Mitigating overvoltage risks in extended underground MV network

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Abstract - This paper discusses the challenges posed by the expanding underground MV electrical networks, leading to various electrical phenomena that affect the equipment deployed within these networks. Specifically, the high capacitive currents generated by cables in the network require a deep evaluation of various potential risks.

The paper highlights issues such as switching overvoltage and insulation degradation which impact the operational efficiency and durability of the equipment. Furthermore, the article emphasizes the necessity of innovative yet practical (industrially and economically feasible) solutions to effectively manage and mitigate these constraints. This is crucial to ensure the reliability and performance of underground MV power networks and associated equipment.

The end user will provide his vision of the need for protection to mitigate overvoltages and the risks that he agrees to take to avoid protection solutions that are too complex and too expensive.

Index Terms — Switching overvoltage, mitigation, pipeline, cable energization, Back-to-back cable energization, extended cable network, power system studies, capacitive currents.

I. INTRODUCTION

Today, we are seeing a shift in electricity distribution, characterized by an expanding network as more electricity distributors and industrial companies, driven by their growing demand for power and the electrification of processes, opt to bury their power lines. The transition to underground power lines has addressed many issues associated with overhead lines, including visual pollution, vulnerability to weather conditions, accident risks, and interference with other infrastructures.

Examples:

- Following the wildfires in California, the local utility announced a plan to bury 16 000 km of power lines.
- East African Crude Oil Pipeline (EACOP) Project includes around 1400km of underground HV cable.

The shift to underground systems helps to mitigate these issues in the evolution of electricity distribution. However, this approach also brings its own set of complexities and challenges.

This article is focus on the overvoltage phenomenon linked to the extended underground MV network of the EACOP project and the solutions employed within the project to overcome these issues.

The first part describes the EACOP Project, the main electrical architecture, main MV equipment (circuit-breakers & switchgears) and MV cables. Then, a comprehensive overview of the switching analysis studies that need to be conducted to guarantee the reliability and performance of underground MV power networks and their associated equipment is provided.

II. SYSTEM DESCRIPTION

A. EACOP Project

The East African Crude Oil Pipeline Project (EACOP) is a 1,443km pipeline that will transport oil produced from Uganda to the port of Tanga in Tanzania where the oil will be loaded onto tankers. It will have a peak capacity of 246,000 barrels/day.

To transport oil over long distances, various subsystems are necessary. Regular “Long Line Heat Tracing” systems (LLHT) are installed to heat the pipeline and prevent the oil to solidity, with LLHT substations placed every 60 km. Additionally, pumping stations (PS) are essential for moving the oil through the pipeline, and pressure reduction stations (PRS) are required primarily due to the area's topography. Finally, a generation system, including grid connections, photovoltaic (PV) plants and crude oil generators (CRO) is in place to power all these subsystems and utilities.

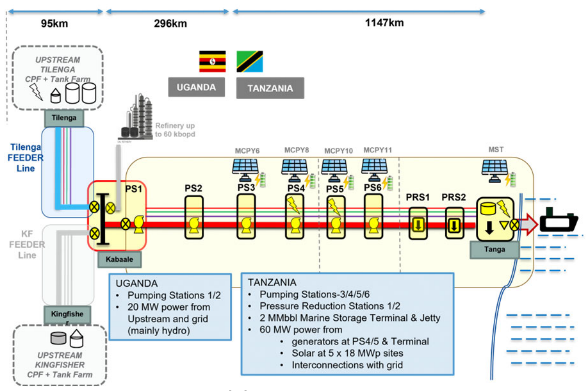


Figure 1: EACOP electrical architecture.

B. Electrical network topology

From an electrical standpoint, the pipeline is segmented into four separate and independent sections, with each section spanning roughly 400 km.

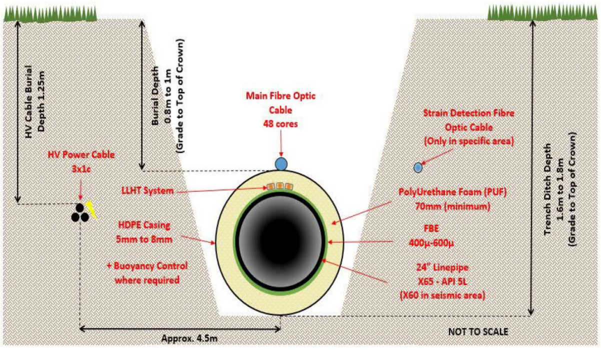


Figure 2: Typical section of the Pipeline.

In addition to the pipeline, 33kV electrical cables are laid and buried along the same right of way.

The first section is in Uganda and is connected only to the grid, while the other three sections are in Tanzania, each linked to their local grid, CRO generators, and a photovoltaic plant.

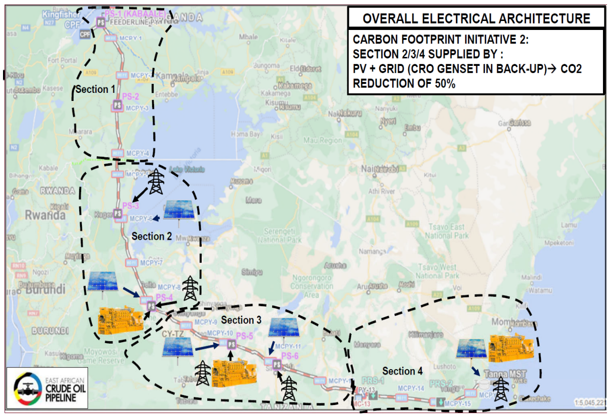


Figure 3: Overall electrical architecture of the 4 sections.

Additionally, each section is a radial network and each substation (pumping stations, pressure reduction stations, and long line heat tracing systems) are interconnected via 33kV buried cables, each approximately 50 km long. A typical EACOP network consists of:

→ Pumping Stations (PS) powered either by CRO generators, a grid connection, or both. These substations are equipped with photovoltaic (PV) panels and battery energy storage systems (BESS). These 33 kV PS substations include motors (pumps), MV/LV transformers, earthing transformers, and shunt reactors to compensate the capacitive effects of long cable connections.

→ Long Line Heat Tracing substations (LLHT) are supplied from the PS and composed of MV/MV transformers for feeding the LLHT systems, MV/LV transformers, and shunt reactors.

→ Pressure Reduction Stations (PRS) are supplied from the PS and composed of MV/LV transformers and shunt reactors.

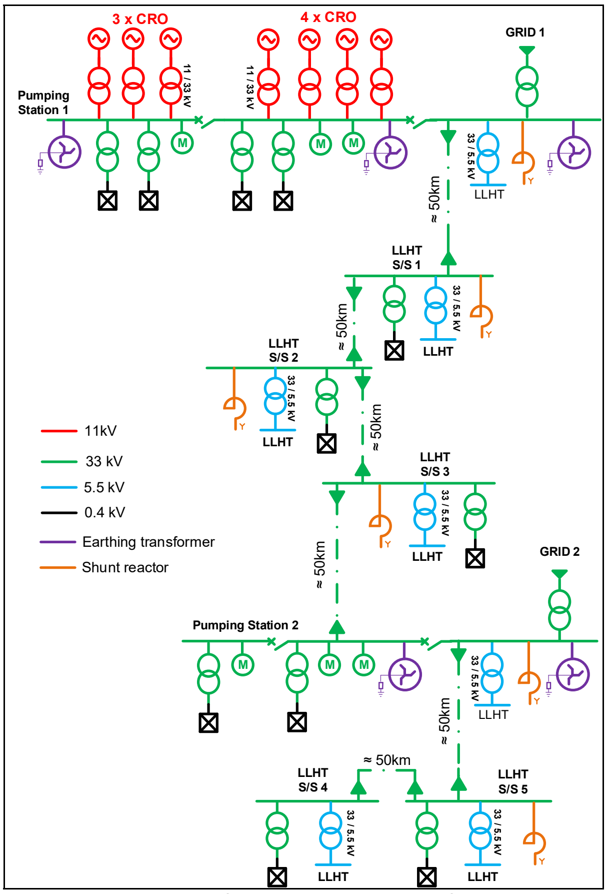


Figure 4: Example of electrical architecture of one section.

C. Derating consideration

Since the HV equipment will be installed at various altitudes near the pipeline, it will be necessary to apply the altitude correction factor (Ka) in accordance with the IEC 60071-2 standard (2023 version) [2] if the altitude exceeds 1000 meters for equipment with external insulation. The altitude correction factor "Ka" is given by:

$$Ka = e^{\left(\frac{H-1000}{8150}\right)}$$

H = installation altitude of the equipment in meters

This formula allows to consider the reduced air density at higher altitudes, which can affect the insulation properties and overall performance of the equipment.

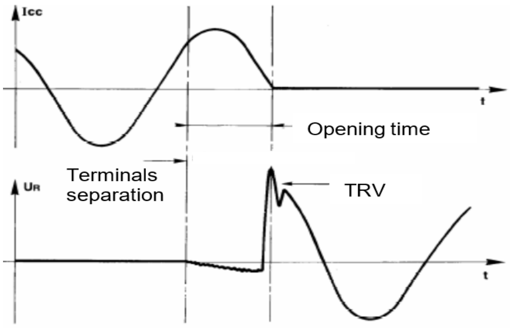
Still within the same IEC 60071-2 standard (2023 version) [2], a safety factor (Ks) of 1.15 should be applied to internal insulation to account for variations in product quality, installation quality, and the aging of insulation throughout the installation's lifespan.

D. HV cables

As described before, the EACOP project is constituted of several HV cables of around 50km for a total of 400km for each section of the project. These HV cables rated for 66 kV or 33 kV voltages with cross-sections ranging from 150 mm² to 630 mm² use a single-core design with aluminum screen and armored shielding, ensuring reliability in underground environments.

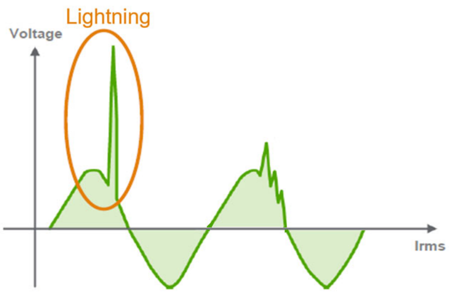
III. STUDIED PHENOMENA IN EACOP PROJECT

A. *Transient Recovery Voltage (TRV)*



When a fault occurs, the circuit breaker must be able to interrupt fault without causing transient stress on circuit breaker itself and other equipment in the network. The voltage that appears across a circuit breaker at the fault current interruption is named Transient Recovery Voltage (TRV). In specific conditions, the TRV values (peak and rate of rise) could exceed the circuit breaker standard withstand. The overvoltage might damage circuit breaker, propagate to other equipment in the network.

B. *Lightning overvoltage*



Since the various sections are linked to the grid via overhead lines (OHL), a lightning strike on the final span of the overhead line before it reaches the transformer that supplies each section can lead to significant overvoltages at the equipment level. This occurs because the lightning discharge can induce a surge in voltage that travels along the overhead line, potentially damaging electrical equipment and affecting the overall system stability.

C. *Switching overvoltage*

Shunt reactors:

The interruption of small inductive currents is one of the switching operations which may lead to switching overvoltages. This operation takes place in switching off shunt reactors, for example. The creation of overvoltages at switching of small inductive currents is due to current chopping.

Current chopping is the premature interruption of alternating current before it reaches zero, causing transient overvoltages. This can happen with any circuit breaker type (Vacuum or SF6). In vacuum breakers, the chopping value depends on the contact material, while in SF6 breakers, it relies on power system characteristics since SF6 extinguishes the current at the first zero crossing without re-arcing. As shunt reactors are present in the EACOP network, current chopping has been calculated for the SF6 circuit breakers installed.

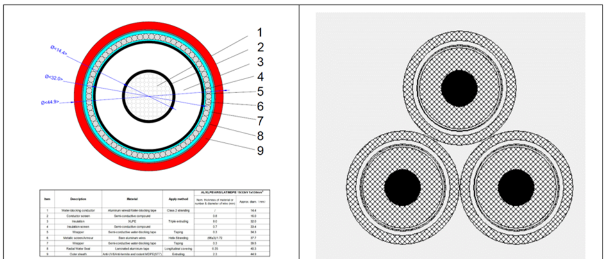
Cable energization:

When energizing very long high-voltage (HV) cables like in the EACOP project (around 50km), the risk of overvoltage increases. The cable's length can amplify inductive and capacitive effects, leading to transient overvoltage that may damage connected equipment and compromise the reliability of the electrical system.

The worst case occurs during the energization of a cable retaining residual charge from a prior de-energization event. This scenario induces critical dielectric stress due to the superposition of the residual voltage and the newly applied system voltage, resulting in amplified overvoltage magnitudes and heightened risks of insulation breakdown and equipment damage. The subsequent analysis in this article will focus on this phenomenon, characterized by peak overvoltage amplitudes and intricate interactions between network parameters and cable properties, through theoretical modeling and numerical simulations to quantify mitigation strategies and operational constraints.

For the analysis of transient overvoltages in high-voltage cable systems, the ATP/EMTP software is widely recognized as a benchmark tool for simulating these complex phenomena. Accurate cable modeling represents a critical parameter in such studies, as the distributed electrical parameters and frequency-dependent behavior of cables directly govern the magnitude and dynamics of transient overvoltages.

ATP/EMTP software utilizes detailed electrical and geometrical data to accurately represent the frequency-dependent impedance characteristics of the cables. The following figure show that the modeled “150mm² - 33kV” cable has the same geometric and electrical characteristics as those given in the manufacturer datasheet.



AC Resistance @20°C (Ω/km)	Reactance 50 Hz (Ω/km)	Capacitance (µF/km)	AC Resistance @20°C (Ω/km)	Reactance 50 Hz (Ω/km)	Capacitance (µF/km)
0.206	0.132	0.18	0.2	0.1318	0.18
33kV - 150mm² Cable datasheet			Characteristics of the modeled cable on “EMTP ATP”		

Figure 5: Example of “33kV-150mm²” Cable model in EMTP ATP.

Furthermore, the metallic screen earthing system needs to be modeled in the EMTP ATP software for these long-buried cables. The planned earthing arrangement in the

EACOP project is *solid bonding system with intermediate earthing points*, which an example is illustrated below for 33kV-150mm² cable:

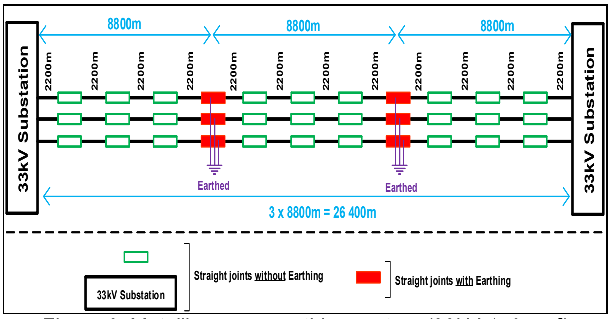


Figure 6: Metallic screen earthing system (33kV-150mm²)

With this bonding arrangement, the sheaths, screens, and armor are solidly earthed at both ends of the cable system and bonds at intermediate points along the cable.

Moreover, as some HV cables are installed in parallel within the installation, it is crucial to verify the circuit breaker's performance in accordance with the IEC 62271-100 standard (2021 version) [3], particularly in the event of a back-to-back energization. This situation can produce a high inrush current, which may pose a risk to the equipment connected to the cables. This phenomenon is like the back-to-back capacitor inrush making phenomena. Circuit breakers must be able to withstand a maximum peak value (Ibi) of 20kA and a maximum frequency of the inrush current transient (fbi) of 4250Hz for all voltage levels (see Table 1 [3]).

IV. SWITCHING OVERVOLTAGE ANALYSIS

D. 33kV Cable Energization

Energizing a cable can cause a transient overvoltage, with its magnitude depending on the timing of the cable connection. This phenomenon will be further clarified by examining the energization of a EACOP 33kV cable that has a cross-sectional area of 300mm² and a length of 52km.

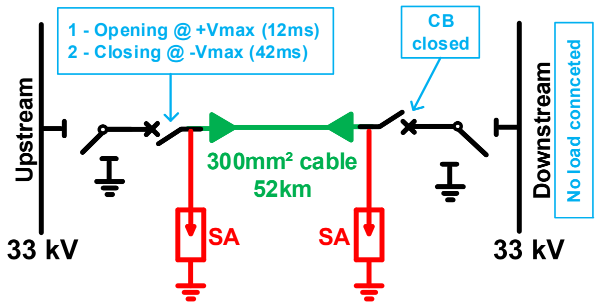


Figure 7: Cable reenergization simplified circuit.

The events studied include the initial energization of the 33kV cable without load. Next, the cable circuit breaker opens at the positive peak voltage (+Vmax). Finally, the cable circuit breaker closes at the negative peak voltage (-Vmax).

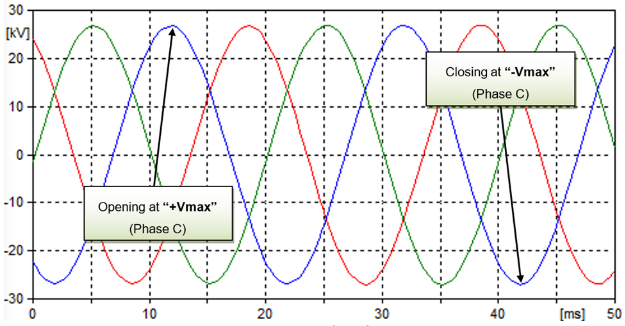


Figure 8: Worst scenario for Cable energization.

This sequence is the most critical because the cable is charged at a potential of +Vmax and it is energized again when the voltage reaches -Vmax. The potential difference between the cable voltage and the main voltage is then maximized. The transient regimes will have a maximum amplitude as it can be seen in the following simulation results presented in Fig. 9 and Fig. 10.:

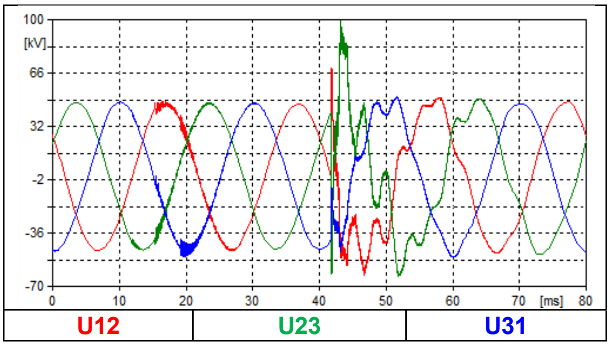


*Figure 9: Phase-to-phase voltage **upstream** the cable.*

We can see above that after the circuit breaker supplying the HV cable closes (@42ms), the overvoltage at the upstream switchgear rises to 100kV, surpassing the equipment limit of 86kV peak.

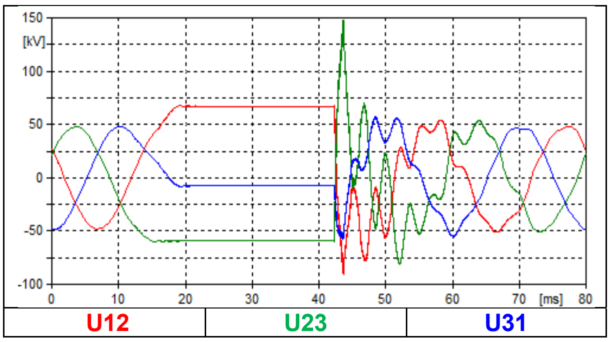


*Figure 10: Phase-to-phase voltage **downstream** the cable.*

In the previous figure, we can observe an overvoltage at the downstream switchgear following the closure of the circuit breaker that supplies the cable. The phase-to-phase voltage downstream of the HV cable increases to 150 kV, exceeding the equipment's limit of 86kV peak. This situation arises because, after the circuit breaker is opened (@ 12 ms), the cable remains energized with a constant voltage defined by its capacitance. The capacitive properties of the cable enable it to retain electrical energy even when it is disconnected from the power source.

Consequently, the cable can sustain a residual voltage for a time, and if the cable is reenergized (@ 42 ms) during this period, the risk of overvoltage is greatly amplified. The voltage downstream of the cable is higher than upstream due to the propagation phenomenon.

In conclusion, the process of reenergizing a cable can cause significant overvoltages that exceed standard limits, highlighting the need for adequate solution.

E. 33kV Cable De-energization

As explained earlier, overvoltages can exceed equipment limits because cables may remain charged after disconnection. To mitigate this risk, it's important to de-energize the cables before re-energizing them.

To achieve this, the disconnector earthing switches on each side of the cable will operate only when the circuit breakers are open and must work simultaneously. The sequence in Fig. 11 must then be followed for each cable to de-energize them. The example below shows only one cable, but the network includes several HV cables in series with cross-sections ranging from 150 mm² to 300 mm² and lengths from 30 km to 52 km.

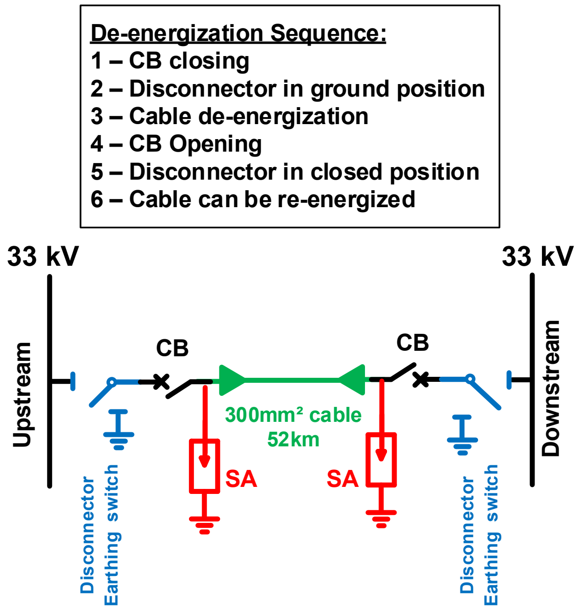


Figure 11: Cable De-energization Sequence for one cable.

In the event of a cable feeder circuit breaker opening – whether triggered intentionally (for maintenance operations) or accidentally (due to faults or protective relaying) – the loss of voltage protection (ANSI 27) will detect the absence of voltage on the downstream network. This detection initiates an automatic, cascading tripping mechanism, disconnecting all associated downstream circuit breakers to isolate the de-energized section.

This cascade tripping event requires operators to strictly follow the sequence described above to perform controlled cable de-energization, ensuring the safety of personnel and equipment.

The following simulation results presented in Fig. 12 and Fig. 13 shows the Phase-to-phase voltage upstream and downstream the cable during the de-energization & Energization of a 33kV cable (300mm² - 51.95km). The event simulated is the worst one (refer to Fig.8).

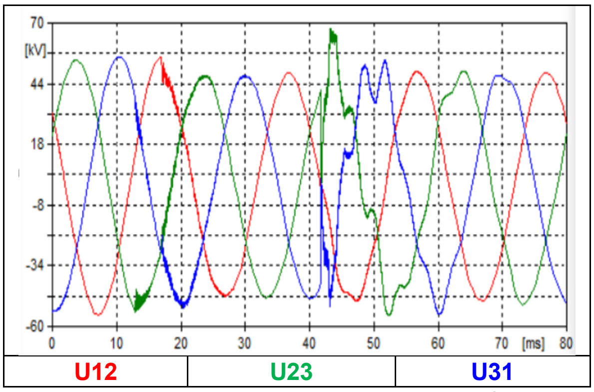


Figure 12: Ph-Ph voltage **upstream** the cable after de-energization.

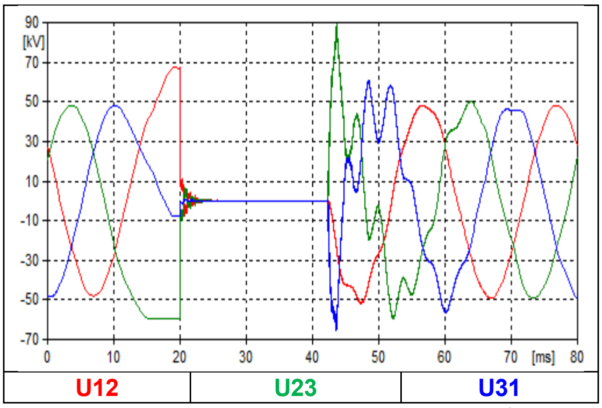


Figure 13: Ph-Ph voltage **downstream** the cable after de-energization.

The simulation results demonstrate that after the circuit breaker is opened, the residual voltage is significantly reduced, bringing the phase-to-phase voltage close to zero. This outcome is a result of the implemented de-energization sequence (@20ms), which plays a crucial role in mitigating the risk of overvoltages during the subsequent re-energization process (@42ms). By following this sequence (Fig. 11), we ensure that the system remains stable and prevents potential damage to equipment from excessive voltage levels.

The disconnector earthing switches reduce the overvoltage to 90kV, just above the equipment limit of 86kV, when applying the 15% safety factor "Ks" as defined in the IEC 60071-2 standard (2023 version) [2]. This solution ensures equipment protection even if the equipment withstand is exceeded by few kV (equipment withstand is 99kV peak and 86kV peak with the safety factor applied). This slight voltage excess has been accepted by the customer.

F. Back-to-back cable energization

The back-to-back cable energization phenomenon occurs when a cable is energized while it is connected in parallel to another cable that is already live. This action can result in the generation of high inrush currents that can significantly exceed normal operating levels. If this situation is not properly managed, it can lead to the deterioration of the newly energized cable and pose a serious risk to the circuit breaker.

To better understand the phenomenon, we will model the cables as RLC circuits. Let's consider a circuit with two cables in parallel (“A” & “B”), as shown in the Fig. 14. When the second circuit breaker “B” is closed to power the second cable “B”, the energy stored in the first cable “A”, which is already energized, will be transferred to the second cable “B”, resulting in an inrush current that can cause damage to the cable and pose a risk to the circuit breaker.

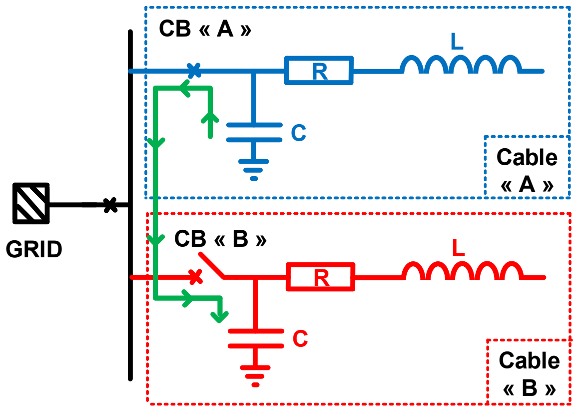


Figure 14: RLC Equivalent Circuit Model for Cable Energization

As explained previously (see paragraph **III. C.**), the parameters to check during the simulations are:

- The voltages at the cable ends, which should be compared to IEC 60071-1 (Table 2) [1].
- The maximum peak current (20kA) and the highest frequency (4250 Hz) of the inrush current at the circuit breaker terminals, which should be compared to IEC 62271-100 (Table 1) [3].

For the EACOP project, the following scenario requires verification of the withstand capabilities of the 66kV circuit breakers:

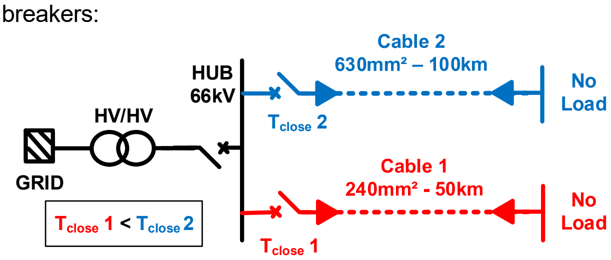


Figure 15: Back-to-back case in EACOP project.

As shown in the figure above (Fig. 18), the simulation will focus on cables "1" and "2" connected to the 66kV Hub. "Cable 1" will be energized first (Tclose 1), followed by back-to-back energization of "Cable 2" (Tclose 2).

For the single cable energization of "Cable 1" from the 66kV Hub, the following simulation results (Fig. 16) indicate a transient overvoltage occurring when the circuit breaker closes, which coincides with the positive peak voltage (+Vmax). This sequence is the most critical, as the cable is charged to a potential of Vmax, leading to transient regimes with maximum amplitude.

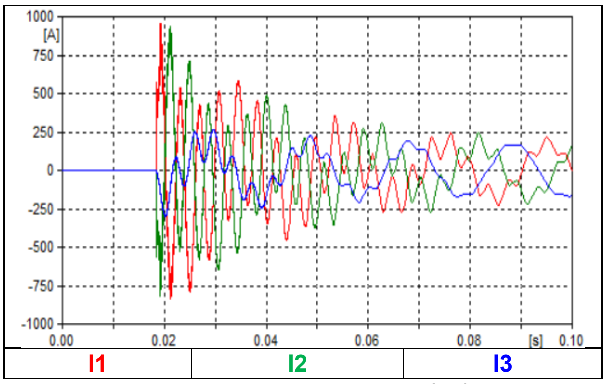


Figure 16: Maximum peak current across the CB feeding cable1.

For the back-to-back energization of "cable 2" from the HUB 66kV, the simulation sequence (Fig. 17) will involve waiting until cable A reaches steady-state conditions. Then, the circuit breaker feeding cable B will be closed at the positive peak voltage (+Vmax), which is the worst-case scenario.

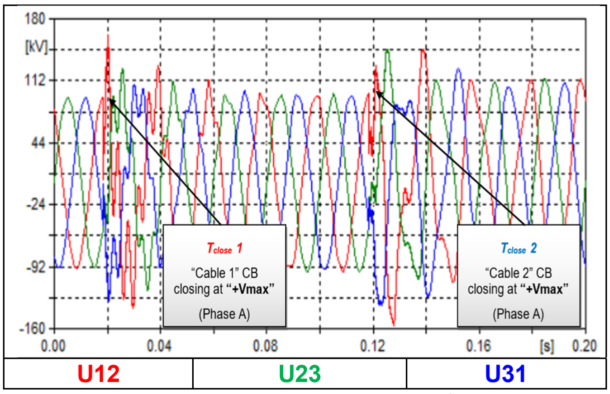


Figure 17: *Back-to-back energization sequence from HUB 66kV.*

The following simulation results presented in Fig. 18 and Fig. 19 shows the Maximum peak current across the circuit breakers feeding the cables 1 and 2 during the Back-to-back energization sequence described previously (Fig. 17).

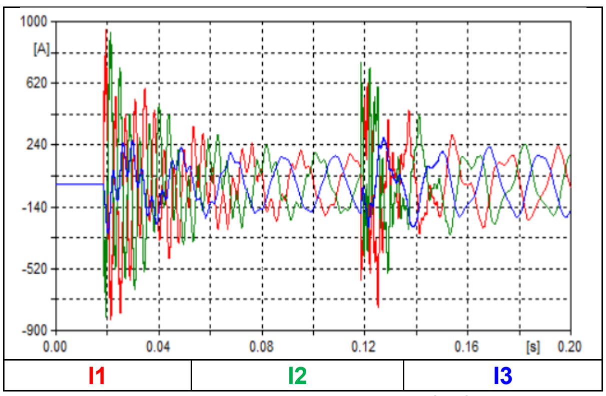


Figure 18: Maximum peak current across the CB feeding **cable1** (*Back-to-back energization)*.

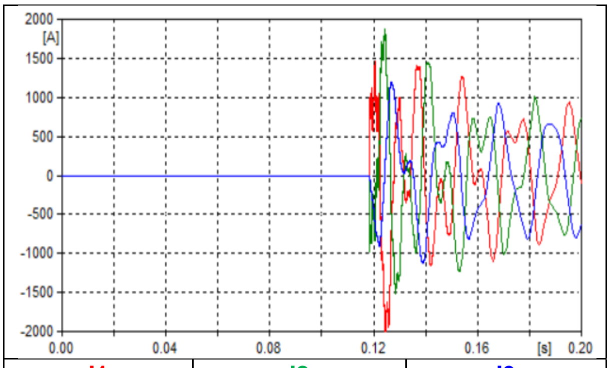


Figure 19: Maximum peak current across the CB feeding **cable2** (*Back-to-back energization*).

We can observe the current across the CB feeding the 66kV cable created by the closing of the circuit breaker at t_{cl2}. The maximum peak value of the inrush current increases (up to 2000A for the Phase 1) with a frequency of 108Hz and does not exceed the limit circuit breaker (20kA & 4250Hz).

The above simulation results (Fig. 19) demonstrate that when a cable is energized in parallel with another already energized cable, the current experience significant increases in peak values compared to the energization of a single cable. In this scenario, the current amplitude can peak at 2kA, which is double the 1kA observed during the energization of a single cable. In case of too high inrush current, Point-on-Wave switching could be considered to avoid energization at Vmax thus minimizing the inrush current.

V. OTHERS POINTS OF ATTENTION

Special attention shall be paid as well due to the simultaneous presence of saturable magnetic circuits (e.g: Power transformers, VT's) with large capacitance of underground cable since transient oscillating overvoltage's due to ferro-resonance could occur when switching breakers. Especially with presence of surge arresters which could be the first victims of these transient oscillating voltages due to their weakness to low frequency voltage temporary surges.

Finally, it can be noted that if a transformer is already energized and connected to the same busbar prior to cable energization, when energizing the cable, the energized transformer could draw an inrush current called sympathetic inrush current caused by the asymmetrical transient voltage resulting of the cable energization sequence which could drive the transformer into saturation.

VI. CONCLUSIONS

In summary, with the anticipated increase in high voltage cable installations over very long distances in distribution and industrial networks, we will face voltage surge phenomena that could potentially damage high voltage (HV) equipment, including cables, circuit breakers, and panels. These surges may also negatively affect network availability.

Transient overvoltage studies are essential for identifying the various risks associated with these conditions. By simulating realistic scenarios, such as the energization or de-energization of HV cables, we can better understand the potential impacts. These analyses enable us to verify the performance of existing equipment or select new equipment that can withstand these challenging conditions.

As pragmatic builders, and thanks to close collaboration with our clients, we have been able to propose optimal solutions to address these issues while reducing costs.

II. REFERENCES

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[2] IEC 60071-2 (2023) Insulation co-ordination - Part 2: Application guidelines.

[3] IEC 62271-100 (2021) High-voltage switchgear and controlgear – Part 100: Alternating-current circuit-breakers

III. VITA

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