

Fig. 5. Variation of cable length, maximum pole-to-ground voltages along the cable due to: (a) backflashover, (b) shielding failure on positive pole, (c) shielding failure on negative pole.

C. Influence of Shield Grounding Conditions

A lightning incidence in the OHL sections causes a lightning surge propagating along the cable sheath. This phenomenon occurs due to the electromagnetic coupling between cable

TABLE II
POLE-TO-GROUND VOLTAGES AT SENDING AND RECEIVING END AND ABSOLUTE PEAK VOLTAGE ALONG CABLE

	BFO				SFO pos. pole				SFO neg. pole			
Cable length [km]	Send [kV]	Abs. Max [kV]	Rec [kV]	Loc. Max [m]	Send [kV]	Abs. Max [kV]	Rec [kV]	Loc. Max [m]	Send [kV]	Abs. Max [kV]	Rec [kV]	Loc. Max [m]
50 km	-947	-1231	-1061	3123	-58	-146	-146	0	-1003	-1021	-995	1608
15 km	-1083	-1326	-1092	2618	-244	-260	-260	0	-1003	-1075	-1016	643
2 km	-1205	-1518	-1129	1516	-1008	-1050	-1012	46	-1085	-1127	-1060	184

core and sheath and due to the the cable screen grounding conditions at the cable entrance. Injected currents in the metallic screen of the cable during a lightning stroke in the vicinity of the cable entrance lead to an increase in sheath-to-ground voltage. The maxima of sheath-to-ground voltages $u_{\mathrm{sheath,p}}$ respective $u_{\mathrm{sheath,n}}$ at the sending end during the investigated lightning incidences are summarized in Tab. IV. The initial peak of the sheath-to-ground voltage is mainly caused by the assumed sheath grounding conditions $L_{\mathrm{shield,ground}}$, $R_{\mathrm{shield,ground}}$ and is independent of cable length. Maximum sheath-to-ground voltages occur during BFO, because the injected current in the metallic screen is maximal during a lightning stroke to a nearby tower. It is import to highlight, that the stated sheath-to-ground voltages are measured at the sheath grounding point in the immediate vicinity of the OHL-cable transition, see Fig. 1. It should be emphasised, that the modelling of sheath grounding and therefore also the evaluation of the sheath-to-ground voltages merits more detailed investigations.

In this paragraph the influence of cable shield grounding distance on sheath overvoltages is discussed for a constant cable length of 50 km. The cable shield grounding distance $l_{\mathrm{s-g}}$ is varied in the range of 1 km, 2.5 km and 5 km. The corresponding sheath-to-ground voltages at the cable entrance are depicted in Fig. 6. It can be seen, that the maxima of cable sheath-to-ground voltage are independent of the shield grounding distance. However, the wavetail time of the lightning overvoltage propagating along the sheath decreases with decreasing shield grounding distance.

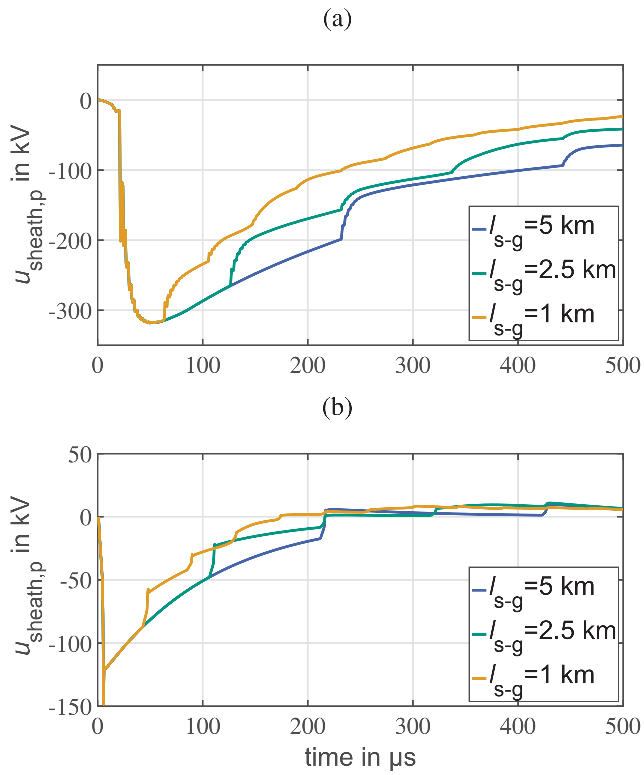

Fig. 6. Variation of shield grounding distance, sheath-to-ground voltages at cable entrance (cable length: 50 km) during different contingencies: (a) backflashover, (b) shielding failure on positive pole.

V. Conclusion

This paper investigates lightning overvoltages in a bipolar HVDC transmission link. The lightning behaviour of a mixed cable-OHL line is outlined for different lightning incidences such as direct lightning strokes to conductor as well as back-flashovers. The impact of cable length on occurring lightning overvoltages along the extruded dc cable is discussed based on the results of a detailed electromagnetic transient program simulation model. The severity of lightning overvoltages is evaluated with regard to impulse voltage level as well as polarity reversal of the cable system. The considered extruded dc cable is protected by SAs at both cable ends. Maximum overvoltages along the cable are determined. A BFO leads to a polarity reversal of 2.34 respective 2.89 p.u. of the rated system voltage depending on cable length. The BFO analysis was performed at worse-case tower grounding conditions. Therefore it should be pointed out, that the risk of BFO is extremely rare in the considered 525-kV-system.

Critical magnitudes of lightning stroke current, where a

TABLE IV
Cable Sheath-to-Ground Voltages at the Sending End

	BFO	**SFO pos. pole**	**SFO neg. pole**
Cable length	Send	Send	Send
[km]	[kV]	[kV]	[kV]
50 km	-318	-149	-116
15 km	-318	-149	-116
2 km	-302	-149	-116

TABLE III
Surge Arrester Energy Absorption at Sending and Receiving End

	BFO		**SFO pos. pole**		**SFO neg. pole**	
Cable length	SA sending end	SA receiving end	SA sending end	SA receiving end	SA sending end	SA receiving end
	$SA_{p,s}$	$SA_{p,r}$	$SA_{p,s}$	$SA_{p,r}$	$SA_{n,s}$	$SA_{n,r}$
[km]	[kJ]	[kJ]	[kJ]	[kJ]	[kJ]	[kJ]
50 km	30	1642	marginal	marginal	71	197
15 km	329	2657	marginal	marginal	141	360
2 km	2984	1646	169	200	778	666

shielding failure can still occur are calculated based on an electrogeometrical model of the investigated line. Direct lightning strokes to the dc pole conductor with the same polarity as the lightning current lead to a constructive superposition of lightning impulse and dc operating voltage. For such lightning incidences, the sum of dc operating voltage and the superimposed lightning surge is below 2.15 p.u. of the rated dc voltage for all cable lengths. Direct lightning strokes on the dc pole conductor with the opposite polarity to the lightning current may result in a polarity reversal at the cable system. For long cable lengths the occurring polarity reversal at the cable system is below 0.28 p.u. of the rated voltage and therefore classified as uncritical for the extruded cable system. However, with decreasing cable length the occurring polarity reversal caused by a SFO on the dc pole with opposite polarity to the lightning stroke, increases. For a short cable length of 2 km the resulting polarity reversal yields up to 2 p.u. of the rated voltage. For this reason, it is recommended to avoid short cable sections in HVDC systems comprising mixed OHL-cable sections. Finally it should be mentioned, that an improved lightning protection of the OHL might reduce the critical shielding failure current and thus reduce the occurring lightning overvoltages resulting from SFO. From an economic point of view, this measure is likely to be cost-effective instead of designing the dc cable for unnecessarily high lightning withstand levels, especially for relatively short OHL sections.

VI. Appendix

The protective characteristic of the dc pole surge arresters is stated in Tab. V.

TABLE V
VOLTAGE-CURRENT CHARACTERISTIC OF THE DC POLE SURGE ARRESTERS

Arrester current [kA]	**Arrester voltage [kV]**
0.00001	756
0.0001	815
0.001	836
0.01	856
0.1	886
1	945
4	1004
10	1052
50	1134
100	1175

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