Transient Effects of DC Fault Current Interruption on HVDC Cable Performance in Multiterminal Network

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Summary

The growing demand for high-voltage direct current (HVDC) transmission is driven by its efficiency in delivering bulk power over long distances. To facilitate carbon-free energy, grid expansion targets 2 GW via ±525 kV HVDC interconnections, ultimately forming interconnected onshore and offshore multi-terminal HVDC (MT-HVDC) networks [1]. Ensuring reliability and availability in these networks necessitates stringent quality assurance for network components.

In MT-HVDC networks, contingencies such as faults or unscheduled events lead to rapid DC voltage decay due to low system impedance, resulting in high fault currents from line discharge and multiple feeding sources. This necessitates fast-acting DC circuit-breaker (DCCB) for selective fault isolation. As point-to-point systems evolve into MT-HVDC networks with new components like DCCB and DC switching stations, knowledge gaps persist regarding transient stress impacts on HVDC cables. Refining technical requirements, test procedures, and waveforms is crucial to accurately represent these stresses and ensure network reliability.

This paper analyses the impact of DC faults on HVDC cables in radial MT-HVDC networks, focusing on their interaction with DCCB. An electromagnetic transient (EMT) based simulation of a simplified, yet representative ±525 kV network is conducted to characterize transient cable overvoltage. The study analyses how network topology, DCCB operation, and fault current limiting reactor (FCLR) influence fault propagation and cable stress. Key findings highlight trade-offs in managing cable insulation stress within qualified test levels, providing critical insights for the reliable deployment of MT-HVDC grids.

Keywords

DC Circuit-breaker, Electromagnetic Transients, HVDC Cables, Multi-terminal.

1 Introduction

HVDC transmission systems have been widely deployed as point-to-point interconnectors for efficient long-distance power transmission, particularly in offshore wind and integration of remote hydro generation. However, as grid expansion initiatives seek to enhance transmission capacity to 2 GW via ±525 kV HVDC systems, the focus is shifting towards developing MT-HVDC networks. Such networks enable interconnection of multiple HVDC links, improving system flexibility, redundancy, and overall efficiency.

Despite their advantages, MT-HVDC networks introduce new technical challenges, particularly in terms of system reliability under fault conditions. Unlike conventional point-to-point systems, MT-HVDC networks experience rapid DC voltage decay during faults due to lower system impedance, leading to higher fault currents from line discharge and multiple fault feeding sources. The resulting transient stresses on HVDC cable systems demand fast-acting protection mechanisms, including DCCB, to ensure selective fault isolation and network stability. Significant progress has been made in deploying DCCB, particularly within MT-HVDC networks [2][3]. While previous studies have examined DC fault current interruption dynamics at system levels [4], they often overlooked the interface between HVDC cables and DCCB and the impact on cables.

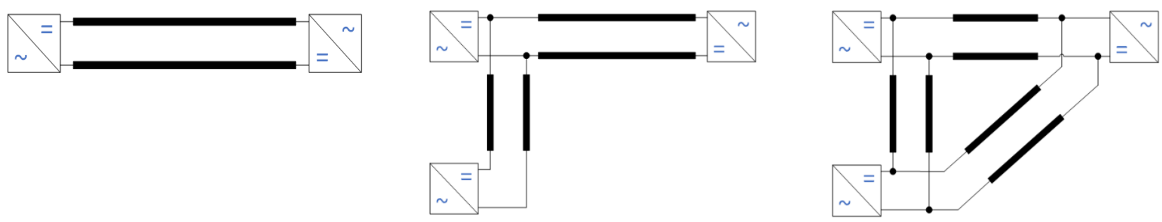
Ensuring the reliability of MT-HVDC networks requires high quality assurance of system components, particularly HVDC cables, which are critical for network operation. However, knowledge gaps remain regarding the transient stress profiles experienced by cables during fault conditions, particularly in radial MT-HVDC network configuration. Existing qualification test procedures may not fully capture the operational stresses encountered in real-world networks, necessitating refinements in technical requirements and testing methodologies.

This paper presents a detailed analysis of DC fault dynamics in radial MT-HVDC networks, with a specific focus on the interaction between HVDC cables and DCCB. An EMT simulation of a reduced but representative single pole of a ±525 kV radial MT-HVDC network is conducted to characterize transient stresses on HVDC cables. The study examines how network topology, DCCB placement in a radial configuration with FCLR at both ends, and varying fault locations along the cable affect fault propagation and transient stresses. Key findings will highlight trade-offs in managing cable stresses to ensure they remain within qualified test levels, thereby enhancing the reliability and operational robustness of future MT-HVDC networks.

2 Overview of HVDC Network Topologies

An HVDC network is defined by the number and location of terminals and switching stations, along with their interconnections, forming a specific topology. Various fundamental topologies (see Figure 1) exist, which – when ensuring compatibility in voltage levels, converter technology, and configurations – can be extended to develop larger HVDC networks. The primary classification of HVDC networks is based on whether they are radial or meshed. In a radial topology two system nodes have a single connection path, whereas a meshed topology provides multiple paths between nodes, enhancing redundancy.

The point-to-point network topology (see Figure 1.a) represents the simplest configuration, comprising two converter terminals linked by cables. A basic expansion involves adding a third terminal via an additional cable connection to the DC switchyard of one of the existing terminals (see Figure 1.b) to form a radial MT-HVDC network. Further extension can include an extra cable link between two existing converters (see Figure 1.c), forming the foundation of a meshed HVDC network. To ensure reliability and fault resilience in a meshed configuration, HVDC circuit-breaker and adequate cable ratings are essential. These enable selective fault isolation, ensuring continuity of reduced power supply even in the event of a potential cable system failure.



(a) Point-to-Point (p2p) Network ***(b) Extension p2p (radial MT-HVDC)*** ***(c) Extension p2p (meshed MT-HVDC)***

Figure 1 – Possible topologies of HVDC networks

2.1 HVDC Switching Station and DC Circuit-breaker

A potential layout for a single-pole connection to a busbar in HVDC switching station consists of an HVDC single busbar, an earthing switch, a surge arrestor, a disconnector, a high-speed switch (HSS, which is an AC circuit-breaker implemented to quickly separate contacts), an insertion resistor, voltage and current measurement equipment, HVDC cable and DCCB. HVDC switching stations facilitate the interconnection of multiple incoming cables and house essential switchgear, such as earthing switches, disconnectors, and DCCB, along with measurement equipment, overvoltage protection, line energization tools, and possibly line discharge systems. The combination of the insertion resistor and HSS is necessary for energizing HVDC cable systems, or potentially a standalone converter, from an operational point-to-point link. The energization process involves first closing the disconnector, followed by the HSS. Once the HVDC cable system is fully charged, the bypass HSS is triggered. Consequently, switching transients are commonly experienced by HVDC cable systems. Such switching transients, characterized by relatively longer durations, are expected to be seen on non-faulted cable systems in MT-HVDC networks due to the operation of DC circuit-breakers to fully interrupt the DC current.

2.2 Mechanical Circuit-breaker and DC Fault Current Interruption

The topology of the DCCB is designed to manage high DC currents during fault conditions. To ensure rapid isolation of faulty sections three functional paths are typically required: the Rated Current Path (RCP), the Current Commutation Path (CCP), and the Energy Absorption Path (EAP), exemplified here for an active current injection (ACI)-based mechanical DCCB (see Figure 2) [5].

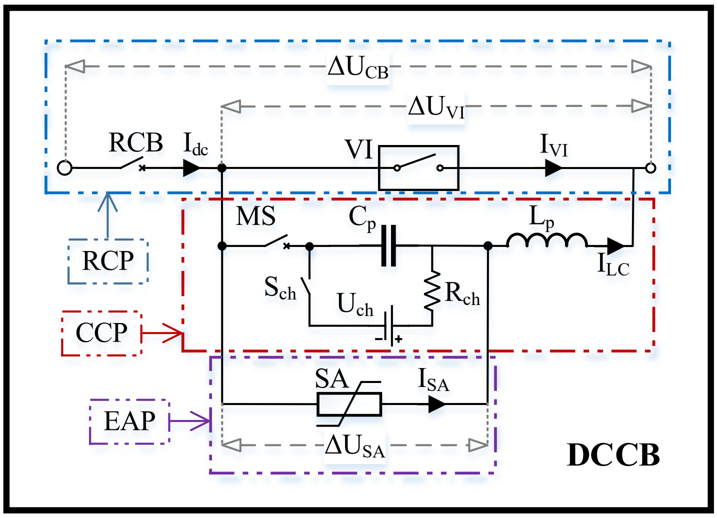


Figure 2 – Structure of an ACI-based mechanical DCCB illustrating its functional paths, and components

The RCP serves as the main conduction branch with minimal resistance to reduce power losses. It contains a mechanical switch, such as a Vacuum Interrupter (VI), capable of operating under load. Additionally, it features a Residual Current Breaker (RCB) with a lower breaking capacity, mainly responsible for completely isolating the two paths of the DC system after a successful current interruption by the DCCB. The first stage of operation, known as neutralization occurs within the RCP, where a local DC current zero is created to initiate the current suppression process.

During a fault, the DC current is diverted into the CCP, allowing the VI in the RCP to open and fully separate its contacts. This initiates the suppression stage, where the CCP generates a Transient Interruption Voltage (TIV) and maintains it above the system DC voltage level. This counteracting voltage forces the fault current to further commutate into the EAP, reducing its magnitude. The total duration of the fault neutralization process is set to 5 ms, with no variations considered in this study.

In the final energy dissipation stage, the EAP plays a crucial role in dissipating the magnetic energy stored in the system inductances. This is achieved through a surge arrester (SA) that absorbs excess energy and de-energizes the system. Once the energy dissipation is complete, the RCB opens to isolate the residual leakage current within the SA, ensuring its protection against long-term degradation

3 Analysis of Fault Current Interruption Dynamics

The simplified circuit model for a radial MT-HVDC network includes a DCCB interfacing the HVDC cable at its both ends – one on the source side and the other on the load side. To capture key electrical stresses on the cables, the model reflects a radial MT-HVDC network configuration (see Figure 3) while isolating cable stress analysis from external network influences. The circuit analysis follows the approach in [6] with an additional cable in radial configuration to the faulty cable. Terminal surge arresters at the cable terminations are excluded to focus on prospective cable stresses. Cable joints are also omitted during transient simulations. A FCLR is placed on both sides of the DCCB by splitting its total inductance equally. This

FCLR mitigates transient current surges and voltage dynamics, ensuring proper DCCB operation and reducing di/dt after a fault to maintain DCCB functionality. The system operates with an ideal 525 kV DC source voltage (U_0). The modelled network comprises two 200 km cable sections (Cable 1 and Cable 2 in Figure 3), totaling 400 km in length, with the DCCB located at the center. The applied land cable data and EMT modelling approach are as outlined [7]. The terminal voltage of the healthy cable at the FCLR is denoted as U_{t0}, while the voltage at its midpoint is U_{tm}. This model provides a fundamental framework for analyzing voltage swings, peak stress levels, and transient interactions among the DCCB, FCLR, and HVDC cables under various operating conditions.

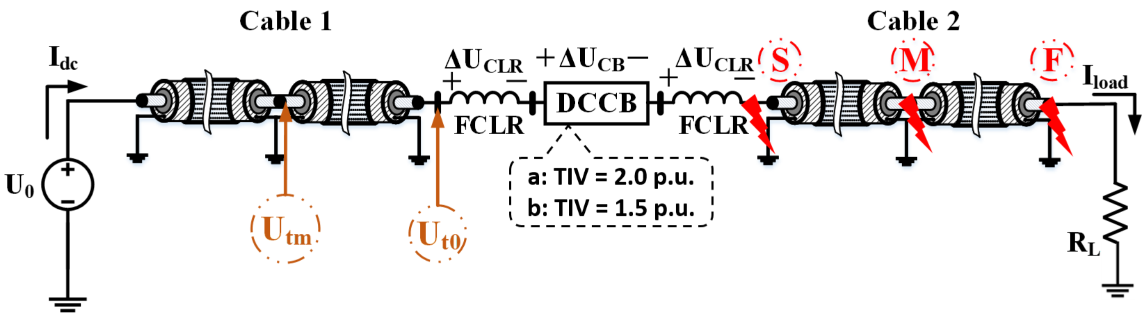


***Figure 3** – Simplified circuit for transient cable overvoltage analysis in radial MT-HVDC network during DCCB operation*

3.1 Modelling Approach and Parameter Variations

This study investigates the impact of the fault location, TIV, and FCLR values on cable stress in a radially configured conceptual MT-HVDC network. The faulted cable (Cable 2 in Figure 3) extends 200 km from the DCCB, with faults applied at its terminal, midpoint, and far end near the load. The healthy cable (Cable 1 in Figure 3), located on the opposite side between the voltage source and the DCCB, also spans 200 km. Cable stress is analysed at two locations on the healthy cable: the terminal near the DCCB interface (U_{t0}) and the midpoint (U_{tm}), under varying fault conditions.

Several parameters remain constant throughout the study: a base voltage of 525 kV, load resistance (R_L) enabling 1000 MW power transfer, and an HVDC cable screen earthing resistance of 1 mΩ, representing perfectly earthed cable system. Fault-to-ground conditions are applied with a grounding resistance of 0.5 Ω. The DCCB fault neutralization time is fixed at 5 ms, while the RCB delay is set at 50 ms for practical considerations. The simulation study considers three fault locations on Cable 2, namely, at its terminal, midpoint, and far end to examine wave reflections and transient propagation along with two measurement points on the Cable 1 (terminal near the DCCB interface, U_{t0}, and midpoint, U_{tm}) to evaluate its influence on fault energy dissipation and cable stress. Moreover, three FCLR values of 50 mH, 100 mH and 200 mH are simulated to study its impacts on overall fault interruption and wave propagation along cable. This results in $3 \times 2 \times 3 = 18$ distinct simulation cases for each measurement point and a particular TIV value. The simulations are conducted separately for two TIV values of 1.5 p.u. and 2.0 p.u. to evaluate its influence on fault energy dissipation and cable stress, leading to a total of $18 \times 2 = 36$ simulation cases. This ensures a comprehensive evaluation of cable stress variations under different fault scenarios.

The interplay of fault location, FCLR, and TIV provides a comprehensive understanding of transient wave interactions between the faulty and healthy cables. Fault location significantly influences traveling wave behaviour. Contrary to expectations, faults at the far end do not introduce higher stress on the healthy cable, as the traveling wave generated by the fault undergoes attenuation along the cable length before reaching the terminal. However, faults near the DCCB result in faster clearance but induce more intense local cable overvoltage. Figure 4 presents cable stress results for a higher TIV of 2.0 p.u., while Figure 5 illustrates the results for a lower TIV of 1.5 p.u. In both these cases the FCLR values have been varied at 50 mH, 100 mH, 200 mH. In both figures, the left-to-right progression corresponds to fault locations shifting from the DCCB terminal to the midpoint and finally to the far end of the faulty cable. Each column contains two plots: the top row (Figures 4.a – 4.c) shows voltage stress at the healthy cable terminal near the DCCB (U_{t0}), while the bottom row (Figures 4.d – 4.f) represents stress at the midpoint (U_{tm}).

A clear trend emerges: as the fault moves farther from the DCCB (Figures 4a – 4c), the terminal voltage stress decreases. A similar attenuation is observed at the cable midpoint (Figures 4d – 4f), indicating that faults closer to the DCCB induce stronger transients on cable, whereas those at the far end result in attenuated waveforms due to energy dissipation of the emerging transient within the cable as it travels along its length.

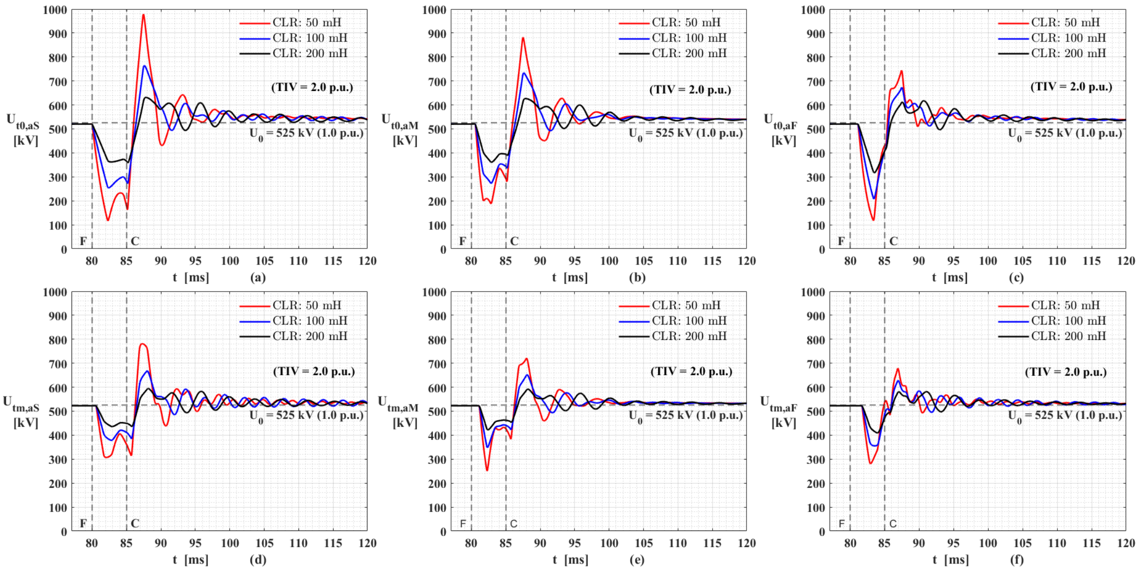


Figure 4 - Impact of fault location, FCLR, and TIV on overvoltage in HVDC cables: A comparative analysis at healthy cable terminals and midpoint for a TIV of 2.0 p.u.

Comparing terminal and midpoint stress within each column (e.g., Figures 4a and 4d; Figures 5a and 5d) further highlights this attenuation effect. These results confirm that worst-case cable stress occurs when faults originate at or near the DCCB terminal. Consequently, in radially connected systems, cable stress assessments should prioritize terminal measurements at the DCCB interface on the non-faulty cable.

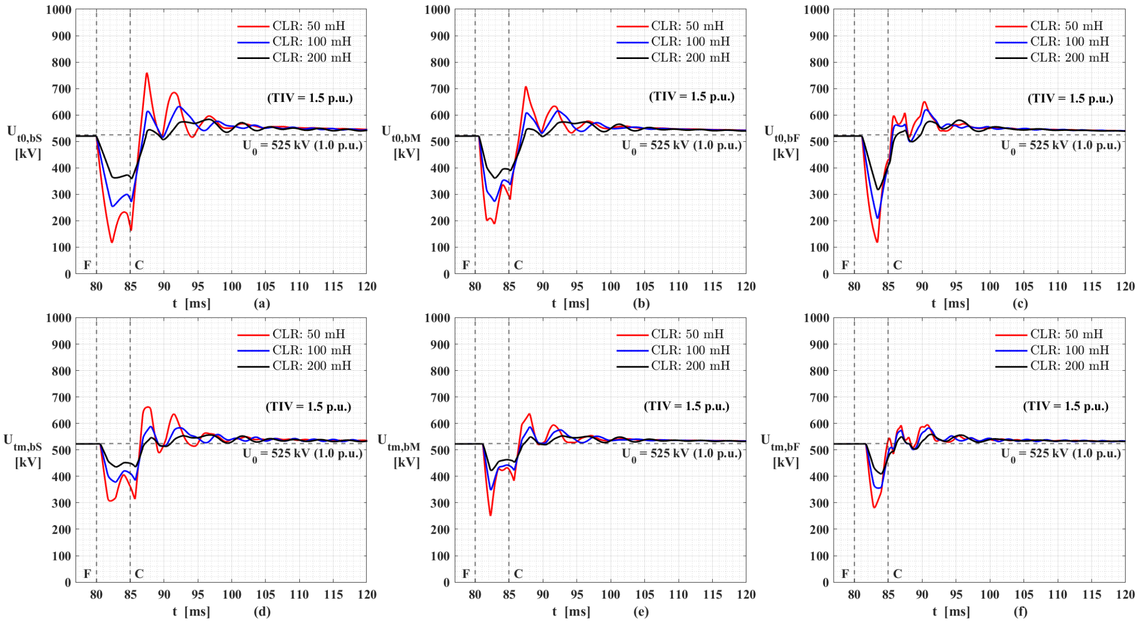


***Figure 5** - Impact of fault location, FCLR, and TIV on overvoltage in HVDC cables: A comparative analysis at healthy cable terminals and midpoint for a TIV of 1.5 p.u.*

Increasing TIV from 1.5 p.u. to 2.0 p.u. amplifies overvoltage conditions on the healthy cable, necessitating an optimal TIV selection to balance fault clearance efficiency and cable stress. FCLR variations between 50 mH and 200 mH affect the rate of current rise (di/dt) and voltage transients, where higher FCLR values ensure smoother current commutation but lead to an increased residual voltage oscillations, whereas lower FCLR values facilitate rapid current suppression but introduce additional switching transients.

The developed simulation framework provides a detailed characterization of fault-induced transients in an MT-HVDC network, particularly their effect on healthy cables in a radial configuration. The study requires a high-fidelity HVDC cable model to capture wave propagation over 400 km, comprehensive transient analysis across key components such as the DCCB and reactors, and extensive computational and post-processing efforts for interpreting high-resolution time-domain simulations. The findings contribute to a deeper understanding of insulation stress limitations in HVDC networks, supporting the optimization of DCCB settings, TIV selection, and FCLR sizing to improve fault management while minimizing stress on the HVDC cable system

4 Discussion

The parametric analysis of TIV and FCLR variations provides key insights into their interaction in determining cable overvoltage in a radial MT-HVDC network. The results highlight their influence on voltage swings, peak stresses, and insulation reliability of HVDC cables. Figure 6 illustrates a severe cable overvoltage case (identified in Figures 4 and 5) for a lower FCLR of 50 mH across two TIV values and three fault locations.

Fault neutralization occurs in 5 ms from fault inception (marked as “F” in Figure 6) and is indicated by “C”. Following neutralization, the healthy cable undergoes oscillatory voltage swings, peaking in about 6 ms before stabilizing as the DCCB enters the fault suppression stage.

No polarity reversals occur, indicating that overvoltage primarily stems from transient interactions rather than sustained voltage inversions. As seen in Figure 6, higher TIV values, for the same FCLR, amplify voltage swings at the healthy cable terminal near the DCCB. At 2.0 p.u., peak voltage stresses rise, intensifying cable insulation stress, while lower TIV values (1.5 p.u.) reduce oscillations, relieving cable insulation stress.

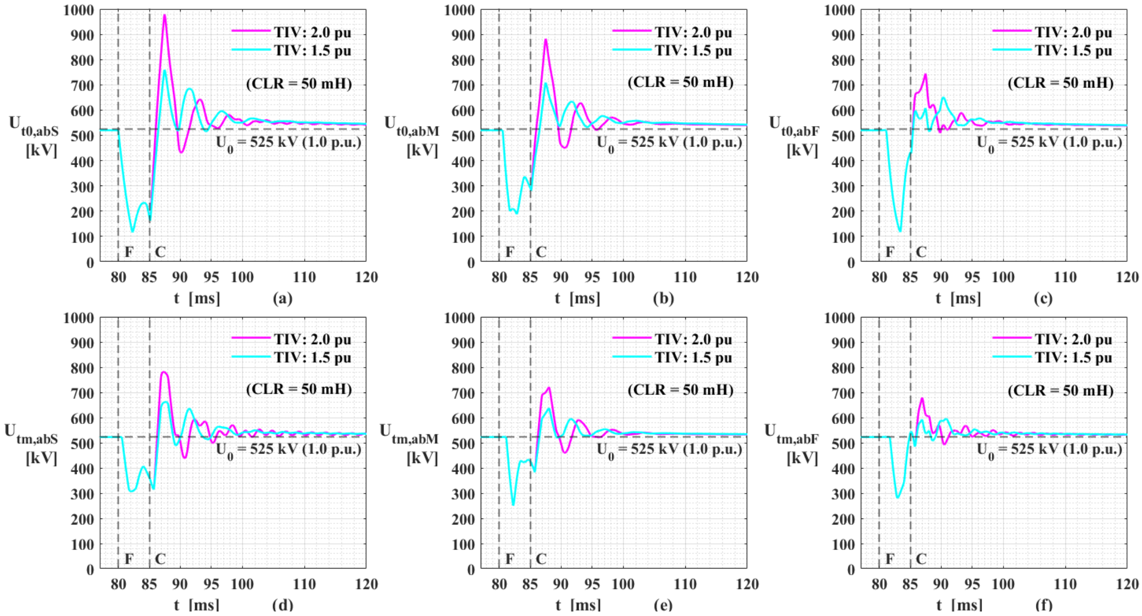


Figure 6 – Interaction between FCLR, and TIV on overvoltage in HVDC cables: A comparative analysis at healthy cable terminals and midpoint for a FCLR of 50 mH

FCLR strongly influences transient response. Lower FCLR values (< 100 mH) result in higher peak-to-peak voltage stress at the cable terminal. While reducing voltage drop across itself, low FCLR increases transient voltages, increasing risks of cable insulation degradation (see Figure 7.a – 7.d). Higher FCLR (200 mH) suppress voltage swings on the healthy cable but introduces an increased voltage drop, impacting system stability (see Figure 7.e – 7.f). This trade-off requires careful consideration in MT-HVDC grid protection design.

Higher TIV facilitates rapid fault clearance and efficient DCCB operation but induces greater voltage stress on the healthy cable. To manage this, a higher FCLR can be used to control transient stresses. Conversely, if lower FCLR is used to limit system-wide voltage drop and improve the dynamic performance of the overall HVDC network, the TIV can be accordingly lowered to prevent cable overvoltage.

The correlation between TIV and FCLR in the presented analysis has been investigated for a network with a fixed cable length. However, with the increasing demand for grid expansion, network extensions through additional cable installations become inevitable. In such evolving MT-HVDC networks, the introduction of additional cables alters the network's capacitance and inductance. Since the capacitance is directly proportional to the cable length, an increase in cable length leads to a higher total capacitance. The inductance also increases, however, its impact is more complex, as it depends on the specific series/parallel configuration of the extended network together with the FCLR values. This change influences network's natural resonance frequencies, so that an increase in cable length results in lower resonance frequencies. Lower resonance frequencies correspond to longer-lasting LC oscillations following DCCB operation. When the network expansion is not accompanied by appropriate damping mechanisms (e.g., resistors, filters), the system may become under-damped, leading to sustained oscillations that could impose significant stress on the network. Therefore, careful adaptation of damping strategies is crucial when extending MTDC grids to mitigate the risk of excessive transient overvoltages.

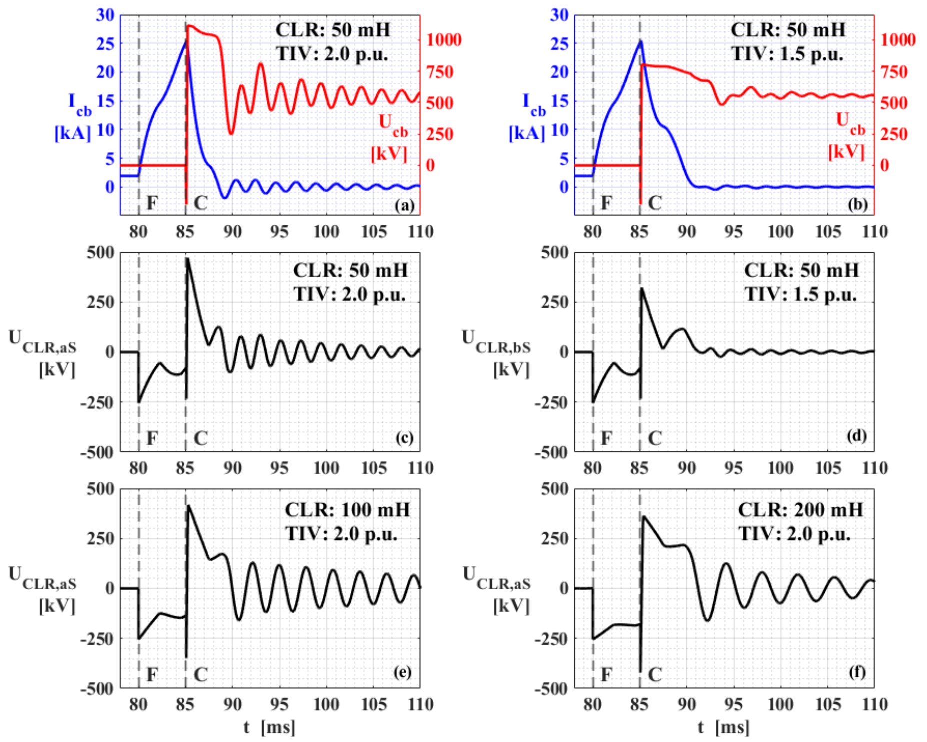


Figure 7 – Voltage drop over the FCLR and its interplay with the two TIV levels: 2.0 p.u., 1.5 p.u.

5 Conclusion

This paper has systematically analysed the impact of fault location, TIV, and FCLR values on cable stress in a simplified radial MT-HVDC network with unchanged cable length. Total of eighteen parametric variations were conducted for two variations in TIV value, measuring voltage transients on the healthy cable at both its terminal (DCCB interface) and midpoint under different fault locations and network conditions.

The findings confirm that cable stress is highly sensitive to TIV and FCLR selection. Higher TIV values (2.0 p.u.) accelerate fault clearance and improve DCCB operation but significantly increase voltage stress on the healthy cable, necessitating a sufficiently high FCLR (200 mH) to suppress cable transients. Conversely, lower TIV values (1.5 p.u.) inherently reduce cable stress but require careful coordination with lower FCLR values to prevent excessive voltage drop across the reactor. Similarly, a low FCLR (50 – 100 mH) limits voltage drop but increases cable transient stresses, whereas a high FCLR (200 mH) mitigates cable transients but introduces greater steady-state voltage drop, impacting overall grid performance.

A balanced protection strategy is essential to ensure insulation reliability while maintaining operational stability. For practical MT-HVDC grid implementation:

- Lower TIV values can reduce overvoltage on cables and accordingly impose less insulation stress but may necessitate trade-offs in determining DCCB operation speed.
- An increased TIV lead to reduced fault clearing times with additional voltage stresses on the cable, accordingly requires coordination with an appropriately sized FCLR to prevent excessive cable overvoltage.
- FCLR dimensioning should be optimized to balance transient suppression and steady-state performance, minimizing overvoltage on cables and switching components.

This study provides insights into the requirement for optimized TIV and FCLR coordination to enhance system resilience while balancing cable overvoltage. Future research should explore adaptive protection strategies, such as hybrid FCLR configurations and dynamic TIV control, to further improve fault management in MT-HVDC networks. This study and its findings offer insights into the design and optimization of DCCB protection strategies in cable-based MT-HVDC network, optimizing HVDC fault management strategies, ensuring system reliability and effective fault isolation and long-term cable reliability.

Future research can apply the results of this study to incorporate detailed system components, such as converter models, cable joints, surge arrestors, and non-ideal elements, to better capture transient voltage disturbances. Additionally, advanced mitigation strategies, including hybrid FCLR configurations, DCCB topologies, and adaptive TIV control, should be explored to manage the stresses on cable systems and enhance system resilience against transient events.

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