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Aspects of insulation coordination for DC links using hybrid lines

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SUMMARY

The development of DC transmission technologies is progressing quite quickly due to the enormous hype of generation from renewables far away from the load centers. Because of the lack of corridors and due to environmental constraints, hybrid systems consisting either of AC/DC overhead lines (OHL) or of DC OHL and underground sections, e. g. DC GIL, are of special interest. Since no standards covering the insulation coordination of those systems are in place, detailed studies for AC/DC hybrid OHL and DC OHL with DC GIL sections will be presented in this paper.

Following the basic insulation coordination procedure, as it is also given in IEC 60071 for HVAC grids, in the first step the voltage and overvoltage stresses of both options will be discussed. In this case, slow front and fast front overvoltages are of special interest. Slow front overvoltages are primarily caused by earth faults either on the transmission line or at the converter. Fast front overvoltages are comparable to those at AC OHL.

In the second, step the requested voltage strength of the arrangements under investigation are considered, taking into account the voltages and overvoltages described above and the overvoltage limiting devices, in particular the application of arresters.

Regarding the basic design and layout of AC/DC OHL, firstly different combined overvoltage stresses are discussed, which are of importance for the clearances between phases and phase to earth. The air clearances are determined by means of gap factors. Examples for the basic design of different tower configurations and different rated voltages are presented. Special consideration is given to the safety clearance.

For the fundamental design of DC GIL, mainly overvoltages subjected to OHL section connected to the GIL section have to be considered. In this respect the voltage withstand characteristic of a typical DC GIL design is considered and measures of overvoltage protection in particular the ratings of the arresters are reflected. Adequate ratings of the GIL design and of the arresters are illustrated by means of a typical example. In principal, the findings are also valid for DC hybrid lines consisting of cable and OHL sections.

The considerations demonstrate that DC links based on hybrid solutions are, in general, feasible, but need some special insulation coordination measures to achieve a sufficient level of reliability and safety.

KEYWORDS

DC links, hybrid lines, overhead lines, gas-insulated lines, Insulation coordination

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1. Introduction

The development of DC transmission technologies is progressing quite quickly due to the enormous hype of generation from renewables far away from the load centers and the need for adequate long distance transmission systems. Because of the lack of corridors and environmental constraints, hybrid systems consisting either of AC/DC overhead lines (OHL) or of DC OHL and underground sections, e. g. DC GIL, are of special interest. From the point of view of insulation coordination these configurations differ from regular AC systems. Since no standards covering this topic are currently in place, special considerations are needed [1-3]. To this end, detailed insulation coordination studies for AC/DC hybrid OHL and DC OHL with DC GIL sections were conducted and are presented in this paper.

2. Configurations under consideration

2.1. AC/DC hybrid overhead lines

The hybrid technology combining AC and DC circuits on the same tower will help to reduce the overall environmental impact of the transmission system considered. It is of interest for the conversion of existing AC circuits into DC circuits, but also for the erection of new lines. Based on the tower configuration in use or on standard tower configurations applied when erecting new lines, the following tower configurations were considered (Fig. 1a-c).

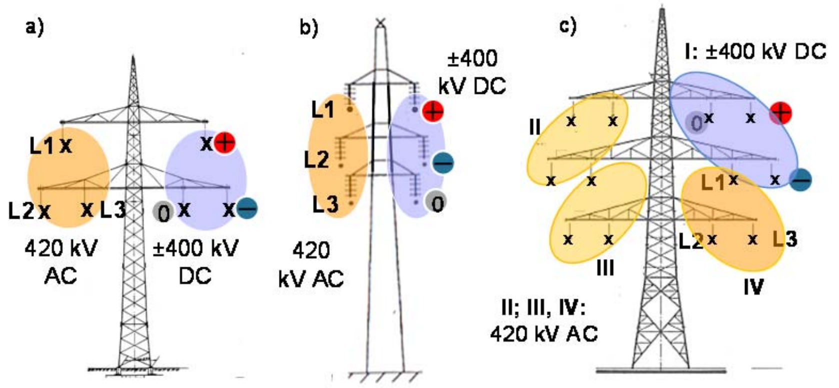

Figure 1: AC-DC configurations under consideration
a) Double-circuit Danube type configuration, b) Double-circuit semi-vertical configuration c) Four-circuit semi-vertical configuration

Figure 1a shows a double-circuit configuration of the Danube type where the AC circuit is arranged on one side of the tower and the DC circuit on the other side. In Figure 1b a double-circuit semi-vertical configuration is given with the same arrangement of the AC and DC circuit as in Figure 1a. In the third configuration (Figure 1c) an AC and a DC circuit are located on the same side of the tower, thus the AC and DC conductors are arranged side by side.

2.2. DC overhead lines with DC GIL sections

If a partial undergrounding of the line is considered, a DC GIL is an option. From the insulation coordination point of view lines consisting of OHL and GIL sections are of most interest. In this regard beside the pure OHL configuration (B1-C1) the GIL-OHL configurations (B2-C2) and (B3-C3) presented in Figure 2 are considered.

Configuration (B2-C2) in Figure 2 shows a DC GIL section between two OHL sections. The stress of the OHL is comparable to that considered in chapter 2.1. (B3-C3) comprises an OHL and a GIL section directly entering the DC

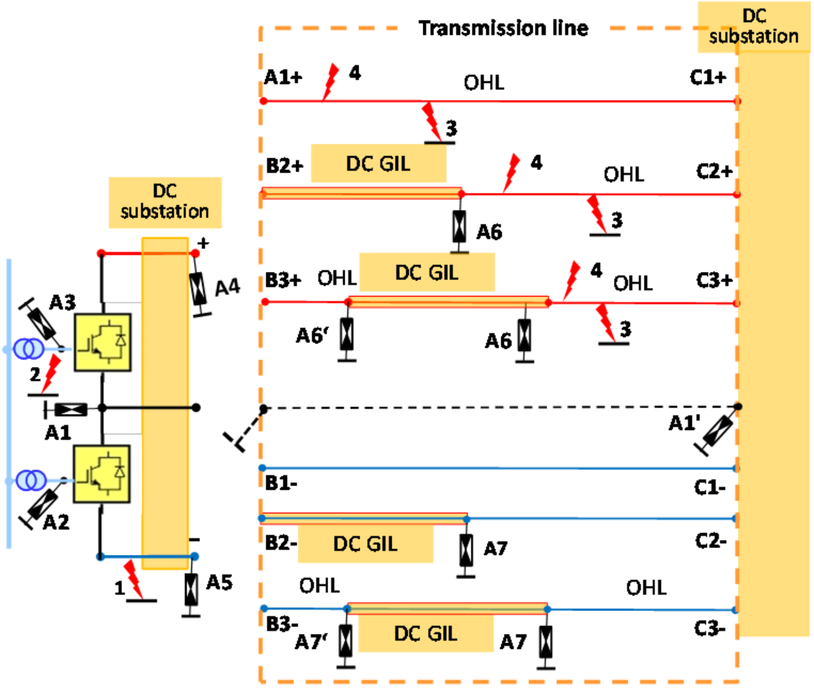

Figure 2 : Hybrid DC line; B1-C1 : OHL
B2-C2: OHL with GIL section entering the converter station;
B3-C3: OHL with GIL section in between

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substation at the converter station. In this case the DC substation will normally be a gas-insulated type and therefore the overvoltages entering the DC GIS substation are of interest.

3. Voltage and overvoltage stresses of hybrid lines

For the insulation coordination procedure, stresses due to the continuous operating voltage, temporary overvoltages, slow front and fast front overvoltage have to be considered.

3.1. Continuous operating voltage

The continuous operating voltage is of special importance for the design and layout of the outdoor insulators. It also affects the audible noise (AN), radio interference (RI) and the corona losses (CL). At AC/DC hybrid OHLs the coupling between the AC circuit and DC circuit and vice versa has to be taken into account. Due to the capacitive coupling a DC component is superimposed on the AC voltage and an AC ripple is superimposed on the DC voltage. These phenomena have to be taken into account when designing the insulators and may also increase the AN as well as the RI. It is also of interest for the definition of the arrester ratings.

3.2. Temporary overvoltages

Temporary overvoltages (TOV) are mainly caused by failures in the control system of the converters of the DC link. They have to be considered when determining the arrester ratings in particular the TOV capability.

3.3. Slow front overvoltages

Slow front overvoltages (SFO) on DC links are mainly caused by overvoltages due to earth faults. SFO caused by line energization and reclosing should not be taken into account, as the DC voltage is ramped up smoothly from zero and in the reclosing process the line de-energization process eliminates the trapped charge. These faults can be subdivided depending on the fault location into converter faults and faults on the transmission line (Figure 2). Faults 1 and 2 are converter faults and faults 3 and 4 are faults on the transmission system. Faults 1, 2 and 3 are caused by earth faults initiating slow front overvoltages whereas fault 4 is caused by lightning.

It has to be noted that all faults stress the converter as well as the transmission system. Therefore adequate overvoltage protection measures coping with both types of faults are needed.

3.4. Fast front overvoltages

Fast front overvoltages are mainly caused by lightning surges. A certain limitation of the overvoltage is achieved by flashovers at the insulator string. The flashover voltage determines the safety clearance. For overvoltages entering the converter station or the GIL section the voltage-time characteristic of the insulator string has to be taken into account.

3.5. Simulation of overvoltages

The overvoltages were calculated by means of the simulation program PSCAD® using the converter models and line models provided. The simulations refer to the configuration shown in Figure 2. The transmission line was assumed to have a length of 400 km. Two cases are under investigation:

1. The line consists of an OHL only
2. The line is fitted with a GIL section, 1 km in length, before entering the converter station

Different converter configurations (symmetrical monopole, bi-pole) and different converter technologies – two level VSC technology, MMC technology and LC technology – with a transmission capacity of 1.2 GW are considered.

The simulations were carried out for a ±320 kV system. The overvoltages are normalized and given in pu values. The values found for slow front overvoltages are also valid for other system voltages, as they are internal overvoltages. The values for fast front overvoltages are valid for ±320 kV as far as the overvoltages are not limited by arresters. If the overvoltages are limited by arresters, the pu values may be transferred to other system voltages, as the arrester ratings, in particular the residual voltage, related to the system are mostly the same.

3.5.1. Slow front overvoltages due to earth faults

- Transmission line

This part of the simulation covered different fault locations on the transmission line – in the middle of the line, 1/8 away from the sending and directly at the converter – and the overvoltages generated by these faults at different locations – at the fault location, at the converter and at the GIL-OHL interface in the case of GIL-OHL hybrid systems. The metallic return is assumed to be directly earthed at the sending end and via an arrester at the receiving end. The results are summarized in Table 1.

Table 1: Slow front overvoltages in pu at fault location, converter terminal and GIL-OHL interface in case of GIL-OHL hybrid lines caused by earth faults at different fault locations, line length 400 km, except $^{1)}$ line length 750 km [4]

SFO at line to earth faults		Bipol								symmetrical monopol, C_{DC} = 100 µF	
		2-level VSC, C_{DC} = 100 µF			MMC			LCC$^{1)}$			
fault location		fault location	conv. term.	GIL-OHL	fault location	conv. term.	GIL-OHL	fault location	conv. term.	fault location	conv. term.
mid	without arresters	2,2	1,5	1,5	1,8	1,2	1,2	1,5	1,2	2,2	2,5
	limited by arresters										1,7
1/8	without arresters	1,7			1,7			1,1	1,1		2,3
	limited by arresters										1,7

An earth fault in the middle of the transmission line is the most critical. Earth faults at other fault locations generate lower overvoltages. At two-level VSC technology higher overvoltages are generated as with other converter technology (Figure 3).

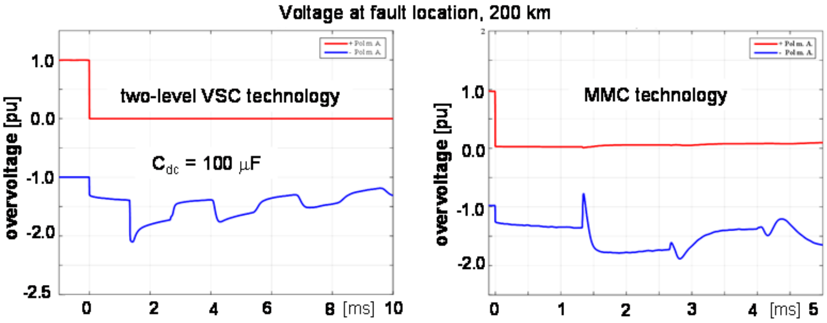

Figure 3: Overvoltages due to an earth fault in the middle of the transmission OHL, 400 km in length

No distinct overvoltage has been observed at the converter terminals of a bi-pole configuration. The same is true for the OHL-GIL interface. Due to the very low overvoltages neither the arrester at the converter nor the arrester at GIL-OHL interface becomes active. That is different from the performance of a symmetrical monopole. In this configuration a considerable overvoltage would occur at the converter terminals. This overvoltage can be limited by the arresters installed at the converter terminals.

The results prove that the overvoltages caused by line faults strongly depend on the converter technology applied.

- Converter

Table 2: Slow front overvoltages at converter terminals caused by earth fault at the DC side or AC side

SFO at converter faults		Bipol		symmetrical monopol
Overvoltage at converter terminals		2-level VSC, C_{DC} = 100 µF	MMC	
		Overvoltage at converter terminals [pu]		
DC side	without arresters	1,8	1,2	2,3
	limited by arresters	1,6		1,8…2,0
AC side	without arresters		2,5	2,1
	limited by arresters		1,9	1,6…1,8

Beside the overvoltages caused by line faults also overvoltages caused by converter faults have to be taken into account. These overvoltages are of interest because they stress the converter itself but also the insulation GIL section connected to the converter station. In this respect converter faults on the DC side as well as on the AC side are considered. The simulation results are summarized in Table 2.

The overvoltages differ with the converter technology applied. Earth faults on the DC side of the converter in two-level VSC technology are limited by the arrester at the converter terminal. If MMC technology is applied, and an earth fault on the AC side of the converter occurs, the overvoltage on the DC side will be limited by arresters at the converter terminals. The graphs of the overvoltages can be taken from Figure 4.

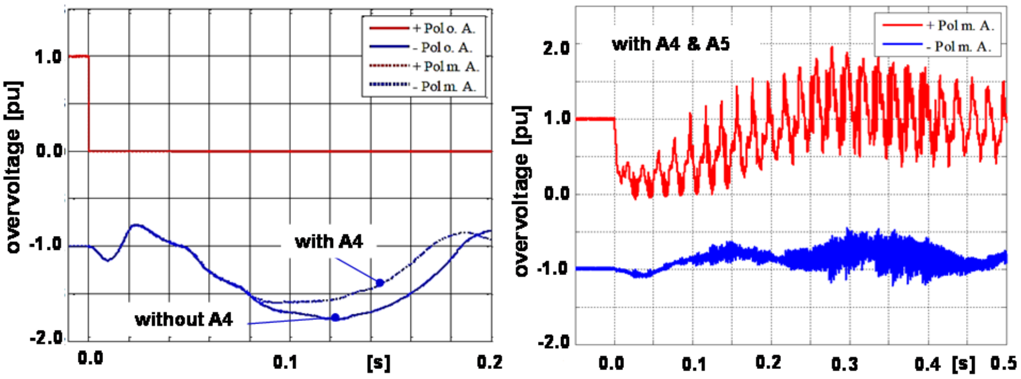

Figure 4: Overvoltages in case of earth faults on the DC side or the AC side of the converter for different converter technologies
Left: Earth fault on the DC side, two level VSC technology
Right: Earth fault on the AC side, MMC technology

The results demonstrate that the overvoltages caused by converter faults stressing the converter, the converter station or the OHL and the GIL section connected respectively do not exceed 2 pu.

3.4.1. Fast front overvoltages due to lightning

These simulations consider overvoltages caused by lightning strokes to the transmission line in the vicinity of the converter station or the GIL-OHL interface respectively. In the latter case the GIL section was assumed to be 1 km in length directly connected to the converter (Figure 2). It was assumed that a lightning current of 18 kA may hit the conductor due to a shielding failure [5]. The simulation results are summarized in Table 3.

Table 3: Fast front overvoltages at the converter terminals or at the GIL-OHL caused by lightning

FFO at llightning strokes to transmission line		Bipol						symmetrical monopol C_{DC} = 1 µF	
		2-level VSC, C_{DC} = 25 µF		2-level VSC, C_{DC} = 1 µF		MMC			
		conv. term.	GIL-OHL	conv. term.	GIL-OHL	conv. term.	GIL-OHL	conv. term.	GIL-OHL
OHL	without arresters	1,15		3,8		16,1		3,8	
	limited by arresters			2,1		2,1		2,1	
OHL/GIL	without arresters	1,15	4,0	3,8	4,0	5,2	5,2	3,8	4,0
	limited by arresters		2,1	2,1	2,1	1,9	2,0	2,1	2,1

Due to the large DC capacitance which is applied in two-level VSC converter technology the fast front overvoltage entering the converter station is strongly damped. If a smaller DC capacitance can be applied, the overvoltage will distinctly increase and limitation by arresters becomes necessary. The largest overvoltages occur when MMC technology is applied. For example the overvoltage at the GIL-OHL interface is shown in Figure 5. These overvoltages have to be limited by arresters at the converter terminal and the GIL-OHL interface. For a sufficient overvoltage protection an adequate arrester rating is required. The selection of arrester rating will be discussed in chapter 4.2.2.

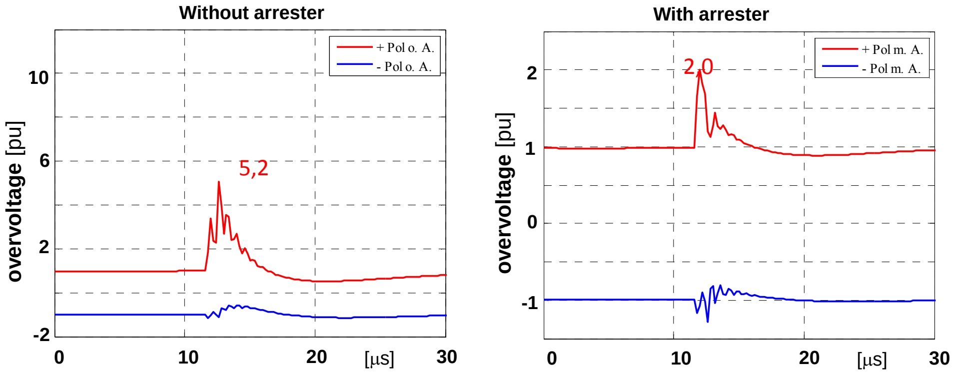
Without arrester
With arrester

Figure 5: Fast front overvoltage at the GIL-OHL interface in case of MMC technology

4. Required voltage strength

4.1. AC/DC overhead lines

In order to achieve the required availability of the overhead lines, the voltage strength must be adequate to withstand the voltage stresses given in chapter 3.

For the considered voltage levels, continuous operating voltage and temporary overvoltages may be neglected, because the required voltage strength is mainly affected by slow front and fast front overvoltages.

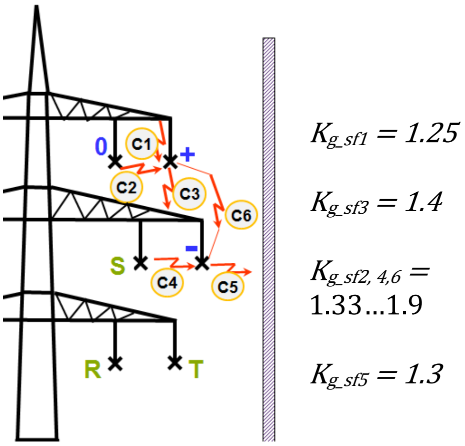

Figure 6 : Gap factor *Kg* for typical arrangements

Figure 4 shows the clearances which have to be defined for the dimensioning of the AC/DC hybrid tower. In the following, the clearances to earth (C1, C3, C5) will be treated differentially to the clearances between the conductors (C2, C4, C6). The reason for this separation is given by the fact that the dielectric strength of air gaps depends on the polarity of the voltage. For combined voltage stress as between conductors, respective adoption has to be applied. This physical phenomenon will be taken into account for both slow front and fast front voltage strengths.

In Figure 6 the clearance C6 is shown only as an example. It is obvious that for presented tower the probability of flash over between plus and minus pole is extremely low. Nevertheless this clearance can be useful in dimensioning the crosses of conductors by transitions between different tower types.

The following approach is based on the basic insulation coordination (IC) principles given in IEC 60071 [6, 7]. It differs from EN 50341 [8]. This standard is valid for AC overhead lines, only. It provides a simple approach based on factors which have been derived via a complex process, partly valid for AC lines, only. Therefore, the dielectric design of AC/DC hybrid overhead lines will be carried out mostly referring to [7, 9].

4.1.1 Determination of air clearances between conductor and earth for slow front overvoltages

The determination of considered clearance will be conducted according to [7], Annex G. The 50% breakdown voltage of an arrangement U_{50} can be presented as a function of the gap distance d_{sf} and the gap factor K_{g_sf}. The withstand voltage U_{rw} corresponding to the 10% breakdown voltage U_{10} can be calculated from U_{50} by means of the deviation factor K_z derived from the standard deviation $z = 0{,}06$. The complete equation is given in Annex 1.

$$U_{50\,sf} = K_{g\_sf} * f(d) = 500 * d^{0,6} \qquad\qquad U_{rw\,sf} = K_{z\_sf} * U_{50\_sf}$$

$$K_{z\_sf} = 1 - 1{,}3 * 0{,}06 = 0{,}922$$

The air clearance is characterized by the gap factor K_{g_sf} of the arrangement. For typical arrangements the gap factor can be taken from literature [7, 9]. For conductor arrangements as in Figure 4, the gap factors ($Kg_{\_sf1,2,3,4,6}$) have been determined by lab measurements. Factor K_{g_sf3} for safety clearance was taken from the Standard EN 50341-1 [8].

Table 4: Air clearances between conductors and earth for slow front overvoltages

U_m^+		K_{ov_DC}	U_{50}	K_{g_sf}	D_{el_sf}
kV			kV		m
400	**C1**	2	1030	1,25	2,30
	C3	2	1030	1,4	1,90
	C5	2	1030	1,3	2,15
500	**C1**	2	1287	1,25	3,34
	C3	2	1287	1,4	2,76
	C5	2	1287	1,3	3,12

The voltage U_{cw} have to be corrected by safety factor for air insulation of K_s = 1.05 according to [7] and by the atmospheric correction factor (K_a) for an altitude of 1000 m of $K_a = 1.13$. For some configurations K_a can be reduced using factor m in Fig 9 in [7]. Nevertheless here the worst case will be assumed. For the DC system with a maximal operating voltage of U_m an overvoltage factor K_{ov} of 2.0 pu was implied, which corresponds the maximum value received in terms of digital simulations in chapter 3.5 for the converter technology applied in the case under consideration. For other converter technologies different overvoltage factors may be assumed.

Table 4 presents examples for dimensioning of clearances between conductors and earth for slow front overvoltages.

The largest air clearance has to be chosen for the clearance to the upper cross-arm (C1). This clearance also affects the selection of the insulator. Assuming a composite insulator designed for medium site pollution severity class c shall be applied a unified specific creepage distance (USCD) of 27 mm/kV according to [10] is adequate which would lead to a creepage factor (CF) of 4.1. As a creepage factor up to 4.5 is acceptable for composite insulators, coordination between required clearance and required creepage distance is achievable with this type of insulators. If conventional insulators will be installed, a longer insulator length not matching the minimum air clearance has to be chosen to fulfill the pollution and creepage requirements.

4.1.2 Determination of air clearances between conductors for slow front overvoltages

In order to fulfill the reliability requirements, flash over between AC and DC conductors as well as between DC conductor and metallic return conductors should be possibly avoided (C2, C4, C6 in Figure 4).

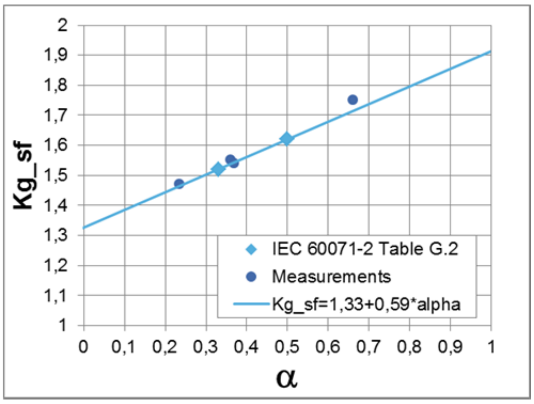

Figure 5: Verification of relation betweenα and K_g

Since the conductors can take the voltages of different polarities, the combined voltage stress of an air gap has to be taken into account. At combined voltage stress a gap factor K_{g_sf} has to be taken into account which is not only depending on the arrangement but also on a factor α which describes the relation of the negative component to the total applied voltage (sum of the negative and positive component). In the test arrangement in question the relation between α and K_{g_sf} for slow front overvoltage has been verified. The results are presented in Figure 5. The results correspond to results also given in literature [7, 9, 11] and can be expressed by equation shown in Figure 5.

The complete equation for determination of clearances between conductor and earth for slow front overvoltages is given in Annex 1. Examples for dimensioning of the clearances between conductors and earth are presented in Table 5.

Table 5: Air clearances between conductors for slow front overvoltages

DC service voltage		U_m^+	U_{sf}^+	U_m^-	U_{cw}	a	K_{g_sf}	U_{50}	D_{pp_sf}
kV		kV	kV	kV	kV			kV	m
400	**C2**	400	800	0	800	0,00	1,33	1030	2,07
	C4a	343	789	400	1189	0,34	1,53	1531	3,18
	C4b	400	800	343	1143	0,30	1,51	1472	3,05
	C6	400	800	400	1200	0,33	1,53	1545	3,24
500	**C2**	500	1000	0	1000	0,00	1,33	1287	3,01
	C4a	343	789	500	1289	0,39	1,56	1659	3,52
	C4b	500	1000	343	1343	0,26	1,48	1729	4,11
	C6	500	1000	500	1500	0,33	1,53	1931	4,70

The air clearance between AC conductor and DC conductor is mainly affected by the switching overvoltage stress on the AC conductor or on the DC conductor respectively. For the AC system an overvoltage factor (K_{ov}) of 2.3 pu was assumed, i.e. energising of pre-charged lines was disregarded. Due to the single-phase auto-reclosure process common in Germany those switching cases do not occur. Similarly to chapter 4.1.1, for DC-System the K_{ov} of 2.0 has been implemented. The exemplary dimensioning of the clearances between conductors for slow from voltages is presented in Table 5. Thereby the positive slow front overvoltage U_{sf}^+ has been applied to one conductor while the other one received a negative maximum operating voltage (conductor-earth) (U_m^-). The application of negative polarity overvoltages is not necessary for this type of surge, since there is a larger dielectric strength under negative switching impulse voltage.

From Table 5 it can be derived that depending on the DC service voltage either the overvoltage of the DC system or of the AC system is decisive for the required air clearance between AC and DC conductor.

4.1.3 Determination of air clearances between conductor and earth for fast front overvoltages

In this voltage range the fast front overvoltages in most of the cases determine the air clearance. This is of special interest with regard to safety reasons. According to the safety philosophy, lightning overvoltage shall not cause a flashover between conductor and earthed objects, but shall lead to flashover across the insulator in the vicinity of the lightning stroke location.

To fulfill this philosophy a proper dimensioning of the safety clearances should be based rather on test results on the insulators under considerations than on estimation with correction factors. For this purpose lab tests were carried out to find out the lightning withstand voltage of the DC insulators chosen for 400 kV and 500 kV applications. From the lightning withstand voltages of +1720 kV and -1930 kV for the 400 kV insulator and +2270 kV and -2375 kV the 500 kV insulator the air clearances between conductor and earthed objects were derived.

Similarly to slow front overvoltages, the withstand voltage U_{rw} corresponding to the 10% breakdown voltage U_{10} and can be calculated from U_{50} by means of the deviation factor K_z and the gap factor K_{g_ff} for fast front overvoltages. With a standard deviation of z 0,06 the deviation factor for fast front overvoltages is

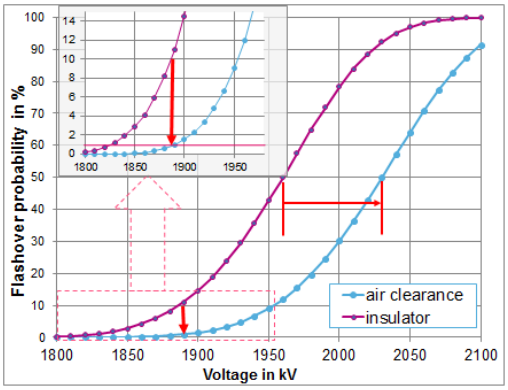

Figure 6: Flashover probability of insulator and safety air clearance

$$K_{z\,ff} = 1 - 1{,}3 * z = 1 - 1{,}3 * 0{,}06 = 0{,}922$$

The gap factor for fast front overvoltages K_{g_ff} can be derived from the gap factor for slow front overvoltages K_{g_sf} according to [6] by the equation

$$K_{g\_ff} = 0{,}74 + 0{,}26 * K_{g\_sf}$$

For positive polarity the clearance is determined by

$$D_{el\_ff\_p} = \frac{U_{50p}}{530 \times K_{g\_ff}}$$

For overvoltages of negative polarity the following equation for K_{g_sf}<1.44 can be used [10]

$$D_{ef\_ff\_n} = \left(\frac{U_{50n}}{950 \times K_{g\_ff}}\right)^{\frac{1}{0{,}8}}$$

However, for negative polarity another gap factor $K_{g\_sf\_n}$ is assumed.

$$K_{g\_ff\_n} = \left(1{,}5 - 0{,}5 \times K_{g\_sf}\right)$$

The complete equation for determination of the clearances to earth for fast front overvoltages is given in Annex 1.

Table 6: Air clearances between conductor and earth for fast front overvoltages

DC service voltage		$U_{10\ ff\ is}$	K_z	$U_{50\%}$	$K_{g\ sf}$	$D_{el\ ff}$	$D_{el\ ff}$
		kV		kV		m	m
400	**C3 pos**	1720	0,961	1790	1,40	3,06	3,37
	C3 neg	1930	0,961	2008	1,40	3,37	
	C5 pos	1720	0,931	1847	1,30	3,23	3,25
	C5 neg	1930	0,931	2073	1,30	3,25	
500	**C3 pos**	2270	0,961	2362	1,40	4,04	4,36
	C3 neg	2370	0,961	2466	1,40	4,36	
	C5 pos	2270	0,931	2438	1,30	4,27	4,27
	C5 neg	2370	0,931	2546	1,30	4,20	

For dimensioning of the clearance to earth the required withstand voltage in most of cases can be equalled to 10% breakdown voltage U_{10} of the insulators. Following this, in 10% of overvoltages the insulator or the air clearance can fail with equal probability. This equality cannot be supported for the safety clearance, since it cannot fulfil basic safety philosophy. Therefore it will be proposed to increase the withstand voltage of the safety clearance by reducing the flashover probability. Therefore the 1% flashover probability corresponding to a conversion factor K_z=1-2.3*z=0,931 is applied instead of the 10% flashover probability of the safety clearance. This principle is shown in Figure 6 and applied in Table 6 for C3. Thereby, the 10% flashover probability voltages of the insulator determined in terms of lab tests have been used.

In cases where these clearances cannot be assured other approaches (e.g. use of geometric model for lightning strikes) or application of line surge arresters or controlled spark gaps for strings can be adopted.

4.1.4 Determination of air clearances between conductors for fast front overvoltages

Most cases given by literature consider the clearance between conductors for slow front overvoltages only. Due to the requirement of high availability of the AC and DC circuit on one same side of the tower, the flashover between the AC and DC conductors should possibly be avoided. For this reason the required clearance due to fast front overvoltages should be considered as well. Hereby the focus will be put on shielding failure, while the back flash over will not be considered, since in considered network no such phenomena have been observed.

The proposed approach is based on the combined voltage stress, a linear dependence between K_{g_sf} and α (similar to the chapter 4.1.2) and a linear dependence between K_{g_sf} and K_{g_ff} :

$$D_{pp\_ff} = \frac{U_{50}}{530 \times K_{g\_ff}} \qquad K_{g\_ff} = 0{,}74 + 0{,}26 \times K_{g\_sf} \qquad K_{g\_sf} = 1.33 + 0.59 \times \propto$$

The complete equation for determination of clearances between conductors for fast front overvoltages is given in Annex 1. Examples for dimensioning of the clearances between conductors are presented in Table 7.

Table 7: Air clearances between conductors for fast front overvoltages

		$U+$	$U-$	U_{cw}	α	K_{g_sf}	K_{g_ff}	U_{rw10}	U_{50air}	D_{pp_ff}	D_{pp_ff}
		kV	kV	kV				kV	kV	m	m
400	**C2a**	1720	0	1720	0,00	1,33	1,09	1720	1790	3,11	3,11
	C2b	0	1930	1930	1,00	1,92	1,24	1930	2008	3,06	
	C4a	1720	343	2063	0,17	1,43	1,11	2063	2147	3,64	3,67
	C4b	343	1930	2273	0,85	1,83	1,22	2273	2365	3,67	
	C6a	1720	400	2120	0,19	1,44	1,11	2120	2206	3,73	3,77
	C6b	400	1930	2330	0,83	1,82	1,21	2330	2425	3,77	
500	**C2a**	2270	0	2270	0,00	1,33	1,09	2270	2362	4,10	4,10
	C2b	0	2370	2370	1,00	1,92	1,24	2370	2466	3,75	
	C4a	2270	343	2613	0,13	1,41	1,11	2613	2719	4,64	4,64
	C4b	343	2370	2713	0,87	1,85	1,22	2713	2823	4,37	
	C6a	2270	500	2770	0,18	1,44	1,11	2770	2882	4,88	4,88
	C6b	500	2370	2870	0,83	1,82	1,21	2870	2986	4,65	

In cases where these clearances cannot be assured other approaches (e.g. use of geometric model for lightning strikes) or application of line surge arresters or controlled spark gaps for strings can be adopted.

4.1.4 Summary of air clearances

Table 8 shows the summary of the air clearances for dimensioning of towers like in Figure 6. It can be noticed, that the clearances for operation depend mostly on the fast front overvoltages.

Table 8: Summary of air clearances for AC/DC OHL

DC service voltage		$D_{\_ff}$	$D_{\_sf}$		D
		m	m		m
400kV	C1		2,30		2,30
	C3	3,37	1,90		3,37
	C5	3,25	2,15		3,25
	C2	3,11	2,07		3,11
	C4	3,67	3,18	3,05	3,67
	C6	3,77	3,24		3,77
500kV	C1		3,34		3,34
	C3	4,36	2,76		4,36
	C5	4,27	3,12		4,27
	C2	4,10	3,01		4,10
	C4	4,64	3,52	4,11	4,64
	C6	4,88	4,70		4,88

4.2. DC OHL with DC GIL sections

4.2.1. Withstand voltage characteristic of typical GIL design

For the required voltage strength of DC GIL mainly overvoltages subjected to OHL section connected to the GIL section have to be considered. The insulation system of a DC GIL consists of gaseous insulation, of solid insulation and of the interface between gaseous and solid insulation. During the charging process charge accumulation takes place on the surface and in the bulk material of the insulators. When transient overvoltages enter the GIL section, the pre-charged insulators are stressed by a superposition of these overvoltages. Therefore the superposition of switching and or lightning overvoltages represents a special stress, the DC GIL has to withstand.

Basically unipolar and bipolar superposition of switching impulse overvoltages may occur.

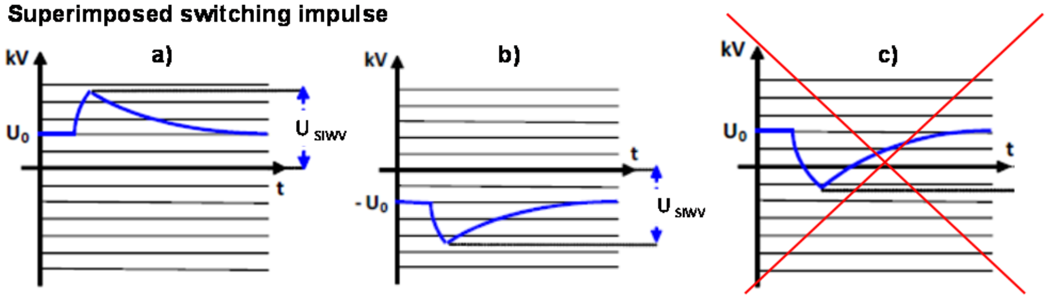

Figure 5: Superimposed switching impulse overvoltage in practice

- **a) Positive switching impulse superimposed on the positive pole in case of an earth fault at the negative pole**
- **b) Negative switching impulse superimposed on the negative pole in case of an earth fault at the positive pole**
- **c) Negative switching impulse superimposed on the positive conductor, not occurring in practice**

As earth faults always cause overvoltages in the sound pole, this overvoltage impulse is superimposed on the service voltage of the sound pole. Therefore, unipolar wave shapes according to Figure 5a and b will occur in practice, only. A bipolar wave shape according to Figure 5c is physically not possible.

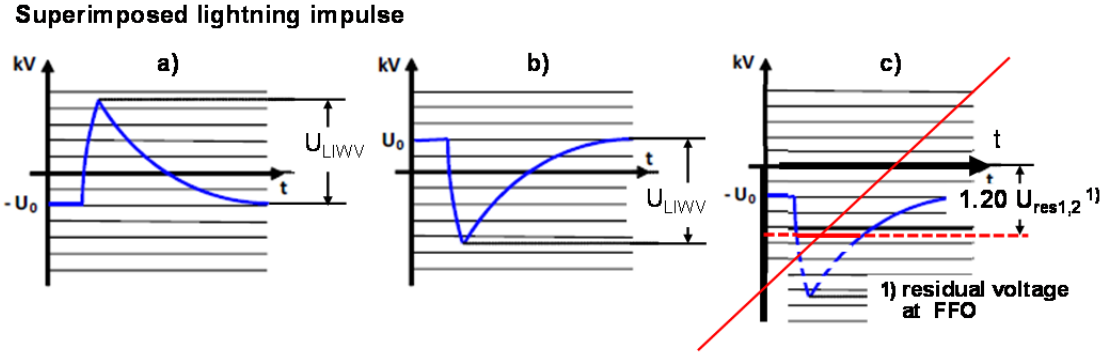

Figure 6: Superimposed lightning impulse overvoltage reasonable in practice

- **a) Positive lightning impulse superimposed on the negative pole**
- **b) Negative lightning impulse superimposed on the positive pole**
- **c) Negative lightning impulse superimposed on the negative pole limited by the arrester at the**

Regarding superimposed lightning overvoltages bipolar wave shapes according to Figure 6a and b are reasonable in practice, only. Unipolar wave shapes as shown in Figure 6c are limited by the arrester at the interface OHL – GIL. Thus the overvoltage protection range of surge arrester cannot exceed the residual voltage of the arrester at fast front overvoltages (FFO) multiplied with the ratio of required lightning impulse withstand voltage (RLIWV) to lightning impulse protection level (LIPL) which should be 1.20 in accordance to [12]. The bipolar stress given in Figure 6b will most commonly occur in practice, as lightning strokes hitting the pole conductor are negative. Furthermore, at all configurations presented in Figure 1 the conductor of the positive pole is arranged on the upper cross arm which will be the conductor most probably be subjected to lightning overvoltages due to shielding failures.

4.2.2. Adequate ratings of GIL design and of arresters ratings

Gas-insulated HVDC systems connected to OHL subjected to fast front overvoltages, mainly caused by lightning, similar as gas-insulated HVAC systems. Figure 7 shows a typical example of a DC OHL with a DC GIL connected and the OHL-GIL interface. An adequate rating of the GIL design and the coordination with the arrester ratings is a crucial issue, as it will be illustrated by means of the example.

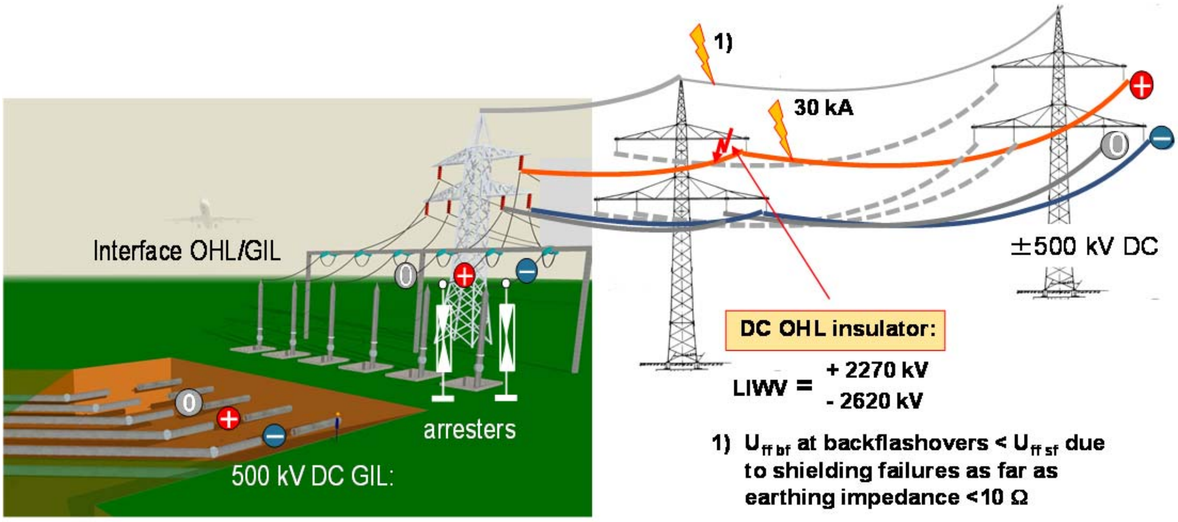

Figure 7: Typical example of a DC GIL section connected to a DC OHL subjected to a lightning overvoltage stress

It is assumed that a lightning stroke hits the last or second last span before the OHL-GIL interface. According to the electro-geometric model (EGM) applied for the tower under consideration [5] lightning strokes of 30 kA at maximum can reach the DC conductor causing an overvoltage with a peak value of

$$\hat{u} = \hat{\imath} * Z_w / 2 = 30\,kA * 300\,\Omega / 2 = 4.5\,MV$$

The overvoltage will be limited by flashover at the next OHL insulator. In consequence a chopped wave will travel towards GIL interface. The peak value can be calculated by means of the voltage-time characteristic of the insulator. Its withstand voltage (LIWL) was determined by lab tests to be +2270 kV and -2620 kV. The peak value of the chopped wave results from the voltage-time characteristic of the insulator which is depending on the voltage steepness. The current steepness can be derived from the current peak value [5]

$$S_{I\,30\text{-}90} = 3.2\, I^{\,0.25}$$
$$(I \text{ in } kA,\ S \text{ in } kA/\mu s)$$

Correspondingly the voltage steepness amounts to

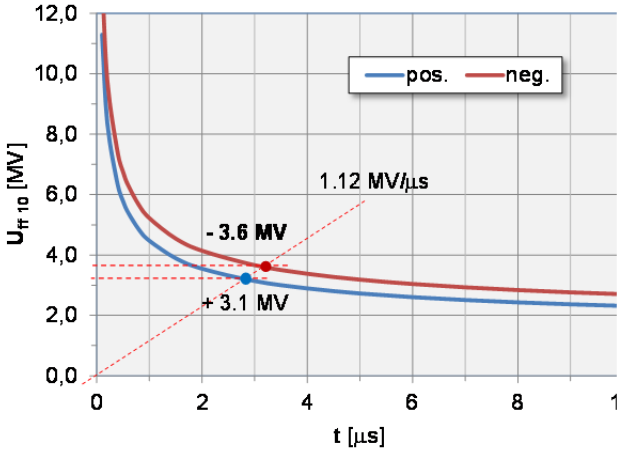

Figure 8: Voltage-time characteristic of the DC OHL insulator

$$S_U = S_I{*}Z_w/2 = 1.12\,MV/\mu s$$

With a given LIWV of the insulator the voltage-time characteristic can be determined as given in Figure 8 using the following equation [11]:

$$U_{ff\,10} = U_{LIWV} * (0.58 + 1.39\,\sqrt{t}) \qquad \text{t in µs}$$

Corresponding with the voltage-time characteristic of the OHL insulator the LIOV is limited to -3.6 MV. Damping effects neglected this fast front overvoltage will enter the GIL. It certainly would overstress the GIL insulation, if not limited by adequate arresters.

The technical data, given in Table 3, deduced from AC applications are applied for definition of the arrester ratings.

If it is intended to design the DC GIL for a LIWL of 1550 kV, this results in a coordination withstand voltage U$_{cw}$ of 1350 kV taking into account a safety factor $K_s = 1.15$ for internal insulation [7].

Table 4: Technical data for definition of arrester ratings

		comment
System voltage ; U_{DC}	500 kV	
Superimposed AC component ; U_{AC}	50 kV_{peak}	superimposed AC component up to 10%
Max. continuous voltage; U_{MCOV}	575 kV_{peak}	1,05 *(U_{DC} + U_{AC})
Rated voltage; U_r	575 kV_{peak}*1,25 ≈ 510 kV_{rms}	ratio U_r/U_{MCOV} = 1,25, as common with AC arresters,
Residual voltage (10 kA, 8/20 µs) ; $U_{res\ 8/20}$	1220 kV	ratio U_{res}/U_r = 2,4, as common with AC arresters
Residual voltage At steep front overvolt. (1/2 µs) ; $U_{res\ 1/2}$	$U_{res\ 8/20}$ *1.05 = 1280 kV	Res. volt. at steep front overvolt. = 1.05 * res. volt. (10 kA, 8/20 µs)

In consequence the ratio between U_{cw} and $U_{res\ 1/2}$ is about 1.05, which is much smaller as in AC applications where the relevant ratio is about 1.3. Such a margin is required to cope with travelling wave phenomena between arrester and GIL, inductive voltage drops on the lead conductors of the arrester and probably higher discharge currents.

Therefore, an arrester with a lower residual voltage and accordingly with a higher energy absorption has to be installed at the OHL-GIL interface.

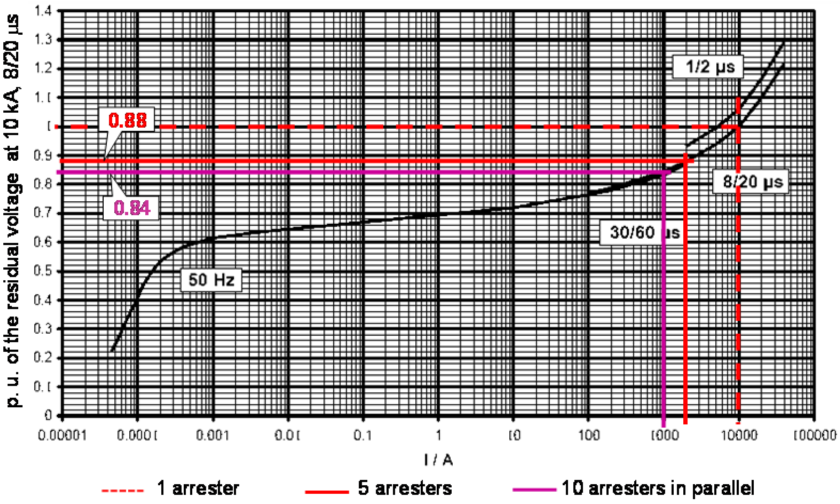

Figure 9: Reduction of residual voltage by switching arresters in parallel

In principal, a lower residual voltage can be achieved by splitting the discharge current onto several arresters in parallel. However, a thorough selection of the arresters is needed, when putting arresters in parallel. As it is shown in Figure 9, the residual voltage can be reduced to 88% by five arresters in parallel and to 84% by ten in parallel. As illustrated in Table 3, the ratio U_{cw} to $U_{res\ 1/2}$ can be improved to 1.2 or 1.25 respectively which should be sufficient for an efficient overvoltage protection for a 500 kV DC GIL with a rated LIWV of 1550 kV assumed. In any case a more sophisticated overvoltage simulation with the real OHL-GIL arrangement is recommended.

Table 10: Improvement of overvoltage protection performance by increasing the ratio U_{cw} / $U_{res\_1/2}$

number of arresters	U_{res} (10 kA, 8/20 us) kV	U_{res} (1/2 us) kV	U_{cw} *) / U_{res}(1/2)
1	1220	1281	1,05
5	1074	1127	1,20
10	1025	1076	1,25

*) U_{cw} = 1350 kV

5. Conclusions

The integration of generation from renewables far away from the load centers requires adequate long distance transmission systems. Because of the lack of corridors and environmental constraints, hybrid systems consisting either of AC/DC overhead lines (OHL) or of DC OHL and underground sections, e. g. DC GIL, are of special interest. As from the insulation coordination point of view these configurations differ from regular AC systems, comprehensive insulation studies were carried out. For AC/DC overhead lines (OHL) the air clearances to earth and between AC and DC conductors were determined based on gap factors gained by pre-investigations on the arrangements under consideration and by lab tests on insulators in question.

For DC OHL with DC GIL sections the special insulation characteristic of the DC GIL had to be considered. The pre-charged insulators are stressed by a superposition of switching and or lightning overvoltages, which represents a special stress, the DC GIL has to withstand. For this purpose superimposed stresses occurring in practice are analyzed. Furthermore, an adequate rating of the arresters determined which have to be installed for a sufficient overvoltage protection of the GIL section.

The considerations demonstrate that DC links based on hybrid solutions are, in general, feasible, but need some special insulation coordination measures to achieve a sufficient level of reliability

Acknowledgement

This paper is dedicated to Dr. Karl-Heinz Weck who passed away in February 2016. He made a lot of contributions and valuable input to this subject.

BIBLIOGRAPHY

[1] C. Neumann, B. Rusek, S. Steevens, K.-H. Weck: Design and layout of AC-DC hybrid lines. CIGRE Symposium “Best practice in transmission and distribution in a changing environment”. Auckland, Sept. 16-17th, 2013.

[2] B. Rusek, C. Neumann, S. Steevens, U. Sundermann, K. Kleinekorte, J. Wulff, F. Jenau, K.-H. Weck: Ohmic coupling between AC and DC circuits on hybrid overhead lines. CIGRE Symposium “Best practice in transmission and distribution in a changing environment”. Auckland, Sept. 16-17th, 2013.

[3] B. Sander, J. Lundquist, I. Gutman, C. Neumann, B. Rusek K.-H. Weck: Conversion of AC multi-circuit lines to AC-DC hybrid lines with respect to the environmental impact. CIGRE B2-105, 2014.

[4] CIGRE Joint Working Group B2/B4/C1.17: Impacts of HVDC Lines on the Economics of HVDC Projects. CIGRE Brochure 388, August 2009.

[5] CIGRE Working Group C4.407: Lightning Parameters for Engineering Applications. Technical Brochure 549, August 2013.

[6] IEC 60071-1: Insulation coordination, Part 1: Principles and rules, Jan 23, 2006.

[7] IEC 60071-2: Insulation coordination, Part 2: Application Guide, December 1996.

[8] EN 50341-1: Overhead electrical lines exceeding 45 kV- Part 1: General requirements: 04-2010.

[9] CIGRE Working Group 33-07: Guidelines for the evaluation of the dielectric strength of external insulation. Technical Brochure 72, 1992.

[10] IEC/TS 60815-4 Ed. 1.0, : Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 4: Insulators for d.c. systems. 36/371/CD, 2015.

[11] A. Hileman: Insulation Coordination for Power Systems. Taylor &Francis Group, Boca Raton London New York, 1999.

[12] IEC 60071-5, Ed. 1: Insulation co-ordination – Part 5: Procedures for high-voltage direct current (HVDC) converter stations.

ANNEX 1

1. Determination of air clearances between conductor and earth for slow front overvoltages

$$D_{el\_sf} = \left(\frac{U_{50}}{500 \times K_{g\_sf}}\right)^{-0.6} = \left(\frac{U_{10} \times K_Z}{500 \times K_{g\_sf}}\right)^{-0.6} = \left(\frac{U_m \times K_{ov} \times K_s \times K_a \times K_Z}{500 \times K_{g\_sf}}\right)^{-0.6}$$

2. Determination of air clearances between conductors for slow front overvoltages

$$D_{pp\_sf} = \left(\frac{U_{50}}{500 \times K_{g\_sf}}\right)^{-0.6} = \left(\frac{(U_m^- + U_m^+ \times K_{ov}) \times K_a \times K_s \times K_Z}{500 \times \left(1.33 + 0.59 \times \frac{U_m^-}{U_m^- + U_m^+ \times K_{ov}}\right)}\right)^{-0.6}$$

3. Determination of air clearances conductor and earth for fast front overvoltages

Positive polarity $D_{el\_ff\_p} = \frac{U_{50p}}{530 \times K_{g\_ff}} = \frac{U_{cw} \times K_Z \times K_s \times K_a}{530 \times (0{,}74 + 0{,}26 \times K_{g\_sf})}$

Negative polarity $D_{el\_ff\_n} = \left(\frac{U_{50n}}{950 \times K_{g\_ff}}\right)^{\frac{1}{0{,}8}} = \left(\frac{U_{cw} \times K_Z \times K_s \times K_a}{950 \times (1{,}5 - 0{,}5 \times K_{g\_sf})}\right)^{\frac{1}{0{,}8}}$

4. Determination of air clearances between conductors for fast front overvoltages

$$D_{pp\_ff} = \frac{U_{50}}{530 \times K_{g\_ff}} = \frac{U_{50} \times K_Z}{530 \times (0{,}74 + 0{,}26 \times K_{g\_sf})} = \frac{U_{cw} \times K_Z \times K_s \times K_a}{530 \times (0{,}74 + 0{,}26 \times (1.33 + 0.59 \times \propto))}$$

$$D_{pp\_ff} = \frac{(U^- + U^+) \times K_Z \times K_s \times K_a}{530 \times \left(0{,}74 + 0{,}26 \times \left(1.33 + 0.59 \times \frac{U^-}{U^- + U^+}\right)\right)}$$