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C4 POWER SYSTEM TECHNICAL PERFORMANCE**PS 3 - Insulation Coordination and Lighting Research: paving the way to net-zero in decarbonised power system****Main Issues Regarding HVDC Overhead Transmission Lines Insulation Coordination: VSC Technology and Dedicated Metallic Return****P.C.V. ESMERALDO*****PowerConsult****Brazil**

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SUMMARY

Despite the insulation coordination in HVDC overhead transmission lines being relatively consolidated, new technologies and new components are used to face environment restrictions, to enhance better power system performance in pursuit of the never-ending search for economic optimization. Keeping this trilemma in mind, VSC (Voltage Source Converters) technology, the usage of the Dedicated Metallic Return (DMR) and the optimization of tower geometry are presently the main issues under discussion in HVDC systems.

This paper evaluates how VSC technology and DMR use affect tower insulation coordination compared to traditional LCC (Line Commutated Converters) methods. It considers both internal and external overvoltages, dielectric strength, pollution, and weather in optimizing tower design. Key factors include the impact of terminal components, such as filters and smoothing reactors, on internal overvoltages resulting from pole short-circuits, as well as the role of various converter types (half-bridge, full-bridge, hybrid).

Insulation coordination for neutral conductors, specifically, DMR insulator configurations under lightning and internal overvoltages, is assessed due to the risk of induced voltages exceeding insulation levels. Both bipolar and monopolar operations are simulated, focusing on how protective devices like spark gaps and surge arresters impact overvoltage limitations in DMR installations.

This paper presents a new approach to selecting tower line insulation for operating voltages, considering pollution and wet conditions, with results from laboratory tests on dielectric strength. The discussion covers glass, porcelain, and composite DC insulators, recommending suitable types and numbers based on regional pollution and moisture. Steps for optimizing HVDC tower configurations are proposed, using statistical risk-of-failure methods to determine insulation distances and account for withstand voltage. These findings may enhance current standards, highlighting the need for ongoing evaluation of new components in insulation coordination.

It is important to emphasize that this contribution is the genesis of the Technical Brochure under development in the WG C4.73

KEYWORDS Dedicated Metallic Return, Overvoltages on VSC Systems, Lightning Performance, Dielectric Strength

1. Introduction

Given the growing environmental restrictions, insulation coordination in HVDC overhead lines needs to be reconsidered. This approach is essential to improve overall power system performance and supports the ongoing pursuit of economic optimization within electric industry. Considering these challenges, several technological and design elements have become central topics of discussion within HVDC systems: the integration of VSC technology is pivotal for enhancing the efficiency and reliability of HVDC transmission and the use of a Dedicated Metallic Return offers significant benefits in transmission performance and less environmental impact. The refining of the design and structure of transmission towers is crucial for addressing insulation coordination and accommodating environmental constraints.

These ongoing discussions and innovations in VSC technology, DMR application, and tower geometry optimization are shaping the future of insulation coordination in HVDC overhead lines, promoting improved performance and economic efficiency in power systems.

As is widely known, HVDC power transmission can be achieved using two main converter technologies: LCC (based on thyristors) and VSC (based on IGBTs). Each plays a distinct role in modern power systems, shaped by differences in converter design, control capabilities, fault behavior, infrastructure footprint, and grid interaction requirements that are relevant for insulation coordination of HVDC overhead lines.

2. Internal Overvoltages

Determining representative overvoltages on the DC line is an essential part of the insulation coordination design process. IEC 60071-12 provides the necessary information and discusses tools for conducting studies that assess overvoltages in LCC HVDC systems. Since faults are transient phenomena, they must be analyzed using EMT simulations with an appropriate model covering the relevant frequency range. The IEC offers a detailed list of the information required to model the system. The principles outlined in [1] are also applicable to VSC technology. Furthermore, reference [2] provides comprehensive guidance on modelling for transient studies involving VSC converters.

However, at the planning stage, detailed information about the converters is rarely available. Since the choice of converter technology affects overvoltage, and consequently, the line design and overall cost, it is important to understand the parameters that most influence these overvoltages. Reference [3] provides insight into the two main types of VSC-MMC technologies used in bipole configurations: half-bridge (HB) and full-bridge (FB) submodules (SMs). Unsurprisingly, FB SMs enable much faster recovery after a DC fault, with timings similar to LCC technology. As demonstrated in [3], the healthy pole experiences approximately 20% higher overvoltages when HB SMs are used, with the greatest difference occurring when the system operates as a rigid bipole.

The voltage stresses experienced by the healthy pole were evaluated using detailed electromagnetic transient (EMT) simulations. The modelling approach and system configuration are similar to those used in [3]. However, the DC system considered is a ± 600 kV, 1.6 GW bipolar HVDC overhead line with a total length of 1000 km, equipped with a

dedicated metallic return. The DC line was segmented into 100 km sections to capture the location of the highest overvoltage. Only pole-to-ground faults were applied along the positive pole. For all cases, the highest overvoltage on the healthy pole occurs during a mid-line fault.

Because the converters with FB SMs do not block but instead enter a fault ride-through mode, the influence of the AC network characteristics is negligible. The resulting behavior is similar to that of the LCC technology. Thus, the first crest overvoltage is primarily influenced by the DC line termination configuration:

- Apparatus connected to the DC line, such as harmonic filters, smoothing reactors, and pole surge capacitors;
- DC surge arresters rating;
- DMR configuration, including grounding resistance value and surge arrester rating.

For the HB SMs technology, overvoltages are also mainly influenced by all the DC-side parameters listed above. The choice of the smoothing reactor and pole surge capacitor will affect the overvoltages associated with each fault location along the line, as well as the overvoltage front rise time. The midpoint fault remains the most severe, and particular attention should be paid to the pole surge capacitor, as it increases the midpoint overvoltage with a very fast front. The simulation time steps must be small enough to capture this effect. Because the converter of the faulty pole blocks after fault detection, an interaction occurs between the AC network and the freewheeling diodes of the faulty converter until the AC breakers open. The timing of the fault extinction sequence (e.g. converter blocking, AC breaker opening time, etc.) must be known, as it can slightly affect the overvoltage. However, the influence of these parameters becomes negligible if the DC line is very long since the overvoltage will be governed by the travelling wave reflections.

3. External Overvoltages - Back-flashover Performance During Lightning Events

Lightning is a major factor affecting electric power system performance and remains a leading cause of failures and outages in AC and DC transmission lines. This section focuses on downward negative lightning, which represents about 90% of cloud-to-ground events, and on the back-flashover mechanism caused by strikes to grounded structures as indicated and that prevails on transmission lines installed over moderate and high resistivity soils [4]. Simulations use the Hybrid Electromagnetic Model (HEM) to calculate overvoltages on insulator strings of a ± 600 kV HVDC line due to direct tower strikes, and the Leader Progression Model (LPM) to evaluate back-flashover occurrence and determine the critical current (I_{CRIT}).

The HEM model simulates lightning-related issues, such as calculating transmission line overvoltages from direct strikes, by representing the system as thin-wire elements and evaluating electromagnetic coupling and propagation effects. Details of its formulation are in [5]. The Leader Progression Model (LPM), a traditional flashover model, incorporates various physical phases; for this study, the parameters for negative flash are based on reference [4].

Figure 1 shows a simulated self-supporting 600 kV HVDC transmission tower, 45 m high, supporting two shield wires, two DMRs, and two poles. The HEM model includes main metallic components such as crossarms and trusses. Simulations use a 500 m span between towers and

represent tower-footing grounding as a concentrated parameter with impulse impedance Z_p , ranging from 10 to 80 Ω .

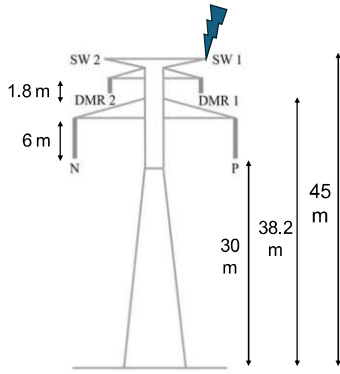


Figure 1 - Simplified representation of the simulated tower of the ± 600 kV HVDC transmission line

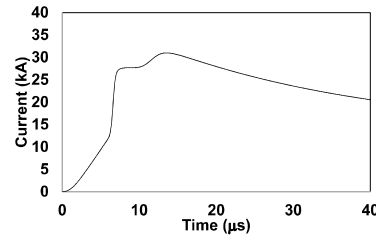


Figure 2 - Simulated lightning current waveform of negative first stroke with median current parameters measured at Mount San Salvatore.

The simulated lightning current waveform is based on measured negative downward lightning at Mount San Salvatore station, as shown in Figure 2. It combines seven Heidler's functions following procedures from [5], matching the median wavefront parameters reported in the technical brochure [4]. Simulations assume a direct strike to the tower's top (see Figure 1).

The assumed calculation procedure is based on the following steps:

1. Lightning striking the top of the tower is simulated by the HEM model that considers the calculation of the overvoltage across the insulators for each value of tower-footing grounding impedance. The DC voltage of the poles is included as a post processing calculation.
2. The critical current (ICRIT) corresponding to each simulated condition is determined by applying the LPM model considering the calculated overvoltages of the previous step.
3. The percentage of lightning currents whose peak value exceeds the critical current is determined according to the lognormal cumulative peak current distributions proposed by reference [4]. This corresponds to the back-flashover probability BF(%).
4. The lightning incidence per 100 km of the line per year is determined according to equation (1) from [6]

$$N_L = N_g \times (28 \times H^{0.6} + b) / 10 \quad (1)$$

where H is the tower height (m), b is the separation distance between shield wires (m), N_g is the Ground Flash Density (flashes/km²/year), N_L is the flashes/100 km/year.

5. The resulting back-flashover outage rate (BFOR) per 100 km of the line per year is calculated according to equation (2):

$$\text{BFOR} = \text{SF} \times N_L \times \% \text{BF} \quad (2)$$

Figure 3 presents the resulting overvoltages across TL insulators of the DMR and insulator string of the positive pole as function of tower-footing impedance, considering the direct lightning strike of the 31-kA peak current illustrated in Fig. 2.

The results show higher overvoltages across TL insulators on the positive pole, primarily due to the increase provided by the 600 kV voltage of the positive pole.

Table 1 presents an evaluation of lightning performance, detailing the calculated critical currents and the associated probabilities of back-flashover occurrence for both the DMR and the positive pole as functions of tower-footing grounding impedance.

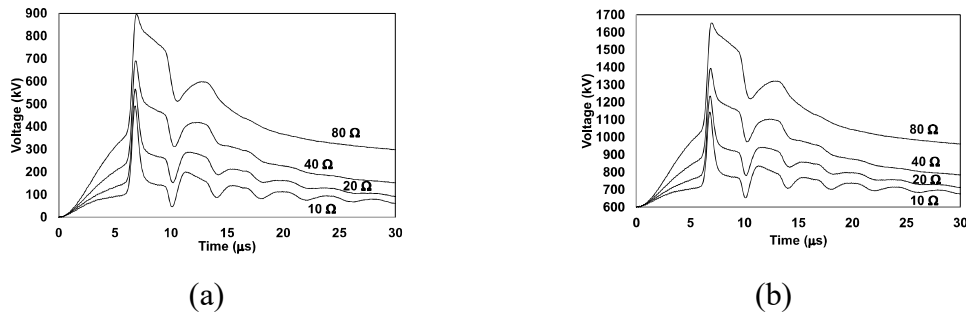


Figure 3 - Overvoltages across TL insulator strings of the DMR (a) and of the positive pole (b) as function of tower-footing impedance Z_p . The effect of the positive pole +600 kV is included in Fig. 3.b

Table 1 – Critical current and corresponding probability of back-flashover occurrence.
Direct lightning strikes at top of the tower.

Z_p (Ω)	DMR Insulator string (L = 1.8 m)		Positive Pole Insulator string (L=6 m)	
	I_{CRIT} (kA)	BF%	I_{CRIT} (kA)	BF%
10	119.04	1.76	298.22	0.01
20	92.07	4.64	222.58	0.08
40	64.48	13.74	152.21	0.60
80	43.71	32.65	101.68	3.25

The results indicate critical currents related to the lightning performance of the DMR about 60% lower than those associated with the insulator string of the pole, thus, resulting in a worse performance of the DMR. Also, the analysis in terms of the probability of back-flashover occurrence reveals probabilities related to DMR of 1.8% to 33%, against 0.01% to 3.3% of the insulator string of the pole. The shorter length of the DMR's insulator string is a relevant factor that contributes to its poorer lightning performance. Even though the voltages are higher on the positive pole insulator, the longer length of its insulator string resulted in a better performance of the pole.

The resulting outage rate per 100 km per year for the DMR and the positive pole is calculated as function of tower-footing grounding impedance Z_p . For the sake of the analysis, three values of ground flash density N_g were assumed: 2, 2.5 and 3 strikes/km²/year, to describe different scenarios of lightning incidence. A span factor equal to 0.6 was assumed from [4]. The results are indicated below.

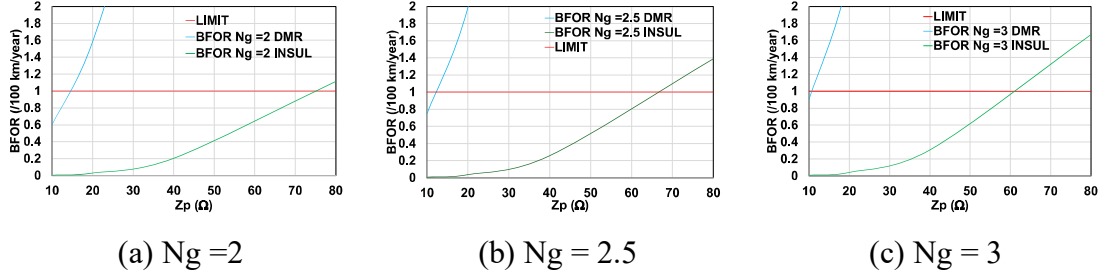


Figure 4 - Calculated back-flashover outage rates of the HVDC line as a function of Z_p . Ground flash density N_g of 2, 2.5 and 3 strikes/km²/year. Blue line: DMR's performance; Green line: positive pole performance; red line: limit of 1 outage/100 km/year.

The intersection of the lightning performance curves with the limit of 1 outage/100 km/year indicates the maximum value of tower-footing impedance to guarantee that expected outage rate. It is important to note that Z_p limit values are significantly lower for the DMR, indicating its worse performance. For the conditions simulated in this study, these values are about 15, 12 and 11 Ω related to the DMR against 75, 66 and 61 Ω related to the positive pole, assuming N_g equal to 2, 2.5 and 3 strikes/km²/year, respectively. Also, it is important to mention that higher N_g would result in major difficulties achieving the required Z_p value. The results obtained suggest the need to adopt longer length counterpoise wires for the HVDC TL towers to match a given performance criterium.

In short, as stated before, lightning-induced faults may cause overvoltages on both DMR and on bipole conductors. As DMR has lower insulation, it may flashover before the bipole conductors in monopolar faults, disrupting dc link function and bipole redundancy. Further insulation coordination studies should prevent this and potential solutions may include more insulators, arcing horns, surge capacitors, high-speed ground switch at the DMR ungrounded end and use of surge arresters. However, it is worth noting that the occurrence of a first flashover will contribute to increasing the value of the critical current to lead to a second flashover in the tower, since it alters the potential distribution along the tower.

4. DMR-Overvoltages Characteristics and Insulation Coordination Implications

The dedicated metallic return (DMR) ensures electrical independence of the two poles and enables continued power transfer in monopolar operation following a permanent pole-to-ground fault. To fulfill this role, the DMR must remain unfaulted during transient events or ensure fast flashover extinction, allowing reliable transition from bipolar to monopolar operation. During DC faults, the DMR may be subjected to significant transient overvoltages despite operating at negligible voltage under normal balanced bipolar conditions. A sustained DMR flashover causes loss of pole independence, potentially preventing reconfiguration to monopolar operation and defeating the intended N-1 functionality. DMR insulation coordination is therefore a critical aspect of HVDC overhead line design, irrespective of converter technology.

Although VSC and LCC technologies differ in fault initiation mechanisms, control strategies, and blocking behavior, these differences primarily affect the very early phase of the disturbance. Once converters block, the subsequent response is governed by the passive

electrical network: DMR overvoltages are dictated by travelling-wave propagation and reflections at line terminations, grounding impedances, and surge arresters. These mechanisms are common to both technologies, making the associated insulation coordination challenges equivalent. The following investigation uses a VSC-based HVDC system as reference; however, a dedicated EMT study remains necessary for each project and configuration to verify applicability and properly assess insulation coordination margins.

The voltage stresses experienced by the DMR were evaluated using EMT simulations. The reference system, described in detail in [7], corresponds to a ± 600 kV, 3 GW bipolar HVDC overhead line of 1000 km, equipped with a DMR and based on half-bridge MMC-VSC technology. The line was segmented to accurately capture travelling-wave effects, and both overhead line and converter-side disturbances were simulated, including pole-to-pole, pole-to-DMR, pole-to-ground, and converter-side DC and AC faults at both terminals.

Under normal balanced bipolar operation, DMR voltage stress is negligible due to cancellation of neutral currents. The highest continuous stress occurs during monopolar operation, when the full DC current returns through the DMR. For the reference system studied in [7], with a rated current of 2.5 kA, a conductor resistance of $0.0578 \text{ } \Omega/\text{km}$, and a line length of 1000 km, the resulting voltage drop is approximately 72 kV, used as the per-unit reference voltage.

EMT simulations show that the most severe DMR stresses arise from transient overvoltages during DC faults, not from continuous or monopolar operation. Pole-to-ground faults on the overhead line were consistently the most critical, generating fast-front overvoltages from travelling waves launched at the fault location and reflected at terminations and grounding impedances. Once converters block, the DMR voltage evolution is governed solely by the electrical network; converter control mode (grid-following or grid-forming) no longer influences the response.

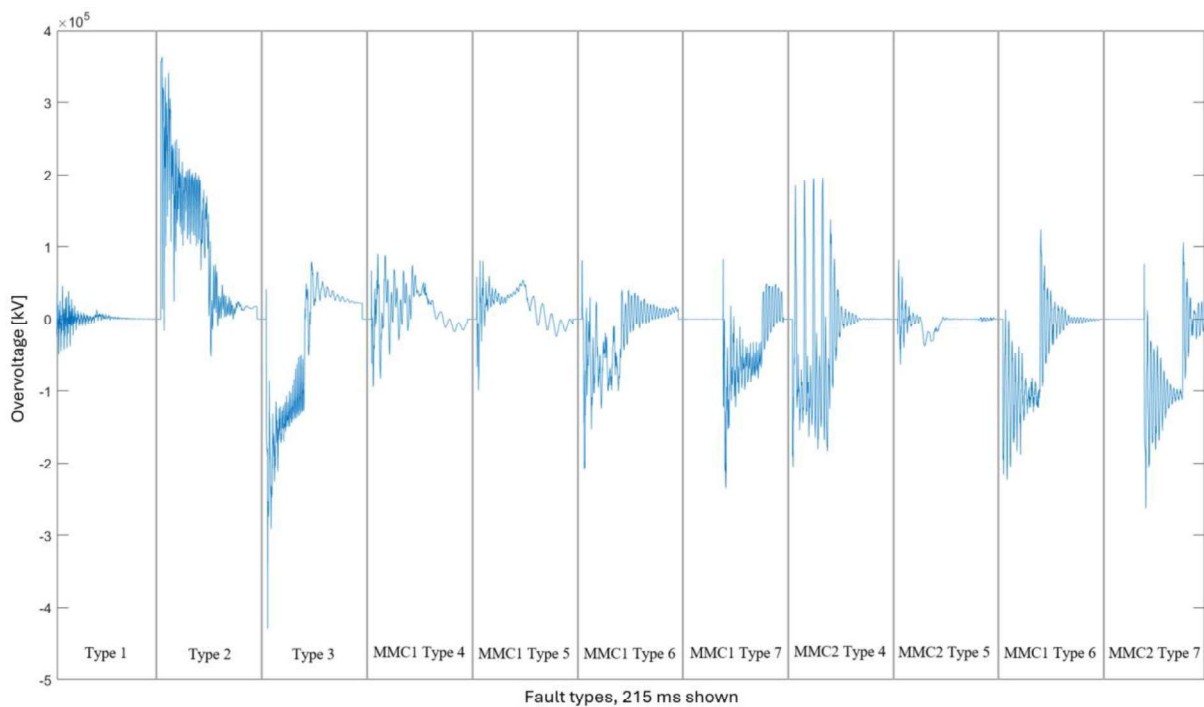


Figure 5 - Overvoltage waveshapes over 215ms for all fault simulated: OHL, MMC1, MMC2

Figure 5 (adapted from [7]) illustrates DMR voltage responses for all simulated fault types over a 215 ms window. Pole-to-ground faults (Type 3) impose significantly higher stress than pole-to-pole (Type 1), pole-to-DMR (Type 2), or converter-side faults, and are therefore used as the governing reference condition for subsequent parametric analyses.

A large-scale parametric EMT study comprising more than 23,000 simulations [8] quantified the influence of key system parameters on DMR overvoltages, results summarized in Table 2.

Table 2: Highest overvoltage measured per fault type and the associated parameters

Fault Type	Max overvoltage	Parameters
P2P	116.48 kV	Fault loc = 19/30; R DMR = 30; ZnO DMR = 2.8; L arm = 0.26; Ltrafo = 0.14; Block delay = 2e-05; AC config = 4
P2DMR	510.54 kV	Fault loc = 10/30; R DMR = 0.5; ZnO DMR = 2.2; L arm = 0.26; Ltrafo = 0.22; Block delay = 4e-04; AC config = 4
P2G	572.62 kV	Fault loc = 14/30; R DMR = 150; ZnO DMR = 2.8; L arm = 0.26; Ltrafo = 0.22; Block delay = 2e-05; AC config = 3

Pole-to-ground faults dominate DMR insulation coordination, with maximum overvoltages typically near the line midpoint. DMR grounding resistance and surge arrester characteristics have the strongest influence on overvoltage magnitude and spatial distribution, while arm inductance, transformer leakage inductance, blocking delay, and AC system strength play secondary roles. These results confirm that DMR insulation coordination is inherently a system-level problem, strongly dependent on terminal grounding philosophy and protection design.

Unlike pole conductors, where pollution performance often governs insulation length, DMR insulation dimensioning is primarily driven by transient overvoltage withstand. The same considerations apply to LCC-based schemes: differences in pre-blocking converter behavior may affect the initial transient, but the subsequent DMR response follows identical physical principles. A dedicated EMT study is therefore required for each project. Finally, laboratory tests reported in [7] confirm that pollution performance is not the governing DMR design criterion, and that standard insulator profiles provide adequate withstand capability with no strong dependence on insulator shape.

5. Insulator Performance

The ionization of air surrounding a DC line increases the pollution level on the insulators compared to an AC line located at the same route, making pollution the main topic for designing a DC string of insulators. It is commonly accepted that for the majority of DC applications the driver in dimensioning a string of insulators is not the classical insulation distance determination based on the usual lightning or switching impulses, but the ability of a given string length to cope with the environmental conditions themselves, enhanced by the polarization of the air surrounding the line. This often leads to longer strings than those strictly required to manage dielectric strength properties of an air gap.

The main question is therefore not a matter of proper definition of the arcing distance or clearance but pollution performance. The selection of the insulator characteristics to manage the contamination conditions is a combination of insulator design and leakage distance.

Concerning insulator types used in DC, among the options for insulators selection, toughened glass and porcelain cap and pin insulators remain the most frequently used type of insulators. Porcelain long rods are not a major actor in this segment. More recently polymer insulators started to be used as well as silicone coated glass and porcelain insulators, mostly for their hydrophobic property. The hydrophobicity of an insulator surface is often presented as a key advantage in highly polluted environments since the water repellency property is transferred to the pollution layer (property of HTM, Hydrophobicity Transfer Material). This can be achieved with composite insulators or silicone coated ceramic and glass insulators.

While classical glass and porcelain have been used extensively, there are fewer DC lines using HTM material in service, mostly in China. The longevity of polymer insulators in DC remains an open question since recently updated standards like [9] and [10], which scope covers AC and DC application still consider that more research is needed to establish a DC test for the interface and connection design, likewise for tracking and erosion. In CIGRE the work done in WG D1.72 has shown that an inclined plan test in DC remains highly questionable with more work needed. Hydrophobicity retention covered by [11] has not yet established clear guidance for DC.

This has led some operators to remain prudent and limit the use of polymers for suspension applications only, while glass or porcelain was used for dead ends, as shown in Figure 6.

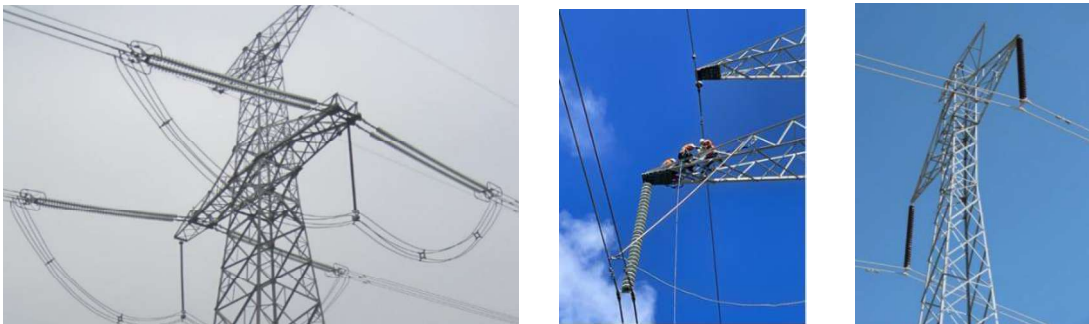


Figure 6 - Left: China 500 kVDC with polymer jumper and glass dead ends. Center: New Zealand 350 kVDC silicone coated glass insulators. Right: USA 500 kVDC porcelain insulators

Silicone coated insulators (Figure 7) have been used in DC for about 20 years in several harsh environments either in desertic or coastal applications as well as in China in mixed pollution conditions. Aging tests and research such as an adaptation of the 2000h multi-stress test used in AC have been performed on silicone coated glass insulators including units returned from the field with positive prospects for the long-term performance.

The performance under pollution of HTM insulators need to be assessed under pollution test conditions taking into consideration the transfer and recovery time. Artificial pollution tests on HTM surfaces have not yet been standardized until very recently with [12] . Recent testing reported in [7] indicates a difference in performance to be further investigated between polymer insulators and silicone coated glass fog type DC insulators to the benefit of the glass insulators which can be explained through considerations of shape [7].

The challenge in DC is the impact of the selection of the USCD (Unified Specific Creepage Distance) to the length of the insulator string. It is commonly accepted that reducing excessively the length of a polymer insulator to take advantage of the hydrophobic performance of silicone can be dangerous if not wisely applied and therefore should be limited by the risk of erosion rather than pure pollution performance. Early degradation of the material could be expected with erosion and loss of hydrophobicity if excessive stress is applied on the housing material.

For glass or porcelain cap and pin insulators the pollution performance is strongly impacted by the shape of the insulator keeping in mind that in DC, the arc tends to jump from one rib to another and subsequently bridge the theoretical leakage distance, as shown in Figure 7. Leakage distance by itself has no meaning without consideration of the most suitable design for DC with respect to the shape of the under skirt of the insulator [13]. Standard [14], a guide for pollution in DC applications, is set for revision. The current USCD recommendation is somewhat conservative, as it relies on comparisons with modern DC insulators that outperform earlier designs in lab tests. These results contrast with IEC standards based on an older EPRI study using average values from shapes that may not reflect new DC designs (see Figure 8), highlighting the need for further validation.

The integration of more realistic USCD values based on real DC insulator performance can help reducing substantially the string length of insulators [13] (Figure 8) and will be discussed in the next standard revision.

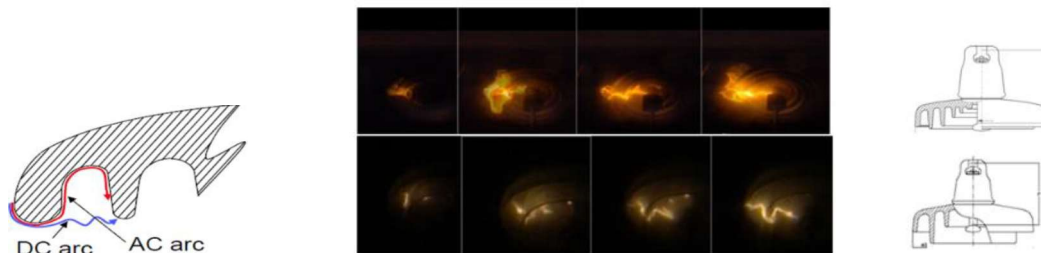


Figure 7 - Arc development in 2 different shapes of insulators: top shape not adapted to DC. Bottom with a specific DC shape. DC arcing will bridge inner ribs if not properly designed

While for relatively normal environments the typical USCD is in the range of 30mm/kV $\pm$ 5mm/kV, more can be needed if the line is in a coastal or desertic region. For example, in Italy DC experience is around 45 to 65 mm/kV with glass fog type insulators, sometimes with silicone coating in extreme coastal areas. Saudi Arabia is building DC lines in coastal areas with glass insulators having a USCD=109mm/kV, including some sections with silicone coated glass insulators. In desertic areas further away from the sea, USCD=90mm/kV was selected.

A practical example for a $\pm$ 600 kV DC line at an ESDD/NSDD = 0.04/0.1mg/cm² with a CUR=1 would require a string length close to 8.7m using curve from [14] in comparison to 6.1m with an appropriate DC shape glass insulator using recent test data as shown in Figure 8 and performed according to [15]. This can be compared to a polymer insulator or a silicone coated glass or porcelain insulator string which would be approximately 5m long (when calculated with [14]) or slightly more to adjust for protection against aging and housing degradation.

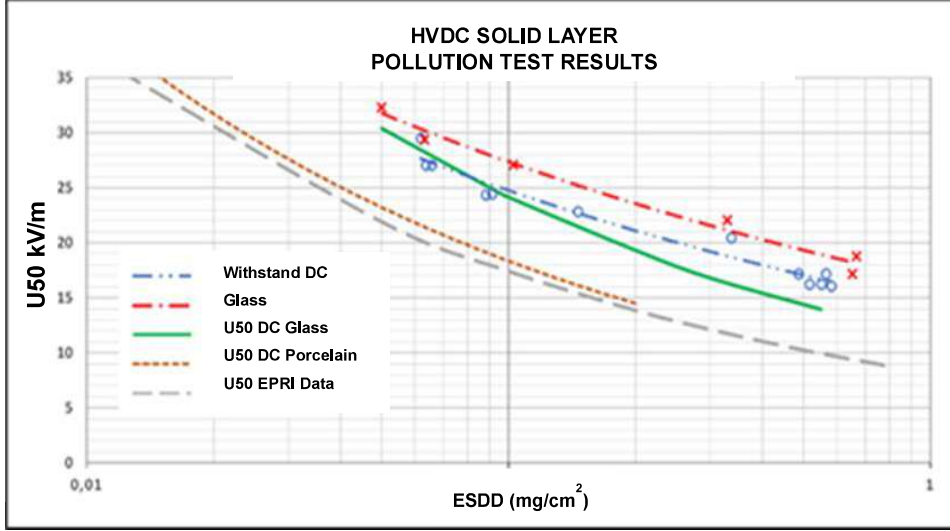


Figure 8 - Comparison of the IEC performance curve with the pollution performance of actual DC-shaped insulators (as per Figure 7), evaluated at NSDD = 0.1 mg/cm² and CUR = 1 (CUR = ESDD_{bottom}/ESDD_{top}). U50 withstand voltage in kV/m of creepage distance tested as per [15].

6. Insulation Coordination Methods

The insulation coordination of HVDC overhead lines follows the same general framework as for AC systems, but its implementation must account for several DC-specific characteristics, notably those related to pollution performance, voltage and pre-stress effects, and environmental influences [16]. In particular, the different mechanisms governing pollution accumulation, dry-band formation, and flashover under DC stress generally require longer insulator strings and adapted insulator profiles, dimensions, and surface properties. For air clearances, available studies indicate that DC breakdown characteristics differ from those observed under AC stress, and a conservative design gradient of approximately 400 kV/m is commonly adopted for continuous DC clearances [17]. For switching and lightning impulses superimposed on DC voltage, the calculation procedures established for AC systems remain generally applicable, especially when the presence of arcing horns allows the insulation to be represented as a plain air gap.

Since the estimation of the risk of failure is a key aspect in insulation coordination of HVDC overhead lines, the statistical approach is recommended. The statistical approach consists of considering the overvoltage profile for different fault locations along the line and determining the probability of failure for each profile, and the corresponding probability of breakdown of the insulation to estimate the risk as follows:

$$R = \int f(U) \times P(U) dU \quad (3)$$

Where $f(U)$ represents the probability density of overvoltages and $P(U)$ the probability of flashover for a voltage U . In DC lines $f(U)$ is not a probability density but a probability of flashover due to a specific voltage value. As for AC systems, insulation coordination starts by defining the representative voltages U_{rp} , the coordination withstand voltages U_{cw} , the required withstand voltages U_{rw} and the specified withstand voltages U_w .

For both VSC and LCC systems, U_{rp} is derived from EMT simulations for the relevant fault scenarios and expressed as high-percentile values, typically the 2% exceedance overvoltage ($U_{2\%}$). The U_{cw} is then determined through a statistical coordination factor based on the insulation breakdown probability distribution. Using the simplified method proposed in [20], the resulting coordination factors are approximately 1.048 for switching impulses and 1.022 for lightning impulses.

The U_{rw} is obtained by converting the U_{cw} to standard reference conditions through the application of the conventional altitude correction [18][20] and safety factors [19]. The U_w is selected as a practical standard value. In the absence of universally standardized DC withstand levels, reference values may be adopted from available guidance, such as Annex C of [19].

In overhead transmission lines, overvoltage might be experienced by several insulators within the same tower and along a number of towers. Given that there is no significant difference in the withstand level of plain air gaps subjected to impulses superposed to AC and DC, the same procedure defined in [20] is applicable to DC:

$$P'(U) = 1 - (1 - P(U))^M \quad (7)$$

Where $P(U)$ is the probability of flashover of a single string and M is the number of identical parallel insulators.

Clearances in air may be determined by assuming a design value of about 400 kV/m for continuous DC voltage, and the same equations featured in [20] **Error! Reference source not found.** for switching and lightning clearances due to the presence of arcing horns, which allow modelling the insulators as plain air gaps. Creepages are determined by the selection of the appropriate USCD for the corresponding site pollution severity. Guidelines provided in [21] are applicable.

In addition to these general principles, some aspects are of particular relevance in HVDC OHL applications. The number and arrangement of poles has a significant impact in the overall electric field and conductor coupling, which may play a major role in the performance, especially for lightning back-flashovers [22]. Moreover, hybrid VSC-LCC systems may require special consideration since differences in technologies and fault types and locations might have different effects in the overvoltages evaluation.

7. Conclusions and Recommendations

It is anticipated that relevant potential improvements to the existing standards can be achieved from this contribution that still has a long way to run until Technical Brochure be published.

Regarding internal overvoltages, an accurate HVDC insulation coordination depends on representative overvoltage assessment via EMT simulations, following [1] and CIGRE guidelines. Early planning must consider converter technology: full-bridge VSCs produce lower overvoltages (similar to LCC), mainly driven by DC-side components, while half-bridge VSCs depend on both DC parameters and AC network interactions, increasing design complexity and cost.

A ± 600 kV HVDC line analysis finds that DMRs are more prone to back-flashover than pole insulator strings due to their shorter insulation level. Tower grounding impedance greatly affects overvoltages and outage rates, requiring stricter grounding for DMR reliability.

The DMR is crucial for HVDC system reliability, as its insulation must withstand transient overvoltages from pole-to-ground faults. EMT studies show these overvoltages are driven by travelling waves and affected by ground resistance and surge arresters' properties. Both VSC and LCC systems require deep EMT analysis for proper DMR insulation coordination.

DC insulator string design is mainly influenced by pollution and air ionization, often requiring longer strings than dielectric strength alone. Glass or porcelain, particularly silicone-coated glass, are favored due to concerns about DC aging in polymer and HTM insulators. Optimizing shape and using precise USCD values can minimize string length while maintaining pollution resistance.

Insulation coordination for HVDC overhead lines is grounded in the same fundamental principles of conventional AC systems. However, the inherent differences between AC and DC systems, as well as between VSC and LCC technologies, must be carefully considered to ensure that these principles are properly adapted and implemented for the specific application.

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