HVAC and HVDC in the same right way: impact of coupling between HVDC and HVAC

Project Report

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Abstract:

The growing need to increase electric power transmission capacity, along with environmental and social constraints associated with the construction of new infrastructure, has driven the development of hybrid towers that combine HVAC and HVDC systems within a single structure. However, this solution presents technical challenges, among which electromagnetic coupling between nearby lines stands out. This work provides a detailed analysis of transient coupling phenomena occurring between HVAC and HVDC systems that share a tower, considering events such as lightning strikes and single phase faults in the AC network.
Different geometric tower configurations (standard, horizontal, and vertical) have been modeled, and the influence of distance and orientation between conductors on the magnitude of induced voltages and currents has been evaluated.
The results show that not only distance, but also geometric symmetry and the three dimensional arrangement of conductors critically influence the severity of the coupling. This study provides valuable insights for the safe and efficient design of hybrid HVAC-HVDC infrastructures, contributing to improved performance under severe disturbances.

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Preface

Aalborg University, May 28, 2025

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Chapter 1

Introduction

The ongoing transition toward a green and decentralized energy system has significantly increased the demand for high capacity, long distance power transmission. This growing demand is driven by the expansion of renewable energy sources, which are often located far from consumption centers, and by the integration of distributed generation into the grid.[1] However, the deployment of new transmission lines faces growing resistance due to environmental, regulatory, and social constraints. Public opposition to the construction of new high voltage corridors has made the approval and implementation of new infrastructure increasingly difficult.[2]

In response to these challenges, one promising solution is the use of hybrid HVAC-HVDC multi circuit towers. These structures allow both alternating current (AC) and direct current (DC) transmission lines to share the same physical support, thus maximizing the utilization of existing rights of way and reducing the environmental footprint of new projects.[3] Integrating HVDC systems into existing HVAC corridors not only optimizes land use and lowers construction costs, but also improves transmission efficiency and operational flexibility, particularly for interconnections across long distances or asynchronous grids.[4], [5]

Despite these advantages, the close physical proximity between AC and DC circuits introduces a new technical challenge: electromagnetic coupling. When conductors are installed within the same structure, time varying electric and magnetic fields generated in one system can induce undesired voltages and currents in the neighboring system. This effect becomes particularly relevant under transient conditions, such as single phase to ground faults or lightning strikes, where the sudden variation in current (di/dt) leads to strong inductive disturbances.[6]

If not properly accounted for, these coupling effects may compromise the operation of HVDC systems, impacting converter stations, protection relays, and insulation coordination. Moreover, the severity of the coupling depends not only on the electrical characteristics of the systems involved, but also on their geometric arrangement, specifically, the distance and spatial orientation between conductors.

1.1 Problem Statement

The increasing demand for power transfer, driven by the green transition and decentralized power generation, is challenging the traditional approach to transmission lines. The use of hybrid HVAC-HVDC multi-circuit towers is a potential solution to increase capacity without constructing new towers. However, the proximity of HVAC and HVDC transmission lines in the same tower may cause electromagnetic coupling, leading to potential issues such as induced voltages and misoperations.

1.2 Motivation

The green transition and decentralized power generation are accelerating the need for efficient power transmission. The construction of new towers for additional lines faces public opposition, making hybrid HVAC-HVDC towers a promising solution. However, the electromagnetic coupling between HVAC and HVDC systems in the same tower is a critical concern, especially under transient conditions like lightning strikes, which may lead to significant operational challenges and safety risks.

1.3 Project Objective

The main objective of this work is to analyze transient electromagnetic coupling phenomena between HVAC and HVDC transmission lines that share the same tower structure, within the context of hybrid configurations. To this end, the following specific objectives have been defined:

- To study how different types of transient events, such as lightning strikes or single phase faults in the HVAC network, induce electrical disturbances in the conductors of an adjacent HVDC line, through the analysis of induced overvoltages and overcurrents.
- To evaluate the effect of the fault initiation instant in the AC network (zero crossing or voltage peak) on the intensity of transient couplings in the HVDC line.
- To analyze how the distance between AC and DC conductors affects the level of electromagnetic coupling, especially considering the relationship between physical separation and the magnitude of the induced voltage or current.

- To compare different geometric configurations of hybrid towers (standard, horizontal, and vertical) to identify how the three dimensional spatial arrangement of conductors influences the distribution and severity of the coupling.
- To characterize the individual behavior of each conductor in the HVDC system (positive pole, negative pole, and metallic return), analyzing how their physical location and electrical configuration determine their susceptibility to coupling.

1.4 Software

The primary software tool used for this project will be PSCAD (Power Systems Computer Aided Design), which will be employed to model and simulate the behavior of HVAC and HVDC lines, especially focusing on the coupling effects and transients caused by lightning strikes.

1.5 Scope and limitations

The scope of the project includes:

- Modeling of simplified tower structures with shared AC and DC conductors using representative geometries: standard, horizontal, and vertical configurations.
- Simulation of lightning strikes (on ground wire, AC conductor, and DC conductor) and AC faults (triggered at voltage zero crossing and at voltage peak).
- Evaluation of induced voltages and currents in the HVDC conductors (positive, negative, and metallic return), and analysis of how these are affected by fault type, conductor proximity, and tower layout.

However, the study is subject to the following limitations:

- The electromagnetic coupling is analyzed under transient conditions only. Steady state or harmonic coupling effects are not within the scope of this work.
- The insulation behavior of the system is simplified. Surge arresters, corona effects, and flashover mechanisms of insulators are not modeled. As such, no breakdown or protection coordination is considered.
- Only the surge impedance of the grounding cable is included in the tower model. The surge impedance of insulator strings is neglected, as they are assumed to act as high impedance elements under non flashover conditions.
- The simulations are performed in PSCAD with a focus on qualitative and comparative insights rather than detailed field measurement validation.

Chapter 2

State of art

2.1 HVAC and HVDC Transmission Lines

With the increase in renewable plants around the world and the desire to locate these plants far from cities [1], the need to transmit energy as efficiently as possible arises. Therefore, DC transmission lines are increasingly used in the long distance transmission. DC transmission systems are more efficient than AC systems for long distance power transmission because they experience lower losses due to the absence of reactive power making them more cost effective over vast distances.

An example of this is in China. The study [7] conducted by Songtao Chen and collaborators focuses on the Yangzhou-Zhenjiang ±200kV transmission project, the first AC to DC transmission project in China. This project uses existing AC transmission towers to carry out DC transmission lines, significantly improving transmission density and efficiency without the need for large additional investments.

Another example is the study [8], which proposes the installation of a ±800 kV bipolar UHVDC line to transmit 6000 MW of energy over 2800 km from Iraq to Romania, as a gateway to Europe.

As can be seen, more and more projects are being proposed that base their transport lines on DC, either by using the old AC transmission system and converting it to DC, as in the case of [7], or by creating the new system from scratch, as in the case of [8]. This has also generated interest in combining both electrical transmission systems in a single tower.

In the case of [9], the study analyzes the feasibility of implementing hybrid transmission corridors in Chile, where alternating current (HVAC) and direct current (HVDC) lines are combined. This arises as a solution to transport energy more efficiently from the north of the country, where the main sources of renewable generation are located, to the metropolitan region, where demand is higher. The conclusion of this study is that electromagnetic interactions are not critical but should be considered in the design of the hybrid corridor, as voltage and current oscillations can affect system stability.

In the case of [10], the study analyzes the electromagnetic interaction between alternating current (AC) and direct current (DC) transmission lines when installed on shared hybrid towers. With the growth in energy demand and limitations in acquiring new transmission corridors, the conversion of existing AC lines to DC or the installation of AC and DC lines on common structures has been proposed. This study arrives at the conclusion that the overvoltages induced by faults in the AC system can be significant, especially in single phase to ground faults and line to line to ground faults.

The project explores the capacitive and inductive coupling effects, both in steady state conditions and transient events. These coupling effects play a relevant role in combining AC with DC, as we will see in the following sections.

2.1.1 Basic Principles of HVAC Transmission

High Voltage Alternating Current transmission is the most common method for transporting electrical energy over medium to long distances. In a typical three phase HVAC system, voltage and current alternate sinusoidally at a frequency of 50 or 60 Hz, depending on the country.

The main components of HVAC transmission include transmission towers, three phase conductors, insulators, grounding wires, and transformers.

From the electromagnetic coupling perspective, AC lines are characterized by their alternating magnetic fields, which can induce voltages and currents in nearby conductors. Additionally, capacitive coupling may occur due to the electric field between conductors. These interactions become especially relevant in hybrid towers where physical proximity enhances mutual influence.

Key aspects to consider:

- AC transmission is affected by reactive power, limiting long distance efficiency.
- The alternating nature of current leads to time-varying electromagnetic fields.
- AC systems can induce 50/60 Hz components on nearby lines during faults.
- They are vulnerable to transient overvoltages during faults.

HVAC lines are a source of significant electromagnetic interference when sharing towers with DC lines. During single phase to ground faults or switching events, strong magnetic and electric fields may couple into the DC system, potentially disturbing its operation and protection schemes.

2.1.2 Basic Principles of HVDC Transmission

High Voltage Direct Current transmission is increasingly used for long distance transfer due to its superior efficiency. Unlike AC, DC does not suffer from reactive power losses and allows transmission with reduced conductor size and fewer losses.

A typical bipolar DC configuration consists of:

- A positive conductor (+V)
- A negative conductor (–V)
- A metallic return (MR) conductor or ground return path

The MR conductor is used to carry the return current under normal or fault conditions. Its role is crucial for balancing the system and providing a low resistance path during monopolar operation or unbalanced faults.

From the coupling perspective, DC lines are generally less sensitive to electromagnetic interference in steady state. However, during transients (such as AC line faults or lightning strikes), induced AC components on the DC side can affect the operation of the transmission system.

Key aspects to consider:

- DC systems use constant polarity current, leading to static magnetic fields.
- Converter transformers are sensitive to induced AC ripple.
- The MR conductor can act as a pathway for induced currents during faults.

Understanding the function of the MR conductor and the behavior of the DC system during AC side disturbances is critical for evaluating the risk of induced voltages and for validating simulation results under fault conditions.

2.2 Electromagnetic Coupling in Transmission Systems

In the search for solutions to increase power transmission capacity efficiently and sustainably, the use of hybrid HVAC HVDC towers emerges as a promising alternative. These structures, which host both alternating current and direct current lines, can optimize the use of existing power corridors, minimizing the need for new constructions. However, the proximity of these systems introduces electromagnetic coupling phenomena, the analysis of which is crucial to ensure operational stability and safety, especially during transient events such as lightning strikes.

In overhead electric power transmission lines that have physically close paths between circuits, such as parallel lines or circuits from different lines, mutual coupling between circuits occurs. This coupling can happen between conductors and ground, both among the conductors of the same circuit and with the conductors of the parallel circuit. This is shown in various studies such as[11] [12]

Electromagnetic coupling in transmission systems refers to the interaction between electrical circuits due to mutual electromagnetic fields. In the context of power transmission, when high voltage alternating current and high voltage direct current lines are in close proximity or share hybrid transmission towers, different coupling effects can influence the performance and stability of both systems [10] [12].

This electromagnetic coupling in hybrid HVAC-HVDC systems primarily occurs due to capacitive and inductive effects. Capacitive coupling arises because of the electric field between conductors generated by the voltage, while inductive coupling occurs due to the magnetic field generated by the current flow. These effects can lead to induced voltages or currents in nearby circuits, affecting the stability and operation of both HVAC and HVDC systems:

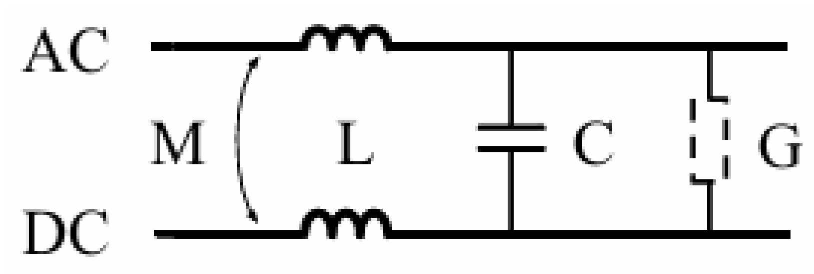

Figure 2.1: Coupling elements of parallel AC and DC lines[10]

To complement the understanding of electromagnetic coupling in hybrid HVAC-HVDC configurations under both normal and transient conditions, it is essential to consider studies such as [13], which specifically analyzes the coupling between MMC-HVDC and AC lines that share the same tower. The authors point out that, due to the inherent asymmetry of transmission lines, the coupling is not limited to ground and zero sequence components, but can exist between each mode and sequence component, potentially affecting adjacent HVDC systems even during normal operation and under AC system faults.

Following the same line of complementing information on electromagnetic coupling in transmission systems that share structures, the study [14] also addresses this topic, focusing on the assessment of electromagnetic coupling between lines of different voltages that share the same structures. In this particular case, the research focuses on a conventional 69 kV transmission line and a compact 11.4 kV overhead distribution line, both sharing the same towers. Electromagnetic interactions were analyzed under steady state conditions, during the occurrence of faults in the high voltage line, and during the energization of the transmission line. The conclusions of this work highlight the importance of considering electromagnetic coupling to ensure the safety of maintenance personnel, proposing appropriate procedures, as well as the need to install surge protection devices in the low voltage network to increase the safety of customer equipment.

2.2.1 Inductive Coupling

Inductive coupling occurs when the magnetic field generated by AC transmission lines induces current in adjacent DC circuits. This phenomenon is influenced by several factors, including the separation distance between the lines, the configuration of the transmission lines, and the system load conditions[15][16][17].

The inductance of a transmission line is a key parameter in understanding inductive coupling. For a single phase two wire system, the inductance L per unit length can be calculated using the formula:

$$L = \frac{\mu_0}{2\pi} \ln\left(\frac{D}{r}\right) \tag{2.1}$$

where:

- μ_0 is the permeability of free space ($4\pi \times 10^{-7}\,\text{H/m}$),
- D is the distance between the centers of the two conductors,
- r is the radius of the conductors.

In a three wire system, the inductance calculation becomes more complex due to the mutual inductance between the phases. For a symmetrical three phase line, the inductance per phase can be approximated by:

$$L = \frac{\mu_0}{2\pi} \ln\left(\frac{D}{r}\right) + \text{mutual inductance terms} \tag{2.2}$$

Inductive coupling can lead to significant issues in hybrid HVAC-HVDC systems. For instance, a transient event in the HVAC line, such as a lightning strike, can induce voltages and currents in the HVDC line that may challenge the converter control systems. Similarly, a transient in the HVDC line can induce voltages in the HVAC line, potentially affecting the protection systems.

2.2.2 Capacitive Coupling

Capacitive coupling occurs when there is a voltage difference between parallel conductors, leading to an electric field interaction. This phenomenon is influenced by several factors, including the separation distance between the lines, the configuration of the transmission lines, and the system load conditions.[18][19]

In hybrid transmission systems, capacitive coupling results in a fundamental AC frequency component being superimposed on the DC voltage. The capacitance C between two parallel conductors can be calculated using the formula:

$$C = \frac{\pi \epsilon_0 \epsilon_r}{\ln\left(\frac{D}{r}\right)} \tag{2.3}$$

where:

- ϵ_0 is the permittivity of free space ($8.854 \times 10^{-12}\,\mathrm{F/m}$),
- ϵ_r is the relative permittivity of the medium between the conductors,
- D is the distance between the centers of the two conductors,
- r is the radius of the conductors.

Capacitive coupling can lead to significant issues in hybrid HVAC-HVDC systems.[10]. For instance, the AC voltage component induced on the DC line can interfere with the operation of HVDC converters and protection systems. Additionally, capacitive coupling can cause unwanted oscillations and voltage spikes, which may affect the stability and reliability of the power transmission system.

Studies have shown that the effects of capacitive coupling can be mitigated by optimizing the configuration of the transmission lines, increasing the separation distance between the AC and DC lines, and using shielding techniques.

2.2.3 System effects

There are numerous studies that analyze the electromagnetic coupling between an AC transmission line and a DC transmission line, as seen in [12][10][11][5].

The study [12] examines the effect that coupling can have during steady state conditions. However, [20] states that there is no significant electromagnetic coupling effect between AC and DC systems under steady state conditions, and no abnormal harmonics were observed in either system.

All studies agree that, during a fault, the coupling effect intensifies, potentially causing various issues in the system. [10] highlight that during faults, the intensified coupling can lead to increased electromagnetic interference, which may disrupt the operation of protection systems and communication links. [12] discuss that faults can cause transient overvoltages and current surges, which can damage equipment and reduce the reliability of both AC and DC systems. [20] indicate that during faults, the coupling can result in harmonic distortions and instability in the power system, affecting the overall performance and safety. [5] identify that faults can lead to overvoltages, electromagnetic interference, and equipment damage, which can compromise the integrity of the high voltage network.

During fault conditions, such as lightning strikes, switching events, or AC line energization, transient overvoltages can be several times higher than steady state induced voltages. These transients can cause insulation stress, overvoltage protection challenges, and potential failures in HVDC converter stations [10].

The study [12] focuses on the analysis of coupling between a DC transmission line and an AC transmission line. When both lines are in close proximity or share the same corridor, electromagnetic interactions occur in both steady state and transient conditions. In steady state operation, capacitive and inductive coupling causes a fundamental frequency component from the AC network to be superimposed on the DC line current, while a DC component can be induced in disconnected AC lines.

According to this study [12], the major issues associated with the fundamental frequency current in the DC circuit are as follows:

- Potential core instability in converter transformers due to flux displacement caused by a DC current component. The presence of a fundamental frequency in the system generates both a DC current and a second harmonic current on the line side of the converter transformer, leading to progressive core saturation in one direction. This phenomenon induces even harmonics in both AC and DC systems, impacting overall system performance and posing a significant challenge to DC converter operation.
- Increased heating in converter transformers due to losses caused by leakage flux.
- Reduced lifespan of converter transformers due to insulation degradation between laminations, caused by intensified magnetostrictive forces.

- Increased audible noise in converter transformers due to a significant rise in magnetostriction resulting from core saturation.
- Saturation of current transformers (CTs) used for DC control and protection. Additionally, AC current transformers can be affected during DC system disturbances.
- Higher harmonic generation by the converters, which must be considered in the design of AC and DC filters.

2.2.4 Coupling in PSCAD

To thoroughly investigate electromagnetic coupling phenomena and their implementation in PSCAD, a representative simulation model was developed. The system under study consists of a AC 400 kV energized conductor sharing the same tower structure with an adjacent non energized line, a configuration that enables comprehensive characterization of coupling effects. The PSCAD implementation, illustrated in Figure 2.2, models two parallel conductors with variable separation distance to study distance dependent coupling effects.

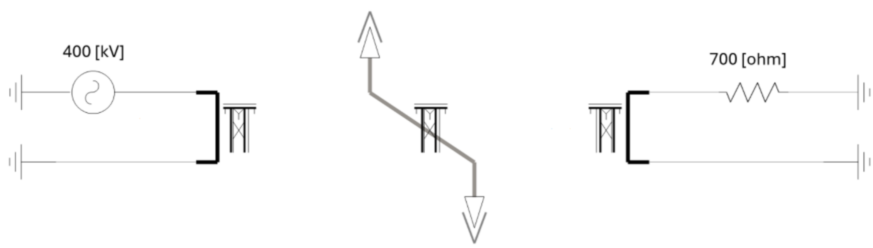

Figure 2.2: Implementation scheme of coupled conductors in PSCAD

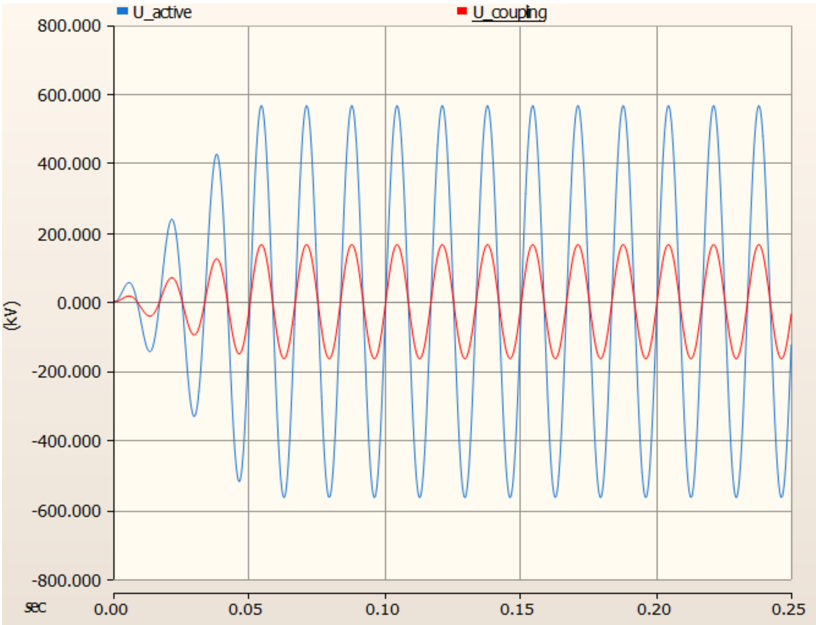

Figure 2.3: Conductor voltages at 5m separation

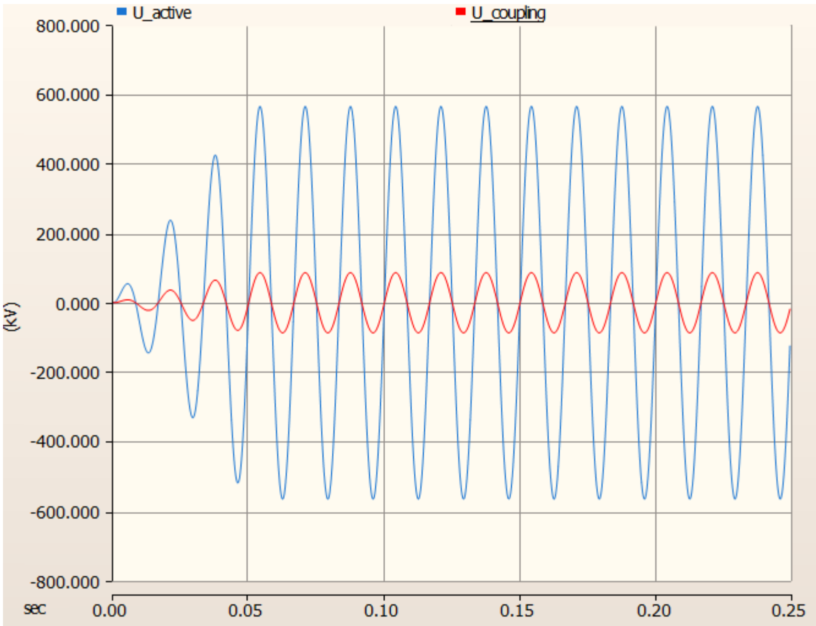

Figure 2.4: Conductor voltages at 15m separation

This PSCAD analysis provides empirical validation of the coupling mechanisms described throughout section 2.2.

Figures Figure 2.3 and Figure 2.4 illustrate the coupling between two parallel conduc-

tors when an AC current flows through the source line. The results correspond to two different separation distances: 5 m and 15 m, respectively.
In both cases, the energized conductor induces both a capacitive signal, caused by existing voltage differences, and an inductive signal, caused by the magnetic field generated by the current.

Given that the source current is sinusoidal, the induced voltage also exhibits a sinusoidal shape, though its amplitude is attenuated based on the mutual inductance M, which depends strongly on the spacing between conductors. This relationship is described in Equation 2.2 and Equation 2.3 explains why the induced voltage in Figure 2.3 (5 m spacing) is significantly higher than in Figure 2.4 (15 m spacing).

These observations confirm that the coupling magnitude is inversely related to the distance between conductors. As conductor spacing increases, the magnetic field linkage, and therefore the induced voltage, decreases. This is consistent with the analytical models and field approximations discussed in section 2.2, as well as with the empirical data reported in [10] and [12].

The trend is further summarized in Figure 2.5, which displays the coupling magnitude as a function of conductor separation. The PSCAD simulations clearly validate the theoretical expectation coupling is strongest when conductors are close, and decays logarithmically with distance.

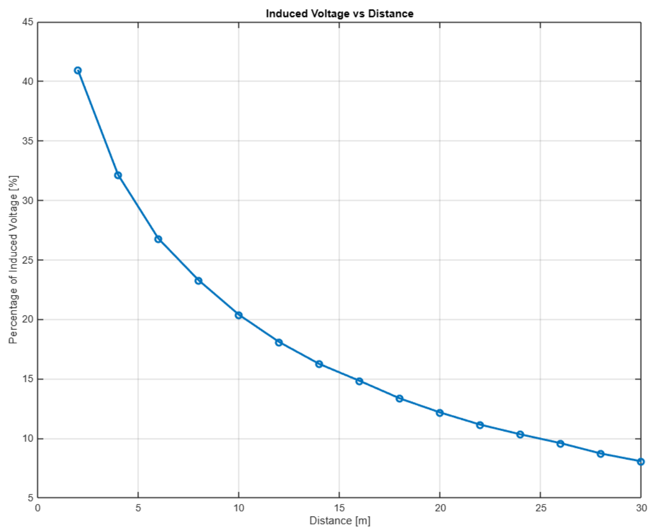

Figure 2.5: Coupling magnitude as a function of conductor separation

This behavior confirms the inverse logarithmic relationship between coupling strength and conductor spacing predicted by electromagnetic theory, and matches findings from [10] and [12] regarding hybrid tower configurations.

These findings underscore the importance of physical layout in mixed transmission corridors. Even in the absence of direct electrical connection, inductive and capacitive interactions can produce measurable disturbances in nearby systems, especially under fault or high current conditions.

2.3 Lightning

2.3.1 Characterization of Atmospheric Discharges

Atmospheric discharges, commonly known as lightning, are natural electrical phenomena that occur when electrical charges accumulate in clouds, generating a significant potential difference with respect to the ground or between different regions of the atmosphere. This electrical imbalance can result in a sudden discharge of electricity, manifested as lightning. These discharges can be classified into several types, with the most common being cloud to ground, intra cloud, and cloud to cloud discharges. [21]

Despite intra cloud discharges being the most frequent within the theoretical framework of the project, cloud to ground discharges have been the subject of greater study due to their direct impact on infrastructure.

Depending on the polarity and direction of the discharge, they can be classified into four categories:

- DownwardNegative
- UpwardNegative
- DownwardPositive
- UpwardPositive

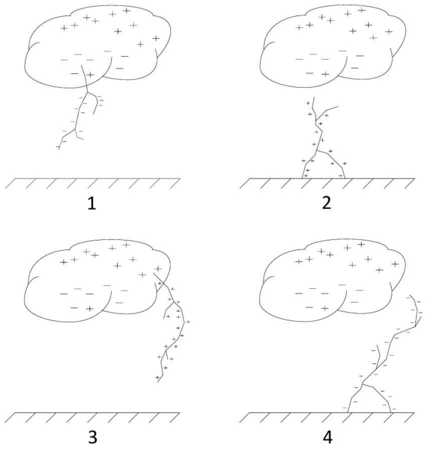

Figure 2.6: Cloud to ground lightning classification[22]

Negative polarity downward lightning flashes are the most common, accounting for about 90% of all global cloud to ground flashes, while positive polarity downward flashes make up the remaining 10%. [2] For this reason, in the present project, when considering a fault caused by lightning, only negative downward lightning will be considered.

2.3.2 Characteristic Parameters of a Lightning

The current generated during an atmospheric discharge, commonly known as lightning, presents a characteristic waveform that is fundamental for the design and analysis of electrical protection systems. This waveform is characterized by a rapid increase until reaching a peak maximum, followed by a slower decrease.

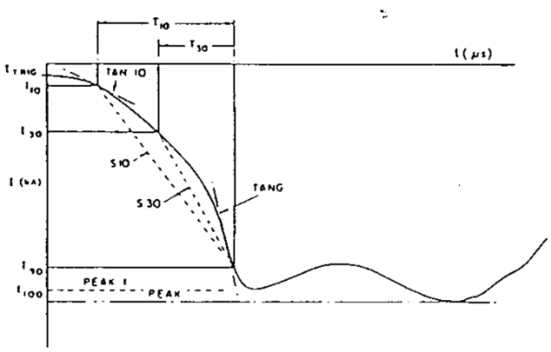

Figure 2.7: Wave Shape Lightning[23]

The key parameters that describe this waveform include:[24]

- Peak current (Ip): Maximum value of the current during the discharge.
- Rise time (T1): Interval from the start of the discharge until the peak current is reached.
- Fall time (T2): Duration from the peak current until it decreases to a specific value, commonly 50% of Ip.
- Transferred charge (Q): Integration of the current over time, representing the total amount of electrical charge transferred.
- Specific energy (W): Energy dissipated by the lightning current, calculated as the integral of the current squared over time.

The waveform of lightning can be very complex. Therefore, from an engineering perspective, approximations are used to mathematically model this waveform. One of the most recognized is the Heidler function, which allows precise representation of both the rising and falling phases of the lightning current. This function is widely used in electromagnetic transient simulations and in the design of lightning protection systems.[25] Another function employed is the double exponential, which, although simpler, offers an adequate approximation for certain studies where a less complex representation of the waveform is required.[25]

For more information about these methods, you can consult [25].

The lightning current waveform used in this project is based on the model proposed by CIGRÉ, which represents the current as a double ramp impulse defined by three key parameters: the peak current (Ic), the front time (Tc), and the tail time (Th). [23] In the following image, the waveform is shown:

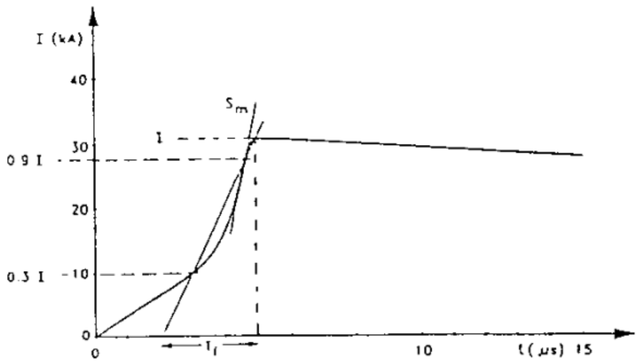

Figure 2.8: Lightning Waveform CIGRE [23]

When representing the characteristic values of lightning, we encounter a problem because not all lightning strikes are the same. To define the characteristics of the lightning used in the simulation, the values used in the following study are employed.

For the values to be used in the characterization of lightning, this project will be based on a study conducted at the Morro do Cachimbo station (MCS) in Brazil. The study analyzes lightning current parameters in a tropical region, specifically focusing on negative cloud to ground return strokes, which are of particular interest in the project, as mentioned in the previous section. The values used for the characterization of lightning are as follows:

Table 2.1: Data of the current of lightning. [26]

	Unit	Geometric mean
Ip	kA	43.3
Td 10/90	μs	6.41
T50	μs	56.2

If more information about the study is desired, it can be consulted in [26].

2.4 Phase Fault

When any event occurs in a circuit that interferes with the normal flow of current, it is considered a fault. In a power system, the element most likely to fail is the transmission line, as it covers a large area.

Most faults in a transmission network are of the unsymmetrical type, especially phase to ground faults, which are statistically the most frequent. For example, in the Nordic European system, 71.4% of such faults are recorded[27], although they are not the most severe.

Faults can be classified into: shunt or short circuit faults, series or open circuit faults, and simultaneous faults[28]. For this project, short circuit faults will be analyzed to understand how they affect coupling between lines.

Below is a brief explanation of the different faults caused by short circuits.[28]

2.4.1 Single Line to Ground Fault

This fault occurs when one of the phases makes contact with the ground at point F with a fault impedance Z_f, which is generally insignificant. In this case, the currents of each of the sequences are represented as in Equation 2.4, assuming the fault occurs in phase A.

$$I_0 = I_1 = I_2 = \frac{V}{Z_0 + Z_1 + Z_2 + 3Z_f} \tag{2.4}$$

2.4.2 Line to Line Fault

A line to line fault occurs when two phases of the network interconnect at a fault point F with a fault impedance Z_f. Assuming the fault occurs between phases b and c, the equation representing this condition is:

$$I_{bc} = \frac{V}{Z_1 + Z_2 + Z_f} \tag{2.5}$$

2.4.3 Double Line to Ground Fault

This fault occurs when two phases and the ground interconnect at point F with a fault impedance Z_f. In this case, the system is represented by the equivalent circuit shown. The total current of the system is given by Equation 2.6, Equation 2.7, and Equation 2.8 where I_{abc} is equal to three times the current of the equivalent circuit $\bar{I}$ plus the short circuit value for each sequence.

$$I_{abc} = 3\bar{I} = \frac{V}{(Z_0 + Z_f)||(Z_2 + Z_f)||(Z_1 + Z_f)} \tag{2.6}$$

$$I_{a2} = \left(\frac{(Z_0 + Z_f + 3Z_g)}{(Z_2 + Z_f) + (Z_0 + Z_f + 3Z_g)} \right) * I_a \tag{2.7}$$

$$I_{a2} = \left(\frac{(Z_2 + Z_f)}{(Z_2 + Z_f) + (Z_0 + Z_f + 3Z_g)} \right) * I_a \tag{2.8}$$

2.4.4 Three Phase Fault

A three phase fault, which is symmetrical, occurs when all phases of the power system connect at a single point F with fault impedances Z_f and ground Z_g. The fault impedance in this case is calculated with Equation 2.9.

$$I_a = \frac{V_l}{Z_l + Z_f} \tag{2.9}$$

Chapter 3

Modelling

In this chapter, the models used to simulate the hybrid HVAC-HVDC system in PSCAD are described in detail, with the aim of evaluating the effects of electromagnetic coupling during transient phenomena such as lightning strikes or phase faults. Each subsection addresses a specific component of the system, explaining the modeling logic, the blocks used, and the configured parameters.

3.1 Tower and Line Model

In Figure 3.1, the transmission tower selected for the project is shown. This tower allows the coexistence of HVAC and HVDC lines, sharing the same physical infrastructure. This type of configuration is known as a hybrid AC/DC tower and is increasingly used to optimize the use of electrical corridors.

The transmission system represented in the simulation consists of two independent sources: an alternating current source and a direct current source. The HVAC source operates at a voltage level of 380 kV RMS, while the HVDC source operates at 500 kV.

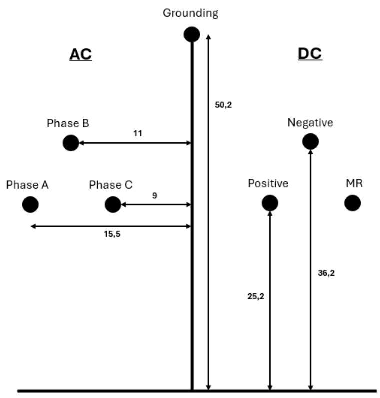

Figure 3.1: Geometry of the conductors in the hybrid HVAC-HVDC tower

The vertical arrangement of the conductors plays a key role in the levels of electromagnetic coupling between the lines. The smaller the distance between the AC and DC conductors, the greater the induced capacitive and inductive effects. This geometry will be especially relevant in the transient analyses carried out in Chapter chapter 4.

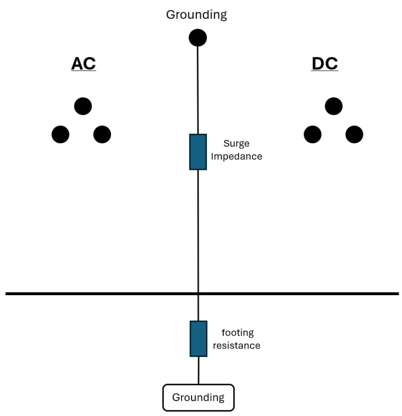

Figure 3.2: Modelling of the tower with surge impedance

In this project, only the surge impedance of the grounding cable has been included in the tower modeling (Figure 3.2), while the surge impedance of the insulators between the phase conductors and the tower structure has been neglected. This simplification is justified by the fact that, under normal conditions and during fast transient events such as lightning, the insulators primarily act as high impedance barriers unless a flashover occurs. Since the study does not simulate insulator breakdown or flashover phenomena, their influence on the electromagnetic coupling is minimal. On the other hand, the grounding cable serves as the main return path for lightning currents.

3.2 Lightning Model

To simulate the impact of a lightning strike on the system, the *Surge Generator* block of PSCAD was used, configured with the standard model proposed by CIGRÉ. This model can accurately represent the typical waveform of atmospheric discharge current.

Once the CIGRÉ model was selected, statistical values obtained from field studies were introduced, as shown in Table 2.1. These parameters include the peak current, front time, and tail time of the impulse.

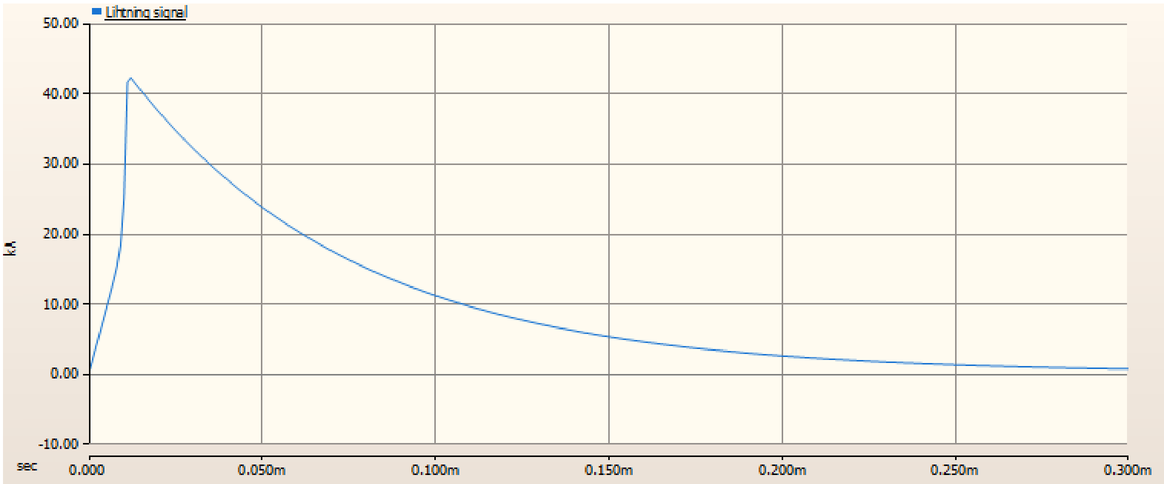

Figure 3.3: Lightning waveform generated in PSCAD

As observed in Figure 3.3, the generated waveform faithfully follows the profile defined by CIGRÉ, with a rapid rise in current followed by a slower decline.

3.3 Phase Fault Model

For the analysis of internal events in the HVAC system, a single phase to ground fault model has been implemented using the *Single Phase Fault* block of PSCAD. This type of fault represents 70% of the faults recorded in high voltage transmission networks, being the most common, as shown in section 2.4, and therefore highly relevant for evaluating the interaction with DC lines.

The model allows selecting both the affected phase and the fault impedance. In this case, a fault has been introduced in phase A with a low grounding impedance. The fault has a duration of 0.2 seconds.

In high voltage systems, a clearing time of 0.2 seconds for a single phase to ground fault can be justified based on international standards such as **IEEE C37.112**[29] and **IEC 60255-151**[30]. These standards indicate that, depending on the type of time-current characteristic curve and the level of fault current, clearing times may range from 0.1 to 0.5 seconds. A value of 0.2 seconds is commonly accepted to ensure rapid fault elimination without compromising protection coordination.

Regarding the fault impedance, a value of 0.01 Ω has been considered as representative of a direct connection to ground, minimizing the attenuation of the phenomenon and allowing the maximum impact on the induced currents to be observed.

Chapter 4

Simulation of Faults in Electrical Distribution Systems

4.1 Lightning strike Ground Wire

In this first simulation case, the impact of a lightning strike on the ground wire (also known as the protection wire) of an electrical transmission tower is modeled in PSCAD. This phenomenon is common in high voltage systems, as lightning tends to strike the conductive elements located at the highest positions, with the guard wire being the component specifically designed to divert the lightning current to ground, thus protecting the main conductors of the transmission system.

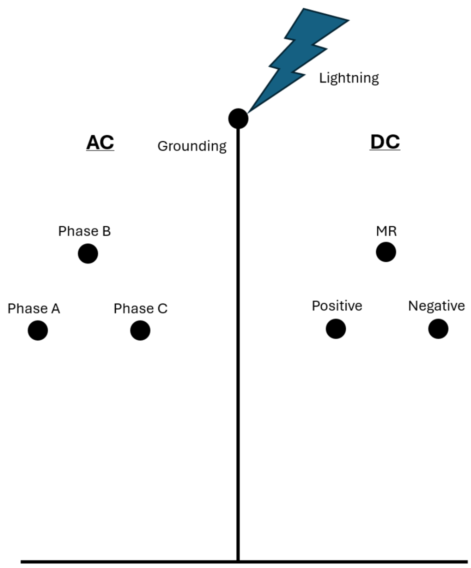

Figure 4.1: Lightning impact zone on the electrical tower

In Figure 4.1, the lightning impact zone within the tower structure is illustrated. The lightning waveform used in the simulation, as well as its characteristics, were previously defined according to the CIGRÉ model described in Figure 3.3. Below, the current results in the electrical transmission lines at the moment of impact are presented.

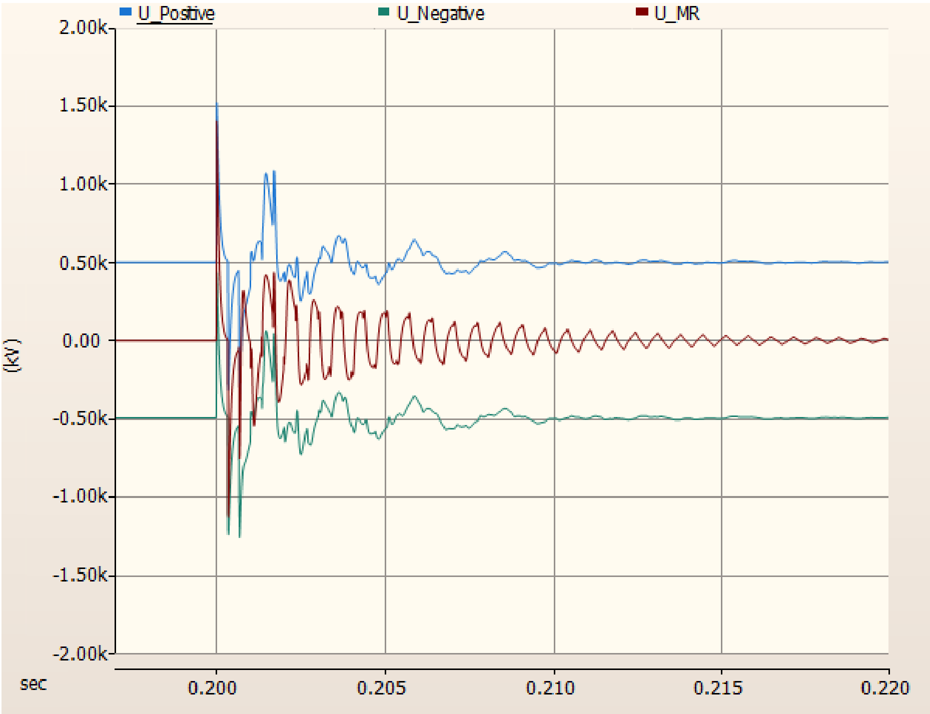

Figure 4.2: Voltages in the DC system lines during a lightning strike on the ground conductor

Figure 4.2 shows the voltage transients induced in the HVDC system conductors (positive, negative, and metallic return) during a lightning strike on the ground wire.

Although the lightning does not impact the HVDC system directly, significant transient overvoltages are clearly induced in its conductors. This phenomenon is a direct consequence of strong electromagnetic coupling between the HVAC and HVDC lines sharing the same tower structure, as discussed in section 2.2 and extensively studied in [10]. This aligns with the findings in [12], where the authors report significant voltage perturbations in HVDC systems due to nearby AC faults via magnetic field interactions.

Despite the HVDC system's operation with constant polarity under steady state conditions (subsection 2.1.2), the induced voltages reveal the system's vulnerability to transient electromagnetic interference. These disturbances can introduce temporary AC components superimposed on the DC voltage, potentially stressing converter stations and control equipment. This effect, also described in subsection 2.2.3 and further examined in

[12], may lead to core saturation, increased harmonic distortion, and other undesirable consequences in the converter transformers.

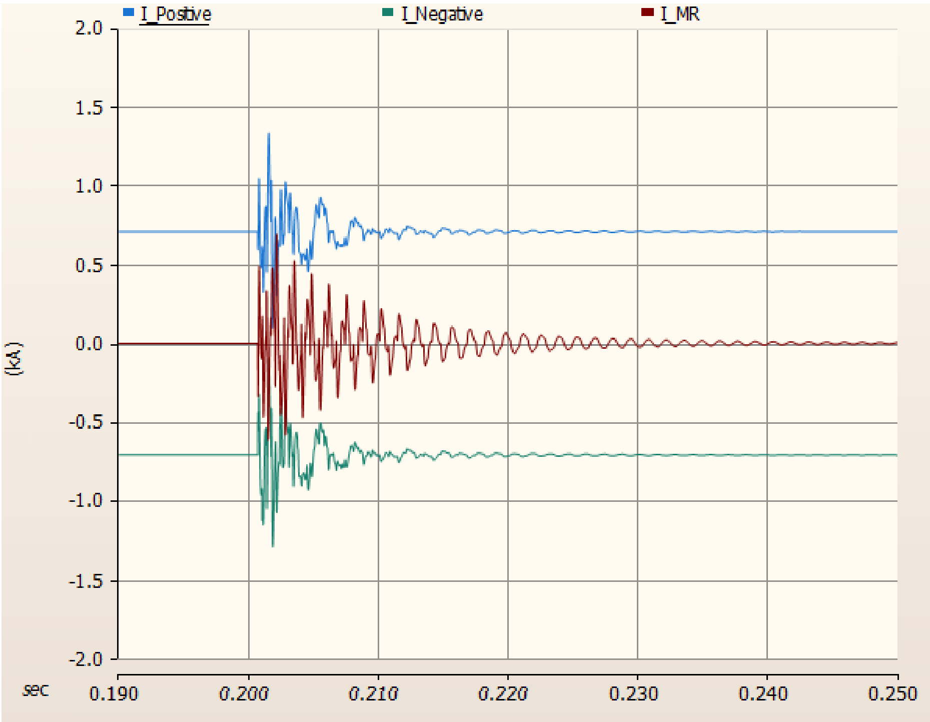

Figure 4.3: Currents in the DC system lines during a lightning strike on the ground conductor

Figure 4.3 shows the currents in the HVDC system conductors after the lightning strike. Although the event occurs in the ground wire, it is evident that current peaks are induced in the DC line due to strong electromagnetic coupling with the AC line.

As indicated in [10] and previously discussed in section 2.2, this coupling can be explained by both inductive and capacitive effects, whose magnitude depends on the physical proximity between the HVAC and HVDC systems, the geometric configuration of the tower, and the duration of the transient.

In particular, the work of [10] highlights that transients generated by faults or lightning strikes in the AC network can induce disturbing currents in the DC lines, affecting the operation of converters and protection elements. Transformer saturation and harmonic generation are some of the possible consequences, as also indicated in subsection 2.2.3.

The waveform asymmetry across conductors observed in Figure 4.3 reflects the influence of conductor placement, as discussed in subsection 2.2.4. The conductor closest to the AC line (in this case, the MR) exhibits the highest peak, confirming that the physical arrangement plays a critical role in coupling intensity, as also emphasized by [10] and shown in subsection 2.2.4.

4.2 Lightning strike on the AC Line

In this second simulation case, the impact of a lightning strike is modeled directly onto one of the phase conductors (phase A) of the HVAC system. Unlike the previous case, where the lightning hit the ground wire, this scenario represents a more critical event as the lightning directly injects energy into an energized conductor.

The aim of this simulation is to analyze the transient behavior of the currents and voltages in HVDC systems, and to evaluate the electromagnetic coupling effects under a more severe disturbance. This analysis is essential for understanding the increased risks associated with direct strikes on phase conductors in hybrid HVAC-HVDC shared infrastructure.

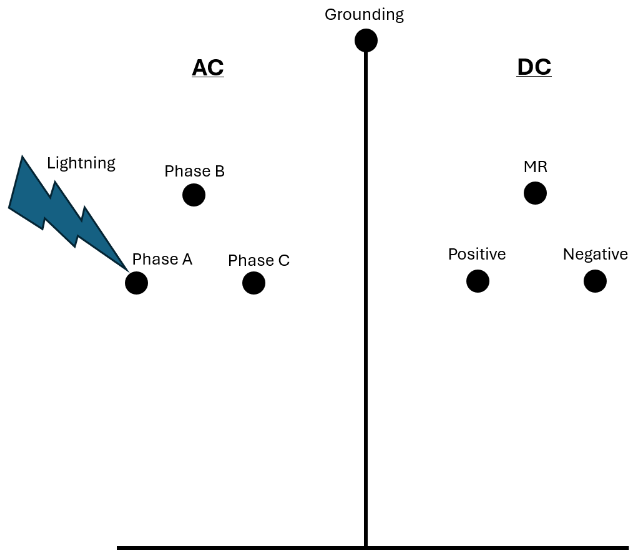

Figure 4.4: Lightning impact zone on the electrical tower on AC line.

In Figure 4.4, the impact zone of the lightning on the phase conductor (phase A) of the transmission tower is illustrated. In this scenario, the lightning current flows directly into the energized AC line, resulting in a much stronger electromagnetic disturbance compared to a strike on the ground wire.

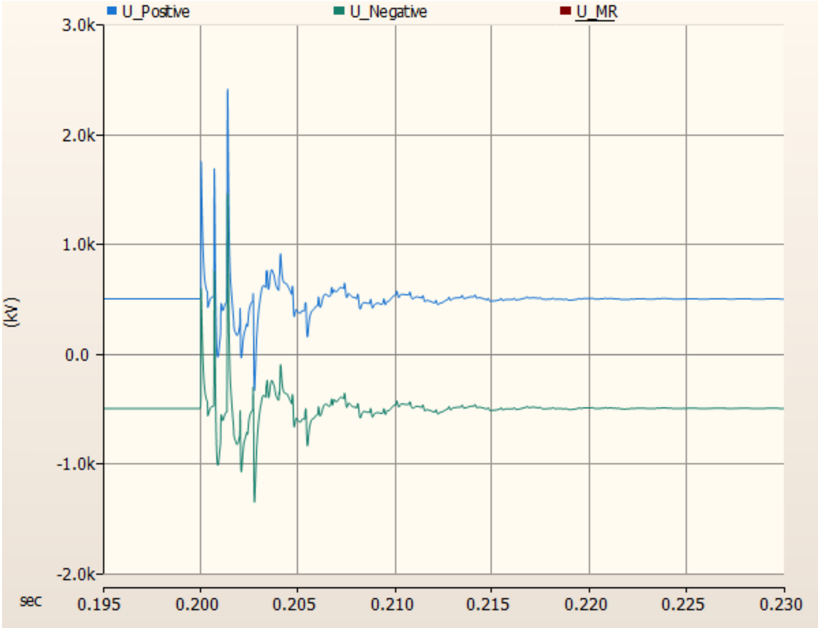

Figure 4.5: Voltages in the DC system lines(positive and negative) during a lightning strike on the AC transmission line

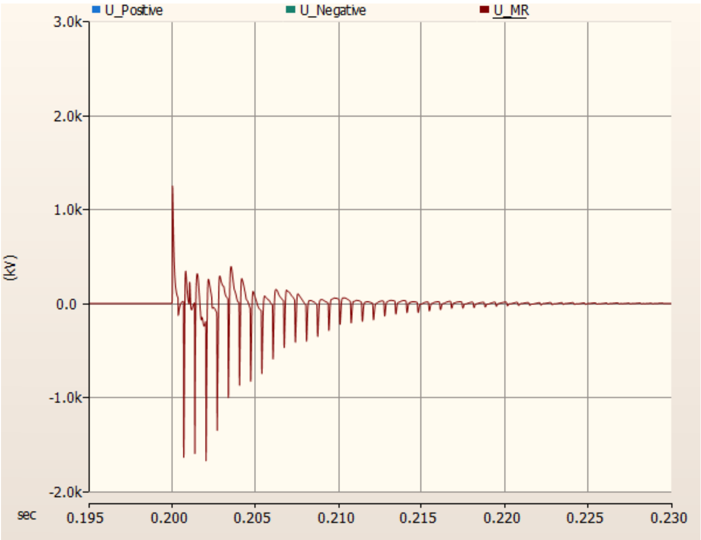

Figure 4.6: Voltages at the MR conductor during a lightning strike on the AC transmission line

Figure 4.5 and Figure 4.6 show the voltage waveforms measured in the HVDC conductors during a direct lightning strike on phase A of the HVAC line. Unlike previous cases involving the ground wire, this event introduces a significantly more aggressive disturbance in the DC system.

When lightning directly strikes an energized phase, the fault current injected into the HVAC system is not only larger in magnitude but also propagates through a lower impedance path compared to a strike on the ground wire. This generates a more intense time varying magnetic field, which strongly couples with nearby HVDC conductors through both inductive and capacitive mechanisms. As discussed in section 2.2 and supported by the findings in [10].

The waveforms reveal high frequency voltage oscillations superimposed on the DC levels. Both the positive and negative conductors exhibit similar transient behavior, despite the positive conductor being physically closer to the struck AC phase (see Figure 3.1). The relatively small separation between the HVDC poles means that the difference in induced voltage magnitudes is minimal, and both conductors experience comparable overvoltage levels. These oscillations present greater amplitude and duration compared to the previous ground wire strike, indicating a more intense electromagnetic disturbance.

Comparing these results with those in Figure 4.2, where the lightning impacted the ground wire, the difference in coupling severity is clear. The significantly higher voltage peaks and spectral content observed here are consistent with the increased energy delivered by a fault involving an energized conductor. This supports the conclusion in [10], where the authors stress that fault location critically determine the intensity of the coupling in hybrid systems.

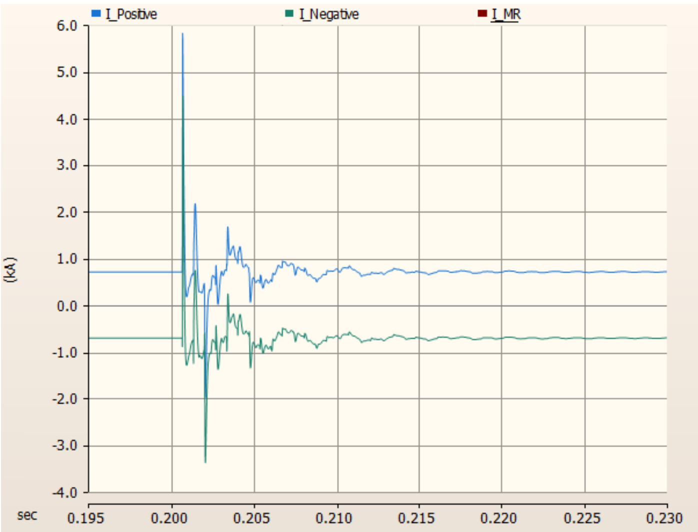

Figure 4.7: Currents in the DC system lines(positive and negative) during a lightning strike on the AC transmission line

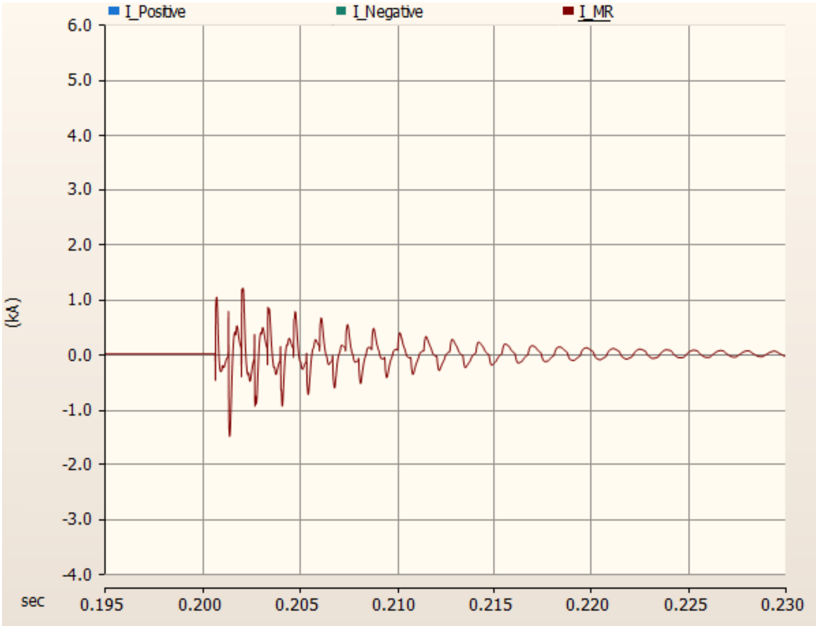

Figure 4.8: Currents at the MR conductor during a lightning strike on the AC transmission line

Figure 4.7 and Figure 4.8 show the transient currents induced in the HVDC system conductors following a direct lightning strike on phase A of the HVAC line.

In contrast to the previous case shown in Figure 4.3, where the strike occurred on the ground wire, the induced current peaks here are noticeably higher. This reinforces the idea that direct strikes on energized conductors produce stronger electromagnetic coupling effects.

Both the positive and negative HVDC conductors exhibit similar current transients, with only slight differences in amplitude. Although the positive conductor is physically closer to the struck AC phase (Figure 3.1), the relatively small spatial separation between the DC poles results in comparable induced current magnitudes across both conductors. This is consistent with the coupling behavior described in subsection 2.2.1 and subsection 2.2.4, where mutual inductance depends on the geometry, and also with [12], which emphasizes the role of proximity and transient energy in determining the strength of coupled currents.

4.3 Lightning strike DC Line

In this third simulation case, the impact of a lightning strike is modeled directly into one of the HVDC system conductors (negative pole). Unlike the previous cases where the lightning impacted the ground wire (section 4.1) or the AC phase (section 4.2), this scenario represents the situation where the lightning is striking directly into the DC system.

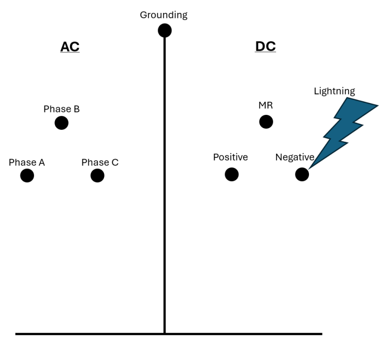

Figure 4.9: Lightning impact zone on the electrical tower on DC line.

In Figure 4.9, the lightning impact point is illustrated on the negative conductor of the DC system. In this case, the energy of the lightning is injected directly into the HVDC circuit, resulting in significant transient phenomena, not only within the DC system but also coupled into the adjacent HVAC lines through electromagnetic interaction.

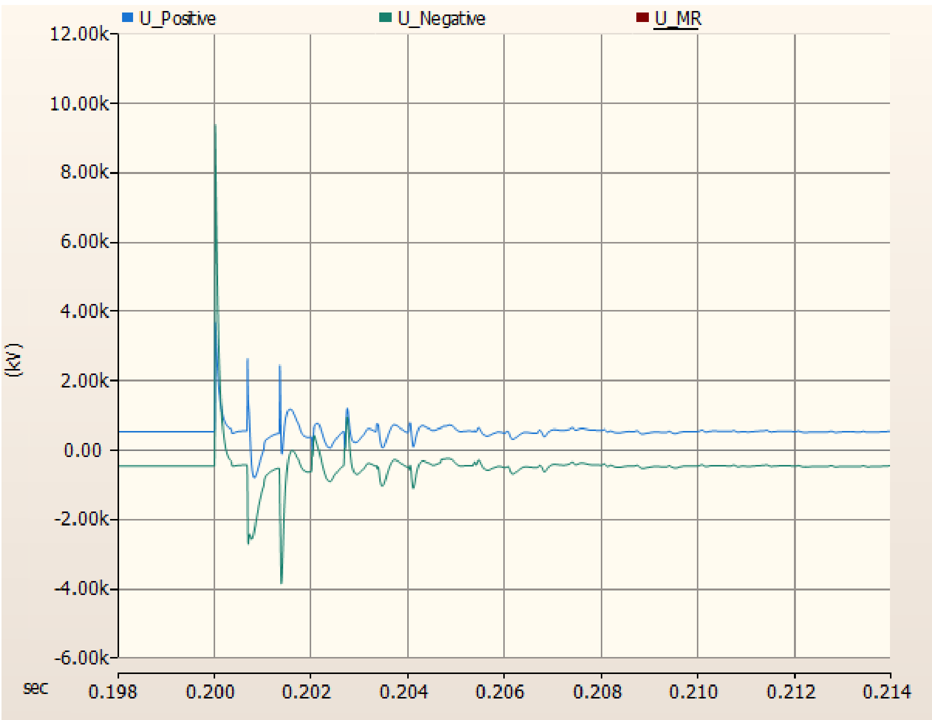

Figure 4.10: Voltages in the DC system lines(positive and negative) during a lightning strike on the DC transmission line

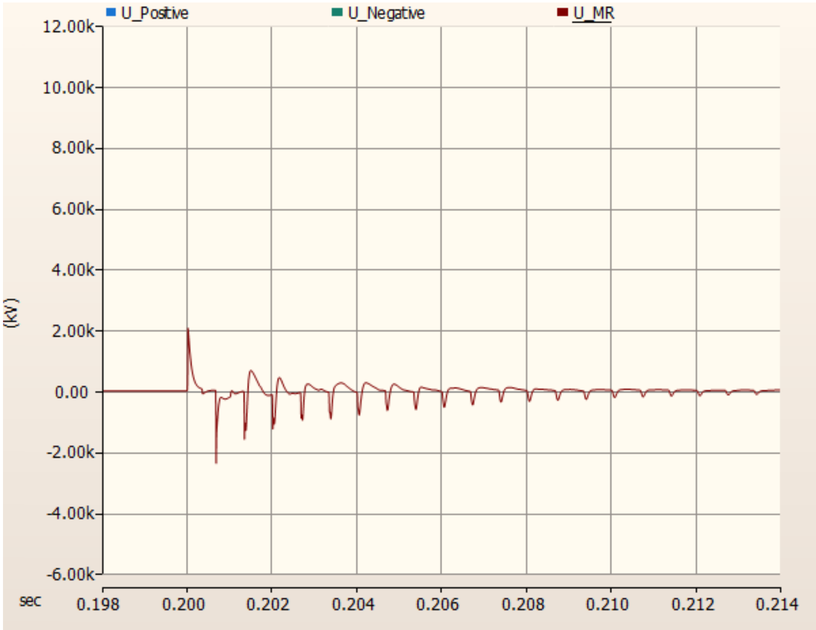

Figure 4.11: Voltages at the MR conductor during a lightning strike on the DC transmission line

Figure 4.10 and Figure 4.11 show the voltage waveforms in the HVDC conductors during a lightning strike directly on the negative pole of the DC line. This case represents a direct interaction with the HVDC system itself, rather than an indirect coupling via the HVAC infrastructure.

The waveforms reveal sharp overvoltage spikes primarily localized in the negative conductor, where the lightning impact occurs. This direct injection results in a steep voltage transient, characterized by high frequency oscillations and a sudden deviation from the nominal DC level. As discussed in section 3.2 and modeled using the CIGRÉ standard impulse, such a current impulse introduces an intense, localized disturbance with fast front times and significant energy content.

In contrast to inductive or capacitive coupling, which act through mutual fields as described in subsection 2.2.1 and subsection 2.2.2, this scenario illustrates the consequences of a direct conductive coupling. The observed transient is symmetrically propagated across the other DC conductors, confirming the strong mutual coupling paths within the HVDC system itself.

When compared to the previous cases lightning strike on the ground wire (Figure 4.2) and on the AC phase conductor (Figure 4.5) this scenario produces the most intense overvoltage in a single conductor. While coupling effects in those cases induced disturbances across all HVDC poles.

These results highlight the unique risk posed by direct lightning strikes on HVDC conductors. Unlike AC induced coupling, which tends to distribute transients more evenly, direct impacts increase the voltages more extremely in the DC side.

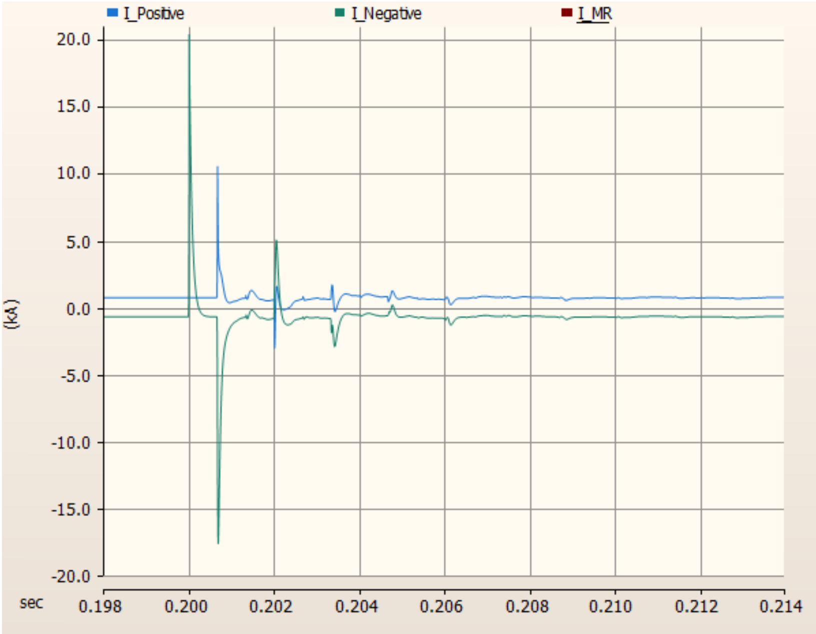

Figure 4.12: Currents in the DC system lines(positive and negative) during a lightning strike on the DC transmission line.

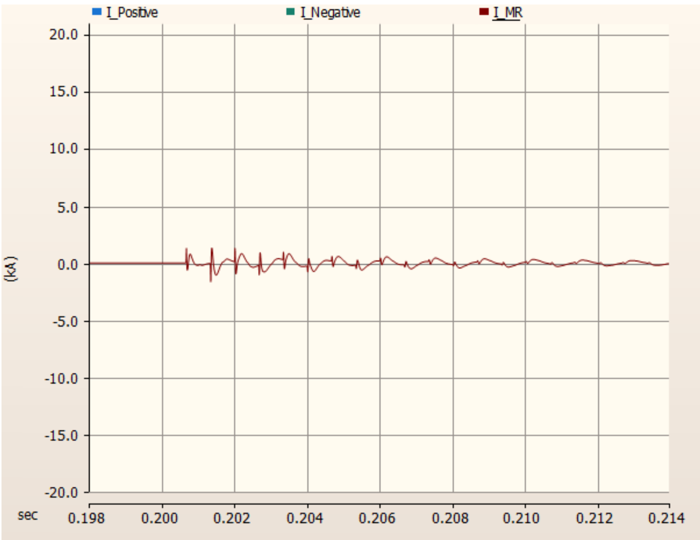

Figure 4.13: Currents at the MR conductor during a lightning strike on the DC transmission line.

The Figure 4.12 and Figure 4.13 shows the currents in the DC system conductors during the lightning strike.

Figure 4.12 and Figure 4.13 show the current waveforms in the HVDC system conductors during a lightning strike directly on the negative pole.

As expected, the negative conductor registers a sharp and high amplitude current peak at the moment of impact. However, transient currents are also clearly induced in the metallic return and in the positive conductor.

When compared with the previous scenarios, lightning on the ground wire (Figure 4.3) and on the AC phase (Figure 4.7), this case stands out for producing the highest current in a single conductor, but also exhibits notable induced currents in the rest of the HVDC system. In contrast to the more distributed and symmetric current responses observed in AC related events, this case demonstrates a highly asymmetric and concentrated disturbance, with secondary coupling effects still present due to electromagnetic interaction.

Comparing the results of section 4.2, section 4.1, and section 4.3, important trends can be observed:

- A lightning strike directly on the DC conductor (section 4.3) results in the most severe transient response, with the highest voltage and current peaks observed. The injected energy causes intense disturbances, which also induce significant transients in the other HVDC conductors due to electromagnetic coupling, as described in section 3.2 and section 2.2.
- A strike on an energized AC phase conductor (section 4.2) also produces severe coupling effects in the HVDC system, although the energy is introduced indirectly. The oscillatory nature of the AC system facilitates wide propagation of the transient and strong interaction with adjacent DC conductors (subsection 2.2.1, [10]).
- A strike on the ground wire (section 4.1) generates the least severe disturbances. The energy is partially dissipated through the grounding system, resulting in weaker electromagnetic fields and smaller induced transients in the HVDC line.
- The tower geometry and physical proximity between conductors strongly influence the intensity of induced disturbances. As shown throughout the simulations and in Figure 3.1, conductors placed closer to the faulted line consistently experience larger transients, even in the absence of direct contact.

4.4 Single Line to Ground Fault

4.4.1 Fault at Zero Voltage Point

In this simulation case, a single phase to ground fault is applied to phase A of the AC transmission system. The fault initiates at second 4 and lasts until 4.02, as defined in section 3.3. This is one of the most common types of faults in high voltage AC systems and is particularly relevant for evaluating the transient coupling between HVAC and HVDC lines sharing the same tower infrastructure.

The simulation aims to analyze the transient evolution of currents in the three phases and evaluate the effects of electromagnetic coupling with the neighboring HVDC line, considering the hybrid AC/DC model in shared towers.

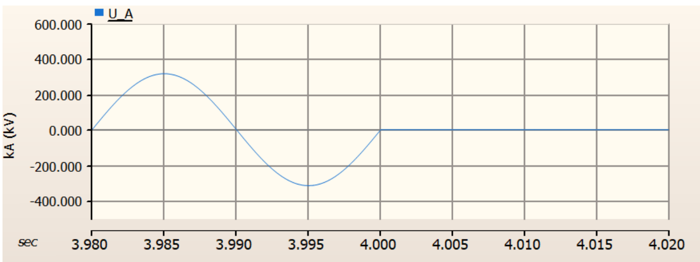

Figure 4.14: Voltage Phase A during the fault.

The Figure 4.14 illustrates the voltage waveform of Phase A at the exact instant when the single phase to ground fault occurs this results in a low di/dt (Equation 2.4). As observed, the voltage drops sharply to 0 V, indicating that the fault is applied precisely when the instantaneous voltage of Phase A is zero. According to the analysis presented in section 2.4, the impact of the fault significantly depends on the voltage at the time of initiation.

From the sinusoidal voltage expression:

$$v(t) = V_{peak} \cdot \sin(\omega t + \phi), \tag{4.1}$$

we know that if the fault occurs when $v(t) = 0$, the instantaneous potential difference is minimal, resulting in a less intense transient. This leads to a lower initial short circuit current and reduced electromagnetic coupling effects, as the induced magnetic field is proportional to the rate of change of current. Consequently, faults occurring near the voltage zero crossing are less severe than those initiated near voltage peaks, where $v(t)$ is maximum and the resulting fault current is substantially higher. As shown in Figure 4.14, the fault is applied exactly when the instantaneous voltage of Phase A is zero.

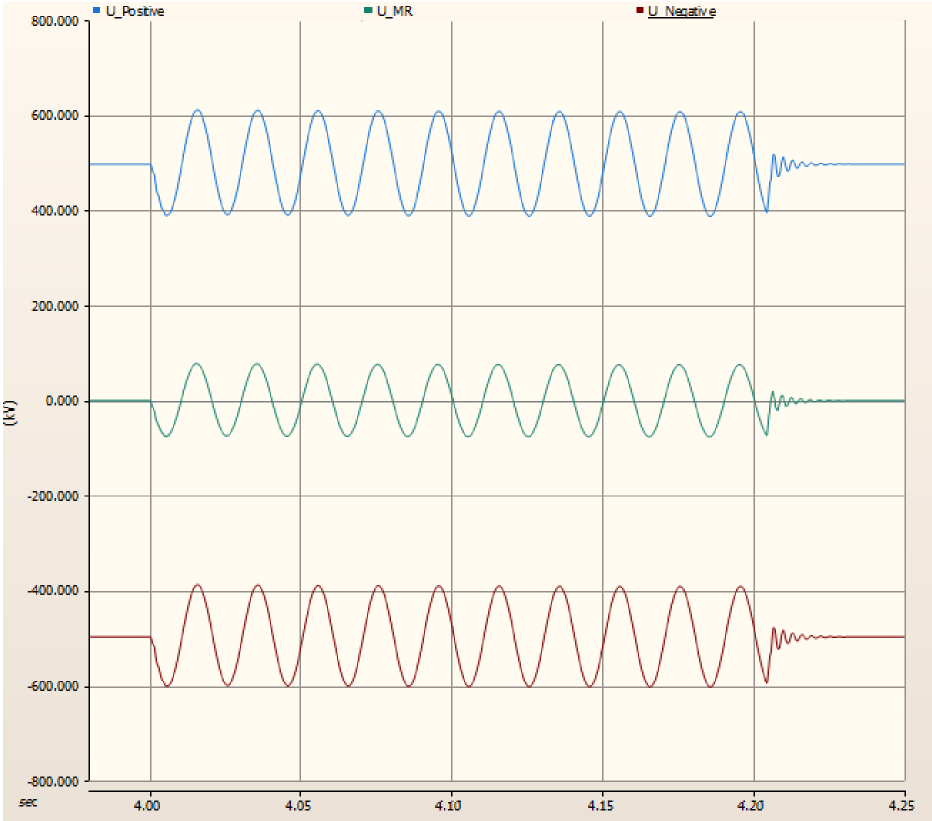

Figure 4.15: Voltages of the DC system during the fault in Phase A at zero voltage point.

Figure 4.15 shows the voltage waveforms of the HVDC conductors during a single phase to ground fault in the HVAC system, occurring at the zero voltage point of phase A.

Although the fault originates on the AC side, transient voltage perturbations are clearly observed in all three HVDC conductors. These differences are not solely due to spatial proximity, as might be expected. While the positive pole is physically closest to phase A (see Figure 3.1) and exhibits the highest induced voltage with an increase approximately of 111.79 kV, the negative pole also shows a significant increase of 106.94 kV), despite being farther away, the MR conductor, although less affected, still experiences a notable rise of 74.43 kV kV.

This behavior can be explained by the circuital role of the conductors. The positive and negative poles form the main current carrying path in the DC system, and therefore have higher mutual inductance with the AC phases than the MR conductor. The MR, designed mainly as a return path under certain operational or fault conditions, is often electrically decoupled or weakly coupled through the network's topology and has lower mutual inductance with the AC phases.

This asymmetry in coupling confirms what is reported in [12], where both physical geometry and electrical configuration determine the severity of induced disturbances. It also highlights the fact that coupling is not only a matter of distance, but also of electromagnetic linkage through the system's structure and current paths.

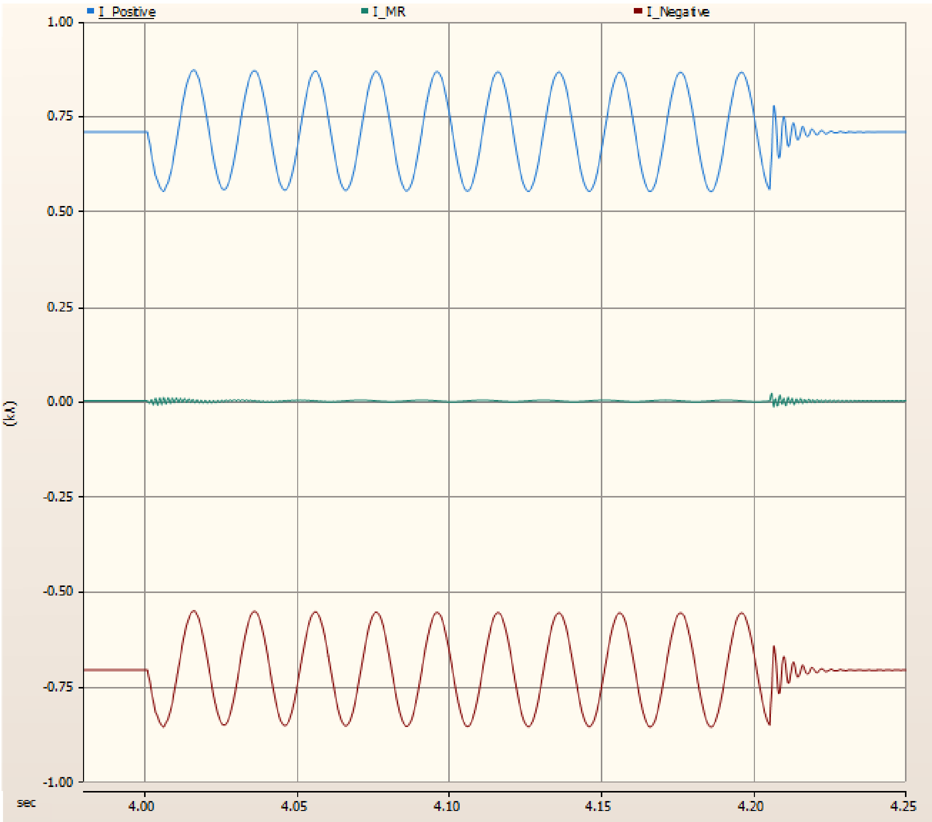

Figure 4.16: Currents of the DC system during the fault in Phase A at zero voltage point.

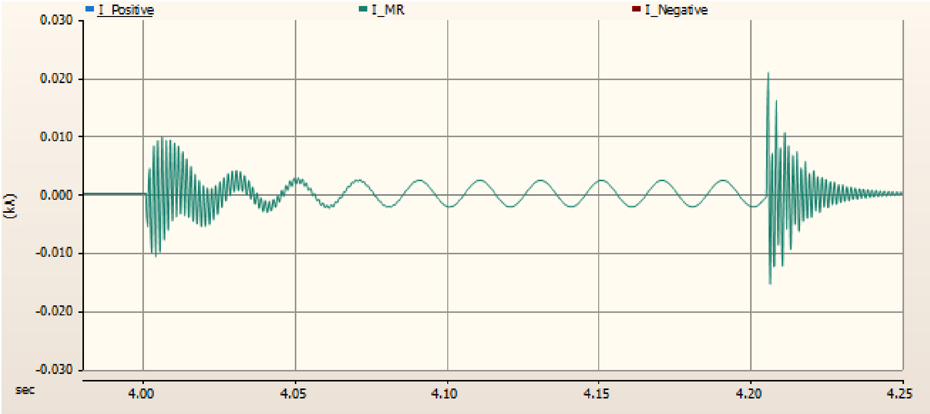

Figure 4.17: Currents of the MR conductor during the fault in Phase A at zero voltage point.

Figure 4.17 shows the induced current waveforms in the three HVDC conductors during a single phase fault in phase A of the AC system.

A significant transient increase in current is observed in all three conductors at the onset and clearance of the fault. The positive conductor exhibits peak current approximately of 0.157 kA, while the negative conductor reaches a difference in value of 0.149 kA. In contrast, the metallic return conductor shows a much smaller peak current, on the order of 0.02 kA of variation.

The MR conductor shows much weaker coupling. This is not due to geometric distance but rather its electrical configuration: in typical HVDC systems, the MR is often electrically floating or weakly referenced, limiting its ability to sustain induced currents. Even though it is exposed to the same varying magnetic field, its role as a metallic return path under specific conditions reduces its linkage to the fault induced electromagnetic flux.

These results are consistent with the findings of [12], which highlight that the magnitude of induced currents depends not only on proximity but also on the electrical and functional characteristics of the conductor.

Although the MR currents are smaller in magnitude, they remain relevant to system operation. As noted in subsection 2.2.3, transient currents in the MR can interfere with HVDC converter protection strategies, particularly during repeated fault conditions or in scenarios with high harmonic distortion.

4.4.2 Fault at Maximum Voltage Point

In this section, the same type of fault analyzed in the subsection 4.4.1 is repeated, a single phase to ground fault in phase A. However, this time, the fault occurs at the moment when the voltage of phase A reaches its positive peak. The impact of a fault is highly dependent on the instantaneous voltage at the faulted phase when the event occurs, as we can see at the Figure 4.18. When the fault happens at the voltage peak, the system is subjected to the maximum potential difference between the conductor and ground, resulting in a more severe transient response. The Figure 4.18 shows that immediately after the fault, the voltage in phase A collapses to 0V.

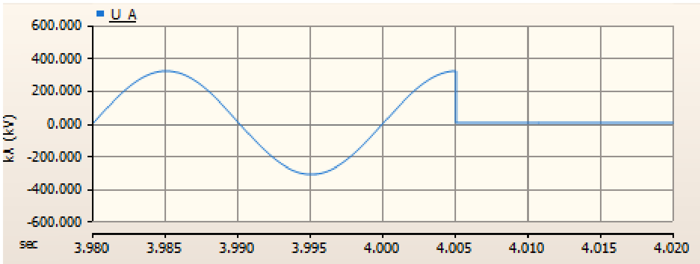

Figure 4.18: Voltage Phase A during the fault.

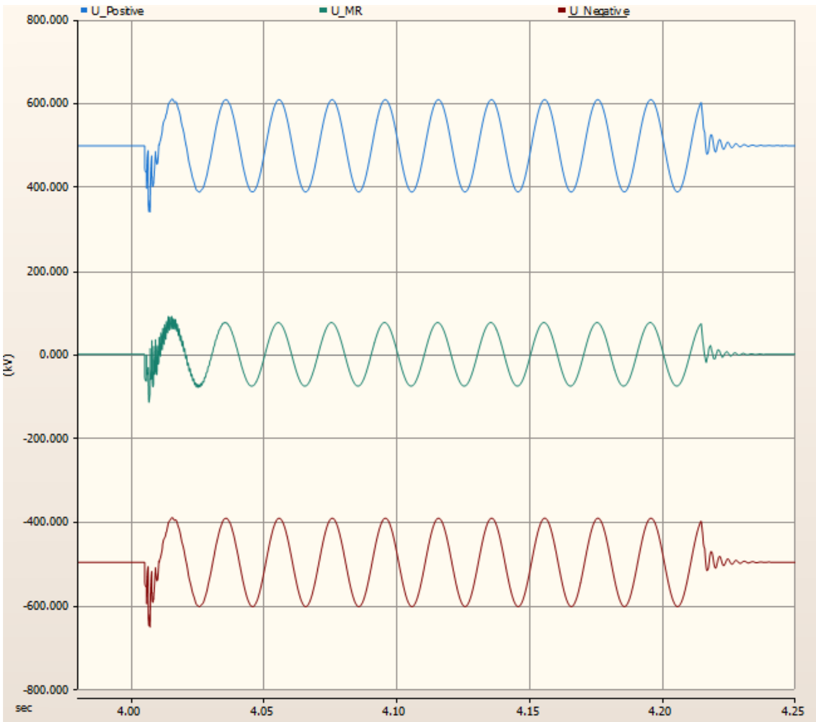

Figure 4.19: Voltages of the DC system during the fault in phase A at Zero Voltage Point

Figure 4.19 presents the voltage response of the HVDC system conductors, positive, negative, and metallic return, during a single phase to ground fault in AC phase A, triggered at its maximum voltage.

Although the fault originates on the AC side, all HVDC conductors experience noticeable transient overvoltages due to electromagnetic coupling mechanisms.

The induced voltage waveforms show strong initial peaks followed by high frequency oscillations. The positive pole reaches a maximum variation in voltage of approximately 160.25 kV, the negative pole around 157.07 kV, and the metallic return conductor peaks at about 90.1 kV. These results are significantly higher than those observed in Figure 4.15, where the same fault was triggered at the AC zero crossing, and confirm that the fault initiation instant has a direct impact on coupling intensity.

This behavior is explained by the fact that faults occurring at the peak of the AC voltage result in larger instantaneous fault currents, due to the higher initial potential difference at the fault point (section 2.4). Consequently, the magnetic field surrounding the AC phase changes more rapidly, increasing $\frac{d\Phi}{dt}$, and thereby inducing stronger voltages in nearby conductors:

$$V_{\text{ind}} = -\frac{d\Phi}{dt}$$

The high frequency oscillations superimposed on the voltage signal are additionally influenced by capacitive coupling effects (Equation 2.3).

Among the HVDC conductors, the positive pole, which is closest to the faulted AC phase (Figure 3.1), exhibits the highest disturbance. This supports the conclusion that conductor geometry and physical arrangement critically determine the strength of the coupling, as observed in [10] or at section 2.2.

The results from Figure 4.19 compared with Figure 4.15 demonstrate that the same fault type can lead to very different coupling effects, depending solely on the timing within the AC voltage cycle. This emphasizes the need to evaluate fault scenarios not only by type and location but also by their exact temporal triggering conditions.

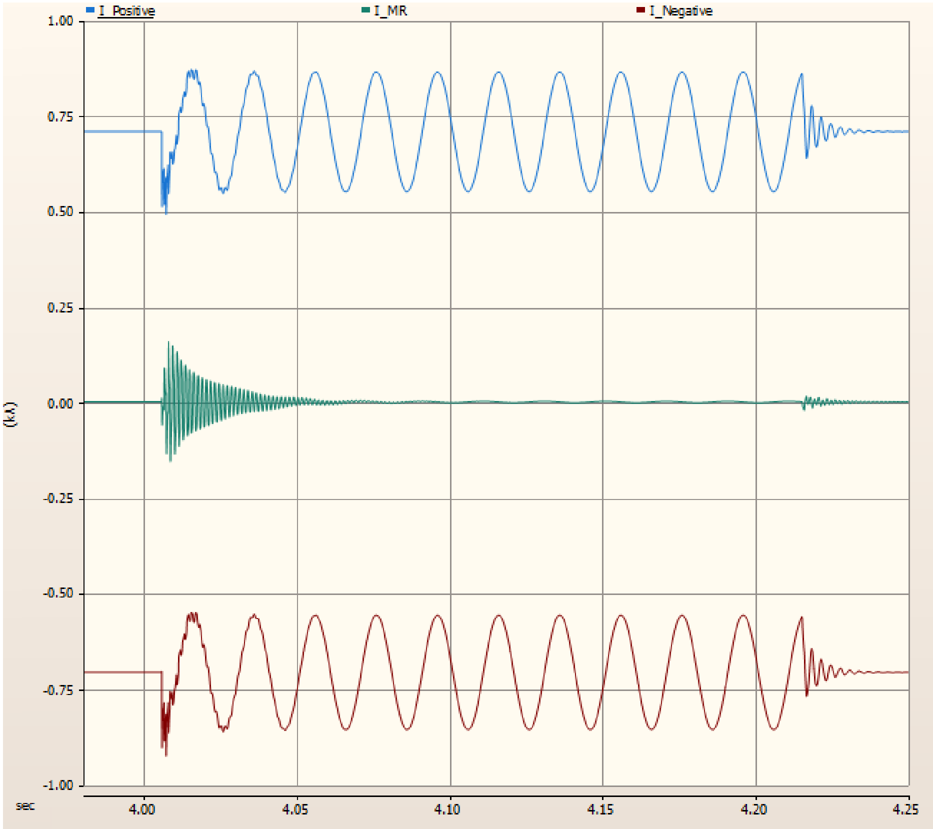

Figure 4.20: Currents of the DC system during the fault in phase A at Zero Voltage Point

Figure 4.20 displays the current waveforms in the HVDC system conductors during a single phase to ground fault in phase A of the AC system, triggered at the maximum voltage point.

In comparison with Figure 4.16, where the same fault was triggered at the zero crossing of the AC voltage, a clear increase in the amplitude of the induced currents is observed across all three HVDC conductors. This difference is expected, as the fault occurring at peak voltage results in a larger instantaneous voltage drop across the fault location, producing a higher fault current.

At the onset of the fault, the induced currents in the HVDC conductors reach peak difference of approximately 0.224 kA for the positive conductor, 0.222 kA at the negative, and about 0.158 kA in the metallic return conductor.

As in the zero crossing case, the positive and negative poles show nearly symmetric responses. The MR conductor, although still showing a weaker response, exhibits a noticeable increase compared to the previous case, indicating that even conductors with limited electrical grounding can be influenced by stronger external field variations.

These findings confirm that the timing of fault initiation has a critical effect on the severity of induced disturbances in nearby DC conductors, and that worst case coupling scenarios are more likely when faults occur at the peaks of the AC voltage waveform.

The results from both simulation cases fault at the zero crossing and fault at the voltage peak of phase A, clearly demonstrate the critical influence of the fault initiation instant on the severity of the electromagnetic coupling between HVAC and HVDC systems.

- When the fault is triggered at the zero voltage point, the induced disturbances in the HVDC conductors are relatively moderate. Peak overvoltages in the positive, negative, and metallic return (MR) conductors were approximately 111.79 kV, 106.94 kV, and 74.43 kV, respectively. The corresponding peak current variations were about 0.157 kA in the positive pole, 0.149 kV at the negative and 0.02 kA in the MR. These values reflect the lower initial fault current associated with a minimal potential difference at the fault inception.
- In contrast, the fault triggered at the maximum voltage point leads to significantly more severe transients. Peak voltage variations increased to approximately –160.25 kV (positive), 157.07 kV (negative), and 90.1 kV (MR). Induced current peaks also rose, reaching about 0.224 kA in the positive pole, 0.222 kA at the negative one and 0.158 kA in the MR. These results represent an increase of up to 43.35% (positive conductor) 46.88% (negative conductor) and 21.05% (MR conductor) in voltage and 42.68% (positive conductor), 48.99% (negative conductor) and 690% (MR conductor) in current magnitudes compared to the zero crossing fault case.
- The difference between the two cases is primarily attributed to the stronger instantaneous current developed during the peak voltage fault. According to the theoretical model in section 2.4, higher voltage at the fault moment results in higher initial short circuit current and, consequently, a stronger time varying magnetic field. This leads to higher electromagnetic coupling.
- In both fault scenarios, the induced currents and voltages in the positive and negative poles are nearly symmetric, due to their role as active conductors in the HVDC circuit. The metallic return conductor consistently exhibits lower coupling, which is not only due to its geometric placement but also its typical electrical configuration (floating or weakly grounded), limiting its ability to sustain induced responses.

Chapter 5

Simulation of Faults in Electrical Distribution Systems Based on Tower Geometry

This chapter compares the results obtained in subsection 2.4.1, where the impact of a single phase to ground fault on line A was analyzed using the geometry shown in Figure 3.1, with the system behavior under different geometric configurations: a vertical arrangement (Figure 5.5) and a horizontal arrangement (Figure 5.1). The aim of this analysis is to study how line geometry influences coupling within a hybrid HVAC-HVDC system.

5.1 Horizontal Tower Configuration

This section analyzes the electromagnetic behavior of a hybrid HVAC-HVDC transmission system under a single phase to ground fault in phase A, using a horizontal conductor arrangement as shown in Figure 5.1. The objective is to evaluate how tower geometry influences coupling effects between AC and DC systems, and to compare the results with those obtained under the standard configuration presented in subsection 2.4.1.

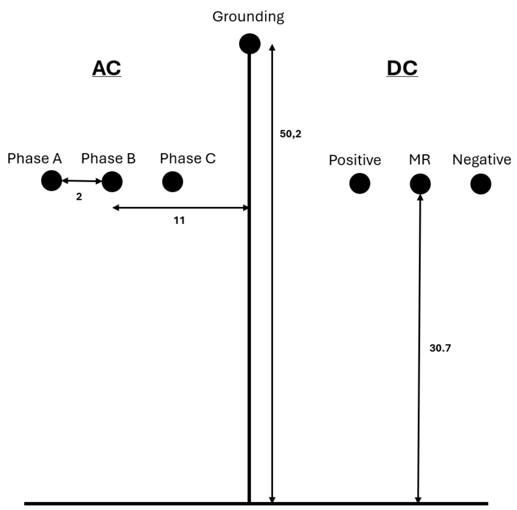

Figure 5.1: Horizontal Geometry of the conductors in the hybrid HVAC-HVDC tower

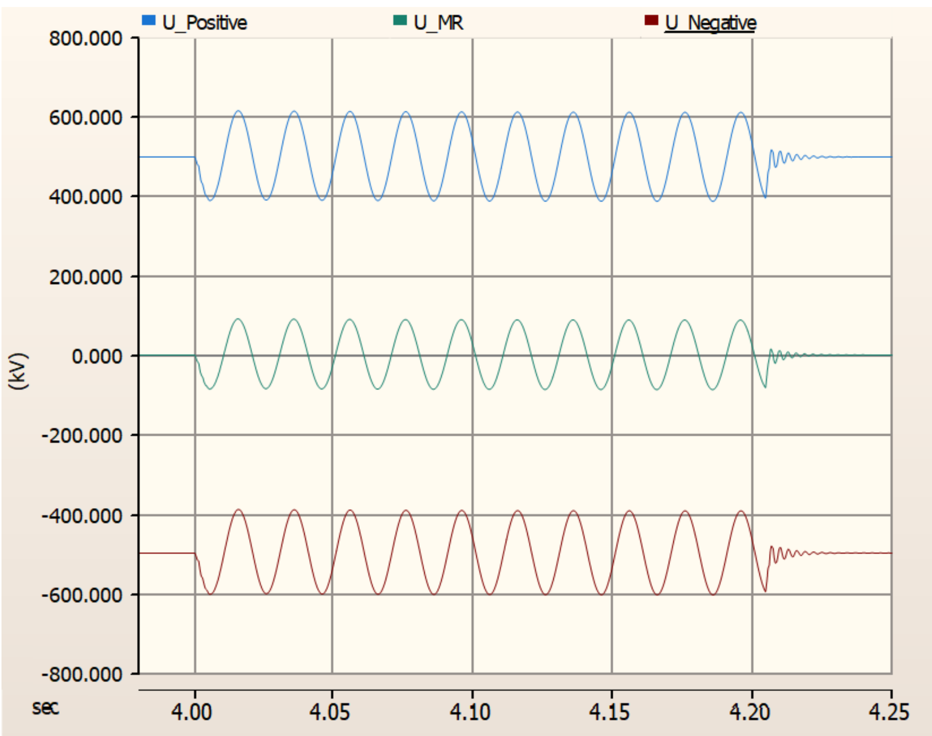

Figure 5.2: Voltages of the DC system during the fault in phase A at Zero Voltage Point with horizontal configuration

Figure Figure 5.2 shows the voltages induced in the HVDC system conductors (positive, negative, and metallic return) during a single phase to ground fault in phase A of the HVAC system, using the horizontal tower configuration illustrated in Figure 5.1. This simulation corresponds to the same fault conditions analyzed in subsection 4.4.1, fault initiated at the zero voltage crossing, but differs in the spatial layout of the conductors.

The measured voltage peaks difference in this configuration are approximately 112.02 kV for the positive pole, 110.67 kV for the negative pole, and 88.85 kV for the metallic return. Compared to the values obtained in subsection 4.4.1, which were 111.79 kV (positive), 106.94 kV (negative), and 74.43 kV (MR), the voltage amplitudes are consistently lower across all conductors.

This behavior can be attributed to the separation distance of the conductors. In the horizontal configuration the distance respect the phase of the failure are 22 m (positive), 26 m (negative) and 24 m (MR) (see Figure 5.1 and in the general case are 24.5 m (positive), 31 m (negative) and 28.68 m (MR) (see Figure 3.1. As a result, the mutual inductance at the conductors increase respect the first case.

The metallic return conductor, although also closer in this configuration (24 m vs. 28.68 m), shows a comparatively larger increase in induced voltage. This can be attributed to its central location between the positive and negative conductors. In the main configuration, the MR was vertically offset, which reduced its net flux linkage. In contrast, in the horizontal setup, the MR is more directly exposed to the magnetic field lines from the AC phase.

These findings confirm that proximity play critical roles in the strength and symmetry of inductive coupling.

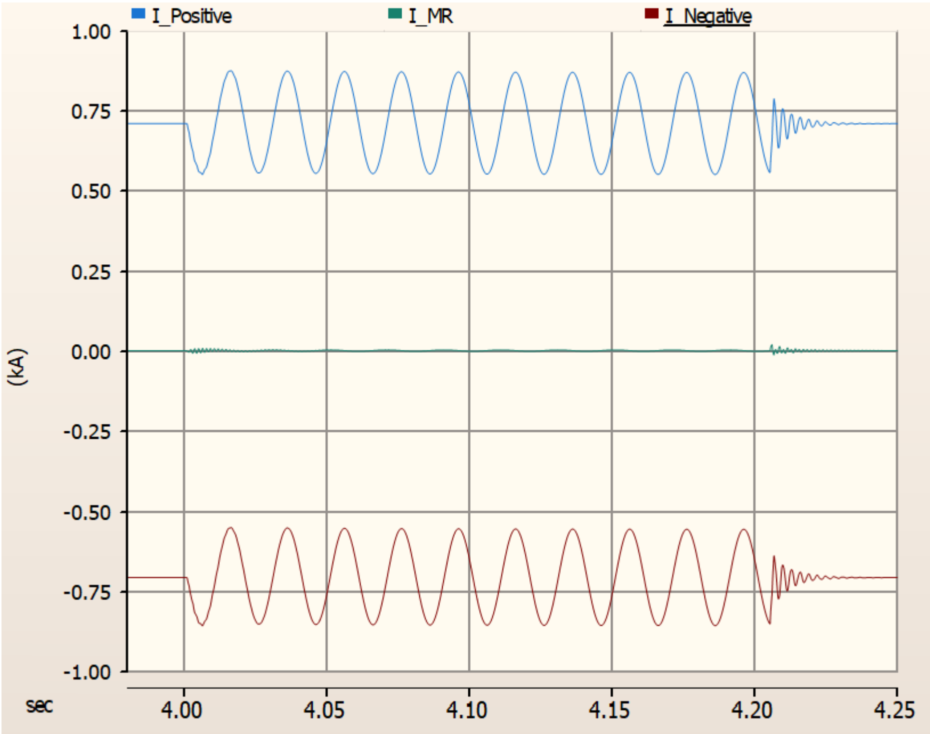

Figure 5.3: Currents of the DC system during the fault in phase A at Zero Voltage Point with horizontal configuration

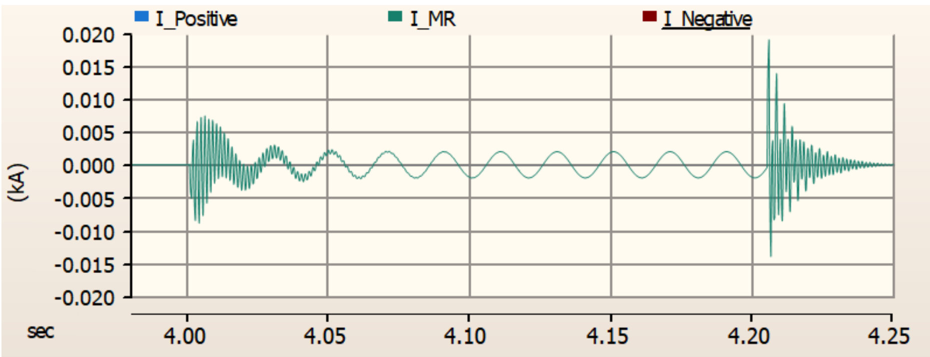

Figure 5.4: MR conductor current of the DC system during the fault in phase A at Zero Voltage Point with horizontal configuration

Figure Figure 5.3 and Figure 5.4 displays the current waveforms in the HVDC conductors during the same fault scenario under the horizontal tower configuration. The induced currents in the positive and negative poles reach similar peak values as in the main case (subsection 4.4.1), maintaining their near symmetrical shape.

Notably, the MR conductor shows a slightly higher induced current peak than in the main configuration, reflecting its more direct exposure to the AC magnetic field due to its central positioning in the horizontal layout. This observation is consistent with the voltage trends discussed in Figure 5.2, and reinforces the role of geometric alignment in coupling severity.

5.2 Vertical Tower Configuration

This section analyzes the electromagnetic behavior of a hybrid HVAC-HVDC transmission system under a single phase to ground fault in phase A, using a vertical conductor arrangement as shown in Figure 5.5. The objective is to evaluate how tower geometry influences coupling effects between AC and DC systems, and to compare the results with those obtained under the standard configuration presented in subsection 2.4.1.

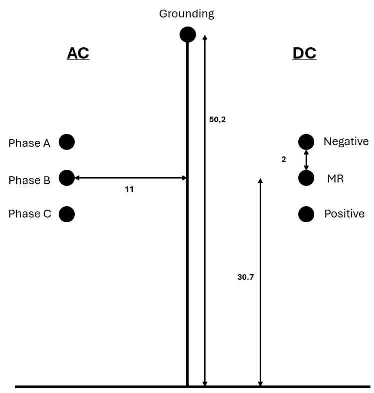

Figure 5.5: Vertical Geometry of the conductors in the hybrid HVAC-HVDC tower

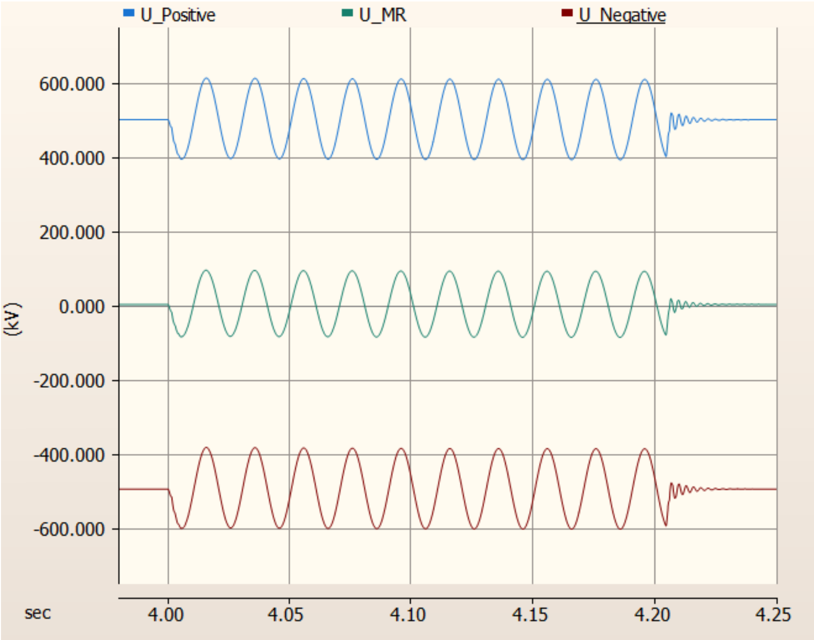

Figure 5.6: Voltages of the DC system during the fault in phase A at Zero Voltage Point with vertical configuration

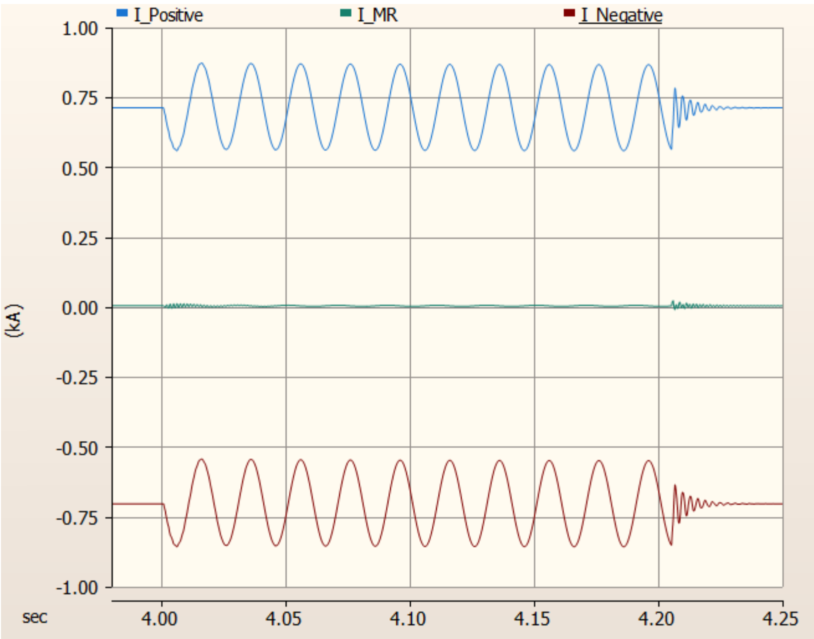

Figure 5.7: Currents of the DC system during the fault in phase A at Zero Voltage Point with vertical configuration

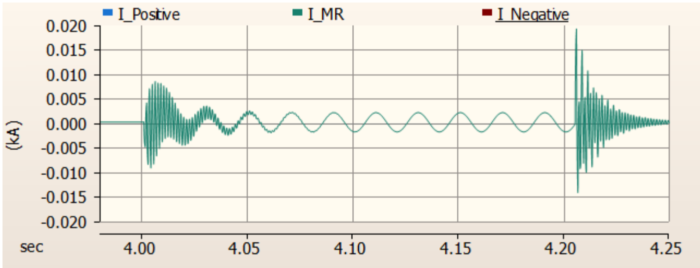

Figure 5.8: MR conductor current of the DC system during the fault in phase A at Zero Voltage Point with vertical configuration

Figure Figure 5.6 presents the voltages induced in the HVDC system conductors during a single phase to ground fault in phase A of the HVAC system, using the vertical tower configuration shown in Figure 5.5. As in the previous cases, the fault is initiated at the zero crossing of the AC voltage. This figure allows comparison with both the standard tower configuration (subsection 4.4.1) and the horizontal arrangement (Figure 5.2).

The measured peak voltages in this vertical configuration are 109.99 kV for the positive conductor, 109.97 kV for the negative, and 89.26 kV for the metallic return. Compared to the standard geometry (111.79 kV, 106.94 kV, and 74.43 kV) and the horizontal configuration (112.02 kV, 110.67 kV, and 88.85 kV), several trends emerge.

First, the induced voltages in all three conductors are relatively high, and the differences between them are minimal, particularly between the positive and negative poles, which differ by only 0.02 kV. This near nperfect symmetry reflects the fact that in the vertical configuration, the conductors are positioned at almost equal distances from the faulted A phase: 22.36 m (positive), 22.00 m (negative), and 22.09 m (MR), as shown in Figure 5.5. According to the inductive coupling expression shown in section 2.2, such symmetrical spacing leads to nearly equal mutual inductance values M, and thus similar induced voltages.

The following table summarizes the induced voltages for the different configurations, along with the distances between each conductor and the faulted AC phase:

Table 5.1: Comparison of distances and peak induced voltages in HVDC conductors for different tower configurations

Conductor	Configuration	Distance to Faulted Phase (m)	Peak Induced Voltage (kV)
Positive	Standard	24.50	111.79
	Horizontal	22.00	112.02
	Vertical	22.36	109.99
Negative	Standard	31.00	106.94
	Horizontal	26.00	110.67
	Vertical	22.00	109.97
Metallic Return (MR)	Standard	28.68	74.43
	Horizontal	24.00	88.85
	Vertical	22.09	89.26

Upon reviewing the results table, some values appear to deviate from expected trends. For example, although the positive conductor in the horizontal configuration is slightly closer to the faulted AC phase (22.00 m compared to 22.36 m in the vertical configuration), the resulting voltage difference is relatively small (112.02 kV versus 109.99 kV). This modest variation suggests that inductive coupling is not determined by physical distance alone. Factors such as the three dimensional arrangement of the conductors, the angle at which magnetic flux lines intersect each conductor, and even secondary effects (such as shielding or mutual influence among DC conductors) can significantly affect the effective mutual inductance. Therefore, small variations in physical layout do not necessarily translate into proportional differences in induced voltage. This highlights the importance of performing a comprehensive electromagnetic field analysis rather than relying solely on distance based estimations.

Chapter 6

Conclusion

Based on the set of simulations carried out, several patterns have been identified that allow for a deeper understanding of the transient electromagnetic coupling phenomenon between HVAC and HVDC systems in shared hybrid infrastructures. The most relevant conclusions are as follows:

- Lightning strikes that directly hit the HVDC conductor generate the most severe disturbances, both in terms of overvoltage and induced overcurrent. This type of event introduces energy directly into the DC system, amplifying its effect on other conductors through inductive coupling.
- Discharges on AC phase conductors also induce significant disturbances in the HVDC line, due to the oscillatory nature of the AC system and the intensity of the generated magnetic field. Although the energy is introduced indirectly, the transient propagation is extensive and highly coupled with nearby DC conductors.
- The severity of coupling during AC faults is strongly influenced by the point in the cycle at which the fault occurs. Faults at the zero crossing generate relatively moderate couplings, whereas faults at the voltage peak cause induced overvoltages and overcurrents up to 40–50% higher, due to the greater instantaneous short circuit current generated.
- The analysis of different geometric tower configurations (standard, horizontal, and vertical) has shown that the intensity and symmetry of electromagnetic coupling do not depend solely on the distance between conductors and the faulted phase. While physical proximity is an important factor, the results show that small variations in distance do not always translate into proportional differences in induced voltages. These findings highlight that factors such as three dimensional orientation, the crossing angle of magnetic flux lines, or mutual shielding between conductors significantly influence the coupling. Therefore, the need for comprehensive elec-

tromagnetic field analyses in the design of hybrid HVAC-HVDC infrastructures is reinforced, rather than relying solely on simplified distance based estimations.

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