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# PROTECTION OF MIXED CIRCUITS

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# Acknowledgements

This ENTSO-E report has been prepared and coordinated by a project team gathered around the WG Protection Equipment Group of the STG Resilient Operation in 2025. The project team included active members of the WG Protection Equipment. The scope of the project was to examine and document the experience and practices of TSOs in protecting mixed lines in networks above 60 kV.

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# Definitions

An **overhead Line (OHL)** is an electrical power transmission or distribution line supported above ground by towers.

An **underground cable (UGC)** is an electrical power transmission or distribution line installed below ground.

A **submarine cable (SMC)** is an electrical power transmission line in which cable is installed on the seabed or riverbed, connecting land-based substations.

**Mixed circuits (mixed lines)** are generally defined as lines of at least two sections, where these two sections have different electrical characteristics.

**A mixed circuit (mixed line, MXD circuit)** is defined in this report as when the protection schemes of the considered transmission line differ from the standard protection applied on the pure OHL or pure UGC/SMC circuits, being based on their mixed circuit structure as defined above.

**Hybrid circuits (hybrid lines)** are circuits with different voltage ratings that are run in parallel on the same tower. In the literature, DC lines running alongside AC lines are referred to as hybrid lines.

The **auto-reclosing (AR)** function is a standard method applied to overhead lines to automatically restore power transmission in the event of a non-permanent fault by briefly interrupting the affected phases and reclosing after the dead time setting expires.

**Selective auto-reclosing (sAR)** is a variation of AR, where the AR function is blocked in case a fault occurs on a specific section of the circuit. In the case of MXD circuits, this applies to the fault in the UGC section. In this case, AR will not be performed for the fault on the cable section. On the other hand, if the fault occurs on the OHL section of the MXD circuit, AR will be performed as usual.

# ABSTRACT

Mixed circuits are increasingly being used in transmission systems to overcome challenges posed by terrain, environmental constraints or urbanisation. These circuits combine overhead lines (OHL) with underground cables (UGC) or submarine cables (SMC) and require specialised protection strategies due to their heterogeneous electrical characteristics and operational complexities.

This document outlines the issues and challenges that TSOs face when protecting a mixed circuit, provides examples of implementation and summarises the experience of different European TSOs.

Chapter 2 discusses the configurations of mixed overhead-cable circuits and the specific role they play in TSO networks. It provides a definition of the mixed circuit and emphasises the importance of tailored protection schemes and accurate fault location to maintain system reliability and safety.

Chapter 3 delves into the implementation aspects of mixed overhead-cable circuits. It covers the primary equipment used, shares experience with faults on the mixed circuit, and provides a brief overview of the operational issues.

Chapter 4 explores the protection challenges and solutions for mixed overhead-cable circuits. It discusses the calculation of impedance and the residual compensation factor K0, which varies with cable sheath earthing and affects distance relay settings. Additionally, the chapter emphasises the importance of selective AR, allowing reclosing on OHL faults while blocking it on cable faults to prevent damage. Various methods for selective AR are discussed, including dedicated distance protection zones, differential protection, travelling-wave detection, secondary arc detection and cable sheath current monitoring. Each method has its advantages and disadvantages concerning complexity, cost and selectivity. The chapter also covers fault location techniques, including single-ended and double-ended impedance-based fault locators and travelling-wave-based fault location.

Chapter 5 discusses case studies and practices of transmission system operators (TSOs) for protecting mixed overhead-cable circuits. It highlights the methods used by different European TSOs to address the unique challenges posed by these circuits. The chapter emphasises the importance of tailored protection schemes, selective AR and accurate fault location to maintain system reliability and safety. Each TSO's approach provides valuable insights into the practical implementation of protection strategies for mixed circuits, showcasing the diversity of solutions and experiences in the field.

Chapter 6 provides insights from questionnaires completed by various TSOs on their experiences with mixed overhead-cable circuits.

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# 1. Introduction

Introducing mixed overhead-cable circuits as a solution for power transfer over terrain where a classical overhead line cannot be installed, or replacing a part of the overhead line with an underground or submarine cable, has equally presented new challenges for the protection teams of TSOs and DSOs.

One of the dilemmas protection teams are facing is what to do with the commonly used AR function. The AR function is a standard method applied to overhead lines to restore power transport in the event of a temporary fault. This is ensured by briefly interrupting the affected phases, breaking the primary arc and reclosing after the secondary arc has vanished. In the new system, which contains mixed circuits, AR cannot be successful for faults on the cable section.

One of the easiest choices here could be to put the AR function out of service for the entire length of the line. This will result in the complete branch being lost from the system, even when a temporary fault occurs on an overhead line section. Losing a line can lead to further problems in the system.

Another option would be to keep the AR function active for the entire branch, which would cause the faulted cable section to reclose. Reclosing a faulted cable section expands the fault and increases damage to the cable, and it might have serious effects on the connected parts of the grid; in the worst case, we could face a loss of system stability. In addition, reclosing the permanent fault represents an additional risk to humans, and the risk of wildfire also increases.

For cases where the cable section is shorter than 1 km or less than a certain percentage of the total cable length – defined by the TSO – it might be easier to allow the AR function to be activated for the whole mixed circuit. [1] For all other cases, it might be reasonable to apply a more complex selective AR philosophy to overcome this dilemma.

The aim of this document is to collect TSO experience on protecting mixed circuits, compare them and provide the reader with an overview of specific challenges and solutions.

# 2. Mixed circuits

## 2.1. Definition of mixed circuits

Circuits connecting two distant substations can be classified into homogeneous and mixed circuits [1]. The term mixed circuit should not be confused with hybrid circuit, as discussed later in this chapter.

A circuit composed entirely of a single section is called a homogeneous circuit. This circuit can be a pure overhead line (OHL), underground cable (UGC), or submarine cable (SMC). Accordingly, the electrical characteristics of these circuits are the same throughout their length. For further simplification, UGCs and SMCs will be addressed as UGCs.

On the other hand, mixed circuits are constructed from at least two sections with different electrical characteristics. In the literature, the term "mixed circuit" is most often used to describe an OHL followed by one or more UGC or SMC sections. However, in general, a mixed circuit can also be a pure OHL or UGC, with sections made of different conductor materials (for example, one section made of aluminium and the other of copper) or even the same material but with different cross sections. As soon as we have two circuit sections with different electrical characteristics, we are talking about mixed circuits.

Here, it is important to underline that this report will refer to a circuit as a mixed circuit only if its protection scheme differs from the standard protection that TSOs apply to pure OHL or pure UGC circuits, based on its mixed circuit structure. It should also be noted that mixed circuits at the TSO network level are protected in the same way as OHL or UGC, but they will not be described in more detail in this report.

Furthermore, this report considers only circuits of the line structure, meaning that mixed circuits, such as those containing lines with series compensation or similar devices, are not included in this definition.

Hybrid circuits are two circuits of different rated voltages carried in parallel on the same tower. This results in mutual interaction between the two parallel circuits. AC and DC circuits in parallel are mostly called hybrid circuits. This means that a mixed circuit can also be a hybrid circuit, although such mixed hybrid circuits are not considered in this report.

## 2.2. Role of mixed circuits in electrical transmission

Power transmission circuits are mostly constructed as overhead lines (OHLs) because their unit-length costs are lower than those of UGCs. UGCs are primarily used in urban areas where space is limited, and power transfer via OHLs could pose risks to the surrounding area. This is why UGCs and mixed lines are mostly common in distribution systems.

With the rise of environmental constraints and the introduction of new power transmission lines, which are in competition with parallel infrastructure (crossing of roads, railways, etc.) or are being planned over difficult terrain (fjords, lakes, etc.), the tendency to introduce UGC sections in an OHL corridor in the transmission system network is increasing. This is also supported by the authorisation processes required when new OHLs are planned. In many cases, it is easier to obtain permits and approvals from residents and local communities to install a new UGC than to install an OHL.

This is also reflected in the responses to the questionnaire published in Chapter 6, in which 20 of 24 TSOs reported having mixed circuits in their systems. Three TSOs have indicated that they do not currently have a mixed circuit in use, although they are in the planning stage for implementing some. Only one does not have this type of circuit and is also not planning to integrate it into their TSO network infrastructure. This suggests that the vast majority of TSOs will have mixed circuits in the years to come.

Figure 1 demonstrates one example in which parallel infrastructure led to the introduction of a UGC section on the OHL between the substation and the first tower. Here, it was not possible to install a tower between the substation and the first tower in the corridor while simultaneously ensuring the safety of the users and owners of the parallel infrastructure. Constructing a pure OHL that meets all safety standards and ensures full line functionality would negatively affect the whole project, increasing its duration and costs. Therefore, it was easier and more cost-effective to plan and construct the cable section to undergo concurrent infrastructure.

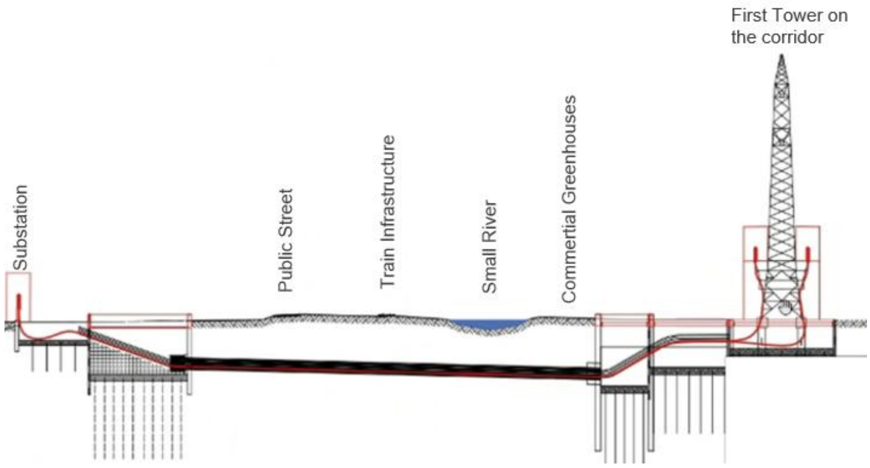


Figure 1. Mixed line based on competition with parallel infrastructure

Another example of a mixed circuit implementation is shown in Figure 2, where a 132 kV line is represented, with the submarine cable replaced by a grounding cable. This example has a line with a total length of 17 km, including a 2.2 km cable crossing a fjord. The cables are now ready for reinvestment, and instead of designing new submarine cables, the new solution is to lay them across a new bridge crossing the fjord, representing a cheaper and easier solution.

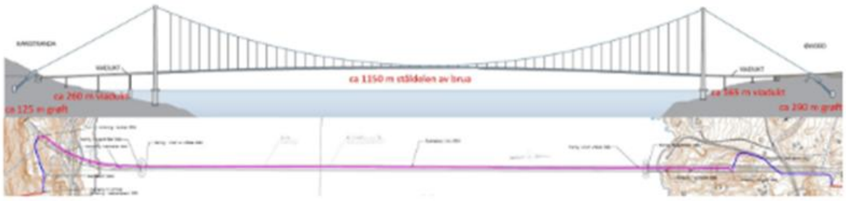

Figure 2. 132 kV earth cable laid in a bridge (to be realised soon)

In Figure 3, a mixed circuit constructed over difficult terrain connecting two 420 kV substations is shown. Points A and B marked in the Figure represent the transmission point between the OHL and UGC. Here, a submarine cable is used to cross the fjord, which is more than 7 km wide and down to 600 m deep. The total length for the line will be approximately. 35 km, including the cable.

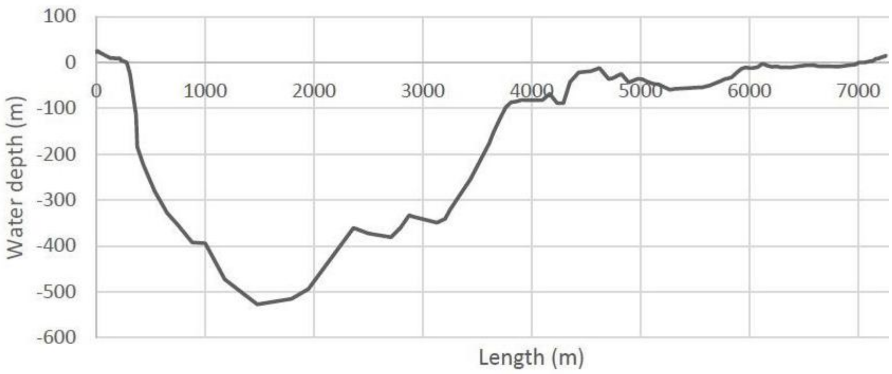


Figure 3. A relevant difficult area for a 420 kV line that had to be crossed

To supply an industrial consumer near the coast, 300 kV lines were constructed. The coastal weather could be rather harsh, and salt drifting from the sea, combined with wind, could be a problem for the OHLs. In this example, the weather conditions are the reason some part of the OHL is replaced with an underground cable. One of these lines is 36 km long, starting with a 19 km OHL, then an underground cable for 15 km, and finally a 2 km OHL into the substation. In addition, it should be noted that the cable is laid across several viaducts along the route. Figure 4 shows the installation of the cable.

Figure 4. Installation of an existing 300 kV cable

When new connections are planned, existing housing, nature, the environment and landscape conditions are considered. This means that, when technically feasible, new high-voltage lines must be constructed as cable systems.

An example of this is an area close to a city with several 150 kV and 400 kV overhead lines. Once new conditions were established, all 150 kV lines were replaced by UGCs, and 7 km of the existing 400 kV OHL was replaced by UGCs, creating a 400 kV mixed circuit. In addition to this work, a new line of 24 km, with a UGC section of 8 km, was constructed. In this case, the 400 kV mixed circuits included two parallel cable systems. The benefit of this is that if one of the two cable systems is out of service, the 400 kV system can still be in operation with half the loading.

All these solutions represent permanent mixed-line construction, which was designed from the beginning for continuous operation. Transitional and temporal mixed circuit solutions should also be mentioned here.

A transitional mixed circuit solution applies when an OHL is partially replaced by a UGC section, with the UGC eventually replacing the entire OHL. For this transitional period, a mixed circuit applies.

Transitional solutions are sometimes driven by government regulations that should support the transition of the electrical power system. An example is the regulation in the Netherlands, where the government has enacted a law that imposes a limit on the total length of high-voltage OHL. Since the total length of OHL is limited, constructing new OHLs requires replacing an existing one or a portion of it with UGC. For these purposes, the Ministry of Economic Affairs and Climate Policy has introduced the Third Electricity Supply Structure Plan (Structuurschema Elektriciteitsvoorziening III) [2] and, on 1 January 2019, the Cable and Relocation Regulation. [3]

By taking the connection underground, lawmakers are ensuring that more land becomes available for residential construction, recreation and public green spaces. In addition, the pylons and lines are clearly visible in many places, and some residents living near the high-voltage lines are concerned about the possible impact on their health (magnetic field). Therefore, taking the connection underground would improve residents' living environment and increase acceptance of future projects.

Temporal mixed circuit solutions would be used if, for example, a section of an OHL is temporarily replaced with a cable, so that necessary work can be undertaken on the OHL section without losing an important system component. This means that the normal operation of the system will not be compromised during reconstruction or maintenance work on a section of the affected circuit. This is mostly done at lower voltage levels.

There are several examples of this practice also being used in high-voltage systems. Figure 5 shows a provisory described in [4] and [5]. For this temporary solution, a prefabricated cable system was used to replace a section of the OHL for a short period during construction. This solution has minimised the duration of the power flow interruption through the affected line. It is being applied in the case that a provisional OHL is not possible due to limited space at disposal. According to [4] and [5], these prefabricated cable system solutions are available only for voltages up to 220 kV. In contrast to permanently loaded cables, prefabricated cable systems are not placed underground but laid on the surface. Being positioned on the surface eliminates the need for digging; instead, a construction fence must be installed to ensure compliance with high safety requirements.

**Figure 5. Example of a 220 kV provisory with cable section [4]**

Figure 6 shows the montage of such a prefabricated cable system on the 110 kV OHL presented in [6].

Figure 6. Montage of a temporal cable solution on a 110 kV line [6]

## 2.3. Configuration of mixed circuits

Depending on the position and number of UGC and OHL sections, different configurations of mixed circuits can be found in the transmission system. The most common configurations are listed below:

- Mixed circuit with one UGC section placed at one of the connecting substations. This can be constructed as a two- or multi-ended circuit, as demonstrated in Figures 7 and 8.

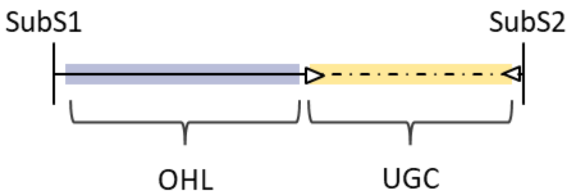


Figure 7. Two-ended mixed circuit with a UGC at one end

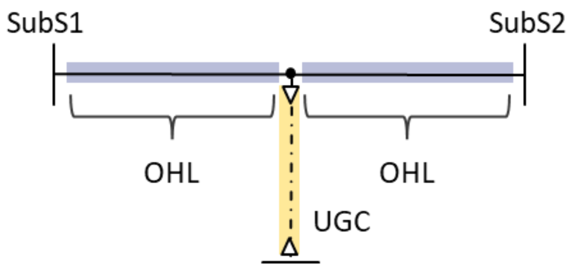


Figure 8. Three-ended mixed circuit with one branch in UGC

- Mixed circuit with one UGC section placed between two OHL sections, or the other way around (an OHL between two UGC sections), as represented in Figure 9.

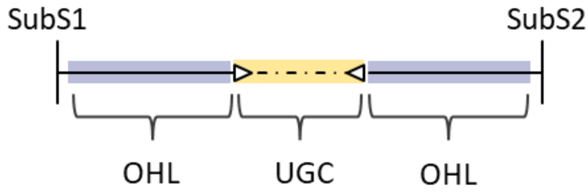


Figure 9. Mixed circuit with a UGC section in the middle of the circuit

- Mixed circuit with more than one UGC section and more than one OHL section (see Figure 10).

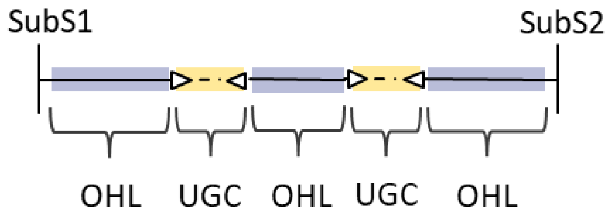


Figure 10. Mixed circuit with multiple UGC sections

- Multi-ended mixed circuit with a transformer tap connected to an OHL, as shown in Figure 11.

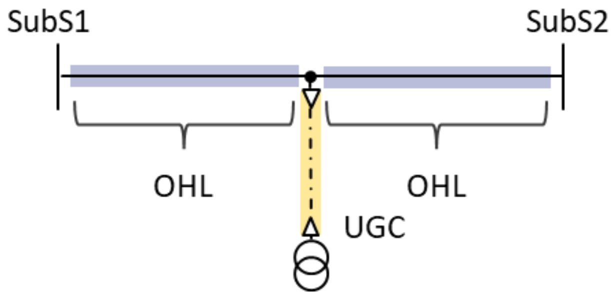


Figure 11. Multi-ended mixed circuit with a transformer connected directly to the UGC section

In [8], the author distinguishes between simple, teed and complex types of mixed circuits. While the simple mixed circuit contains only one OHL and one UGC section, a teed mixed circuit contains one UGC section that is connected via a junction point to an OHL, splitting it into two sections (in this report, described as multi-ended mixed circuits). A complex mixed circuit comprises more than one OHL or more than one UGC section.

Looking at the CIGRE questionnaire results from [2] regarding the use of mixed circuits, which were published in 2014 and contained 14 responses, and comparing them with the answers from 24 participating TSOs around 10 years later, the following can be said:

- The percentage of utilised mixed circuits has significantly risen in the years between the publication of the two reports.
- This tendency can be seen in all configurations of mixed lines.

In conclusion, this comparison shows that mixed circuits are on the way to becoming a standard solution in the transmission grid in the foreseeable future, and their prevalence will continue to grow.

## 2.4. Challenges and issues

Comparing OHL and UGC/SMC, one cannot ignore their different impedance characteristics, which are present in all symmetrical representations. Even the same UGC can have different zero-sequence impedance, dependent on the grounding of its cable sheath. The difference in zero-sequence will be discussed in further detail in Section 4.1.

Moreover, while the OHL has higher inductance (and a higher X/R ratio) than UGC, its capacitance is lower.

A difference in impedance between OHL and UGC can lead to impedance-measurement issues when an OHL is in series with a UGC. All functions based on preside measurements of impedance, such as fault location or distance protection, might experience additional measurement errors. In addition, selecting the proper distance protection settings becomes more complex (k0 factor, discontinuity in circuit impedance, etc.).

Another challenge is distinguishing the exact location of the fault, in terms of whether it was on the UGC or OHL section, which is especially difficult if the fault occurred close to the transition point. Let us consider a case in which an unsuccessful AR on the temporarily faulted OHL section occurred. In this case, we will have difficulty determining whether we are facing a permanent fault on the cable or whether the secondary arc duration for the faulted OHL exceeded the dead time set in the AR function. Solutions include performing complex analysis or measuring the cable before re-energising it.

As previously mentioned, AR on the faulted cables cannot be successful, which is why selective AR is recommended. Selective AR means that, for faults on the UGC section, AR is blocked, whereas for faults on the OHL section, it is permitted. This leads to higher line availability and better fault location. Depending on the applied AR philosophy, additional measurement devices may be needed, which must be considered during the planning process.

Other challenges that focus more on the operation of the mixed circuits are described in Chapter 3.3. For example, in some cases, closing the circuit breaker of the mixed circuit can cause a higher voltage drop. If the voltage drop exceeds the allowed limit, it might be necessary to perform point-on-wave switching. One challenge not covered by this report is the mixed circuit energisation and de-energisation.

# 3. Mixed circuits implementation

## 3.1. Examples of implementation: Primary equipment

The primary equipment used might differ depending on voltage level, terrain, construction year and other factors. This difference is not only noticeable between different system operators, but also within the same system, where different primary equipment solutions can be found.

While OHLs have more or less similar construction, varying, for example, in the type of tower and arrangement, UGCs can vary in many more ways. Depending on the cable insulation, arrangement, bonding and laying techniques, UGC sections can be influenced by the project design. The choice here will influence not only the regular operation of the UGC but also its behaviour during a fault. This is most evident in the example of bonding techniques.

### 3.1.1. Bounding techniques for UGCs

The selection of bonding techniques mostly depends on the length of the UGC and treatment of the system earthing (solid grounded, isolated, compensated system). By selecting the proper bonding, it is possible to influence the cable's thermal losses, induced voltage on the sheath, and capacity.

One-sided earthing of the cable sheath, as shown in Figure 12, is mostly used for short UGC sections. Here, one side of the sheath is directly grounded, while the other is connected to earth via a surge arrest. In case of an internal fault on the UGC, the entire fault current will build its return path over the direct earthed side. Moreover, by earthing the sheath on only one side of the cable, no path for current from an external fault will be provided through the sheath.

In regular operation, cables with a one-sided earthed sheath will also have lower Joule losses.

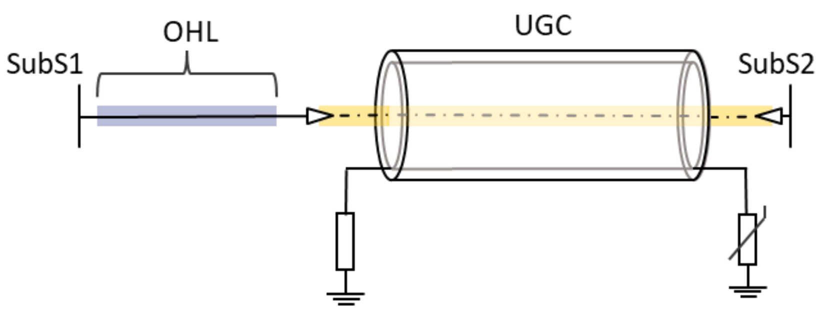


Figure 12. One-sided earthing of the cable section

A two-sided earthing of the cable sheath is presented in Figure 13. Here, both cable sheath ends are directly connected to the earth.

This represents the straightforward solution that demands minimal maintenance and has the easiest implementation.

In regular operation, cables with a two-sided earthed sheath incur higher Joule losses due to the additional low-impedance path for external current flow. For internal faults, it can be expected that the fault current divides and forms two separate return paths.

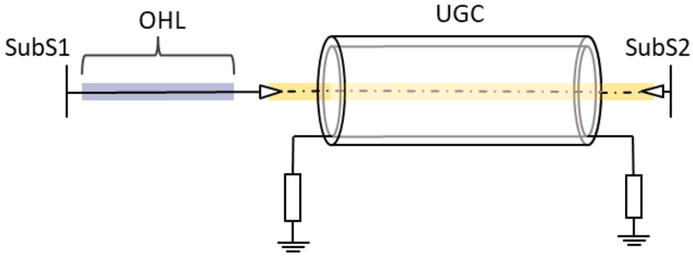


Figure 13. Two-sided earthing of the cable section

The cross-bonding technique is applied primarily to long lines, which deliver higher current capacity. Figure 14Figure 14 represents such a UGC section. Here, both sides of the cable sheath are earthed; however, the cable sheath is divided into sections and cross-connected.

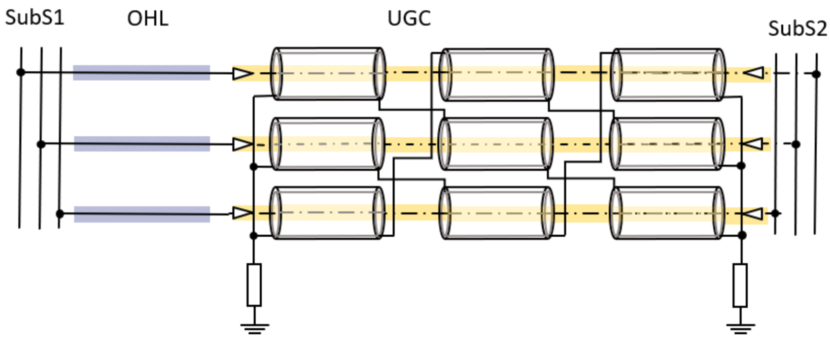


Figure 14. Cross-bonded cable

### 3.1.2. Transition point from OHLs to UGCs

Depending on the available space, the transitional point between OHLs and UGCs can be implemented as shown in Figure 15 on the tower itself, or in Figure 17 in a small field.

When using a tower, it is necessary to consider that all additional elements required, such as a current transformer, will be installed on it. This means the tower must be structurally reinforced to support the extra mechanical loads.

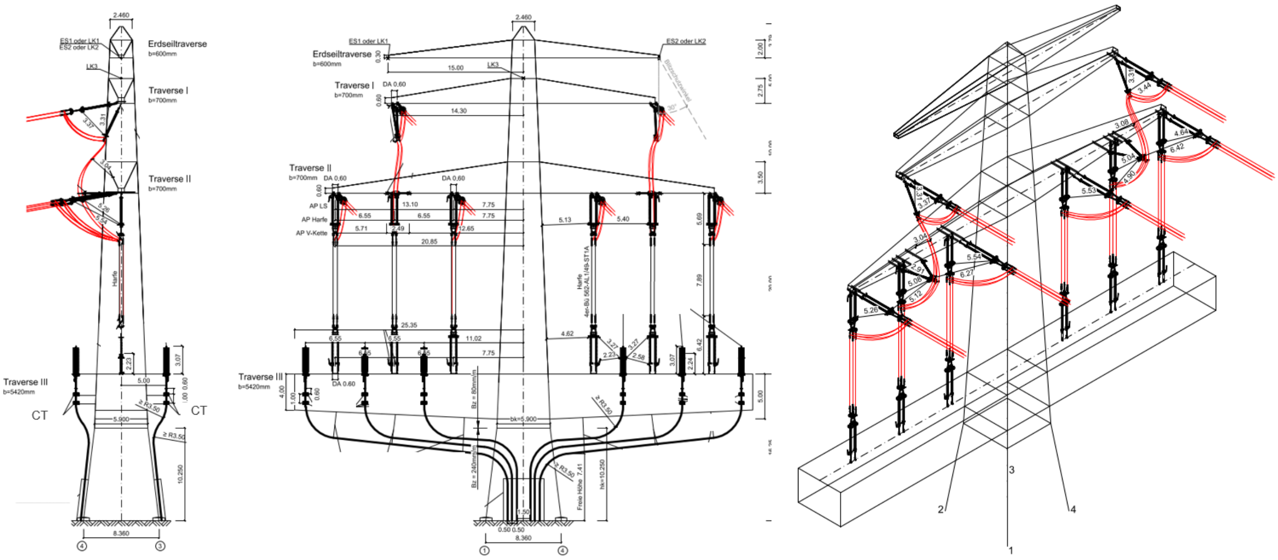


Figure 15. A tower containing a transitional point between OHLs and UGCs

Figure 16 demonstrates different types of towers. One type comprises two circuits (as shown in Figure 15), and the other comprises one circuit per tower. In both cases, the OHL circuit contains one conductor per phase, while the UGC section can have one or, sometimes, two cables in parallel per phase.

Figure 16. Different types of towers with a transitional point

An example of a connection between the OHL section and the UGC section, constructed in the field as a cable station, is shown in  Figure 17 and Figure 18. The following components are represented: 8) earthing switch, 7) surge arrest, 9) cable joints, and 5) a cabin (container) with control and communication equipment.

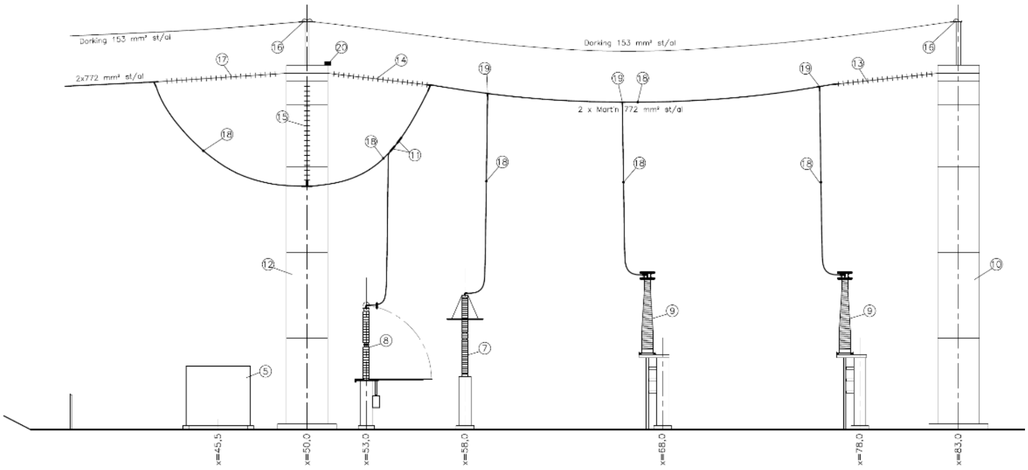

Figure 17. Connection between the OHL and UGC sections

As shown in Figure 18, the transitional station is enclosed by a fence to ensure safe operation.

Figure 18. Cable station as a transitional point

### 3.1.3. Measuring devices

Depending on the applied protection scheme for the mixed circuits and their configuration, measuring the current at different positions of the mixed circuits might be necessary, including at the transition from the cable to the overhead line. If the measurement must be performed on the tower, which is far from the substation, the auxiliary supply may be an issue.

Several measuring solutions have been implemented throughout European power systems. The most obvious solution would be to use standard inductive measurement devices at all points of interest. The high reliability and well-known technology of these inductive measurement devices come with some disadvantages. Typically, the transition point from the UGC section to the OHL section is located at the first power tower in the corridor outside the substation, which means that sufficient space must be available for installing a standard inductive measurement device. If space is limited, this device would need to be installed on the power tower, which would require the tower to be sufficiently robust to support the additional weight.

Depending on the chosen solution's structure, it may also be necessary to install secondary equipment close to the tower or even on the tower itself. In such a case, it is also necessary to address the challenges of supplying these secondary equipment elements with auxiliary voltage.

- One solution for obtaining an auxiliary supply is to use power voltage transformers. These measuring devices merge features of an inductive voltage transformer with the functionality of a power transformer. They are primarily used to deliver low-voltage power directly from a high-voltage line up to 550 kV. [9]

Auxiliary supply is provided only if the circuit is energised.

**Figure 19. Oil-insulated power voltage transformer application**

To address the challenges of implementing a conventional current-measuring device during the UGC transition to OHL on the tower, low-power instrument transformers (LPITs) can be used. Due to their lighter weight, LPITs can be transported and installed more easily, resulting in cost savings. [10]

Figure 20 shows an optical current transformer mounted on a tower. This LIPT is a passive element that does not require auxiliary support at the site of installation. It can be installed on the utility's existing infrastructure without altering it.

**Figure 20. Low-power instrument transformer with dimensions 26.3 x 62.5 x 15.3 cm, weighing a total of 10 kg**

This solution includes a flexible optical fibre sensor, which should be placed around the element where the current is being measured, and a sensor box with standard fibre components inside a metallic box. This passive LPIT can be placed up to 20 km from the unit that is evaluating the optical signal output from the optical sensor. [11]

- Another application considers measuring the current on the screen, using three current transformers (CTs) installed on the screen earth connection of each cable, or a single CT installed on the earth connection common to the screens of all three cables. This solution only considers fault-to-earth faults, including current flow through the sheet. This limitation can be taken into account because the risk of a three-phase or two-phase fault in a system of three single-phase cables is negligible.

**Figure 21. Rogowski coil application for measuring current on a cable section**

- Rogowski coils, as shown in Figure 21, can replace conventional CTs for protection, metering and control. Rogowski coils have been applied at all voltage levels (low, medium, and high). Unlike CTs, which produce a secondary current proportional to the primary current, Rogowski coils produce an output voltage that is a scaled time derivative di(t)/dt of the primary current.

## 3.2. Experience with faults

Faults on the OHL are mostly of a temporary nature. Such a fault is not followed by permanent equipment damage, and simple automatic switching and deenergising of the faulted phase could lead to successful reclosing. The main reason is that the faulted current has followed a path through ionised air. This arc over ionised air is called the primary arc and persists as long as current flows through the faulted phase. Once the phase current is interrupted, the primary arc will disappear. Depending on the OHL environment, a secondary arc can occur due to capacitive coupling from healthy line phases or other parallel circuits. The key parameter here to set is the deadtime of the AR function. This should be sufficiently long to allow complete de-ionisation of the arc path, leaving the faulted circuit de-energised long enough for the secondary arc to completely vanish. Otherwise, if reclosing occurs while the secondary arc still exists, the primary arc will re-strike as soon as the circuit breaker is closed.

According to [12], these temporary faults account for about 88% of all faults that occur on OHLs. This means that the vast majority of faults on OHLs could be solved by the AR function.

While these faults on OHLs are mostly caused by lightning or other external environmental factors, and less by operational issues, faults on the cable are mostly caused by unusual system conditions or problems with applied equipment. Depending on the voltage level at which the cable is applied, a third party performing mechanical work close to the cable can play a dominant role in causing a fault on the cable. Damaging a cable during construction by digging too close to it can result in a direct connection between the faulted phase and the soil.

Faults in UGCs are predominantly permanent. This means that no arc, as we know from OHLs, will exist. An interruption of the faulted phase cannot be followed by a successful reclosing, which is why the AR function is not part of the standard protection scheme for UGCs. If we were to reclose the faulted UGC, the fault would extend during the reclosing. This means that damaged equipment, such as cable terminations and joints, could be irreparably damaged and the additional heat could raise the risk of wildfires.

The impact of a fault on a cable is demonstrated by the following example from Germany, where a fault inside a 380 kV termination cable spread beyond the electrical fault. A fault occurred directly at the termination, developing such high power that the termination exploded, destroying surrounding equipment and sending broken pieces of porcelain at bullet speed through the surrounding area, damaging several nearby parked vehicles. Figure 22 shows the level of damage to the primary equipment.

Figure 22. Destroyed cable after a fault in the termination

Even if only phase 2 was faulted, porcelain isolation of all three phases and the reserve phase, which was available by design of the field, has suffered severe mechanical damage. This means that using the reserve phase to overcome the faulted phase 2 was not possible. Figure 23 demonstrates the implemented transition from the cable to the power transformer, with its three phases and a reserve phase switched in the emergency circuit. This emergency circuit could have been used if the primary equipment had not been damaged.

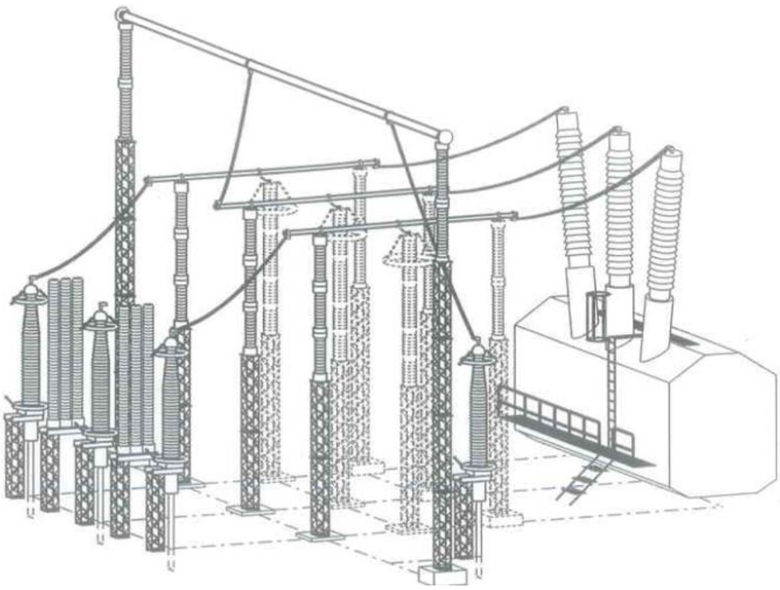

Figure 23. Emergency circuit over the reserve phase infrastructure

The effects of the fault were also visible within the cable's underground infrastructure, as Figure 24 demonstrates.

Figure 24. Destruction in the cable canal

This is one of the reasons why protection engineers are facing the dilemma of what to do with the AR function when protecting a mixed circuit.

While in [13], options without blocking the AR and with selective AR are both discussed and approved, [2] also reports a case of fragments spreading into residential areas for reclosing on the faulted cable. An incident has been reported with AR on faults at the cable termination.

Several TSOs in our questionnaire reported experience with faults on mixed circuits. Some of them also experienced AR in the UGC section.

Even though the majority stated that this fault did not have a significant impact on the system, a few reports of small explosions were noted, as reported in [2].

**Damage to an outdoor 245 kV terminator on the 220 kV Mikulowa–Lesniow mixed line**

This line has approximately 1 km of cable section only at the termination to the Mikulowa substation, with the remaining length in OHL. The section cable is equipped with six terminators (three at the line exit from the station and three installed on the pylon connected to the OHL tower).

The failure was attributed to terminations on the 220 kV mixed line and was caused by a short circuit inside one of them. The protection scheme for this line is typically the same as for an OHV line, and during clearing, a short circuit caused by a termination failure resulted in one cycle of a one-phase auto-recloser operation. Figure 25 shows a visible pylon with a damaged termination on one phase.

Figure 25. Pylon of a 220 kV mixed line with a damaged termination on the phase on the right side

The applied cable system is an outdoor 245 kV terminator for cables with cross-linked polyethylene (XLPE) insulation, housed in a composite insulator filled with fluid silicone oil and silicone rubber sheds, attached to a pylon structure via a solid-rod connection and support insulators.

During the investigation into the cause of the failure, it was determined that the short circuit occurred at a point directly above the mounting of the stress cone. This element is visible in Figure 26, enlarged, with the red arrow indicating the breakdown path inside the failed termination.

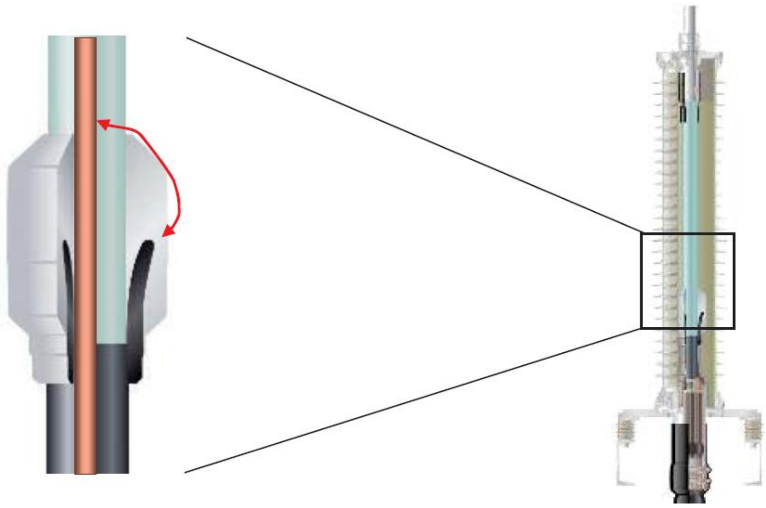

Figure 26. Breakdown path inside the failed termination

The discharge path did not go through the stress cone but went outside on its surface. Figure 27 shows the discharge marks on the stress cone and cable line. The position of the stress cone changed during failure, and it was completely split (the position before damage is marked with red tape).

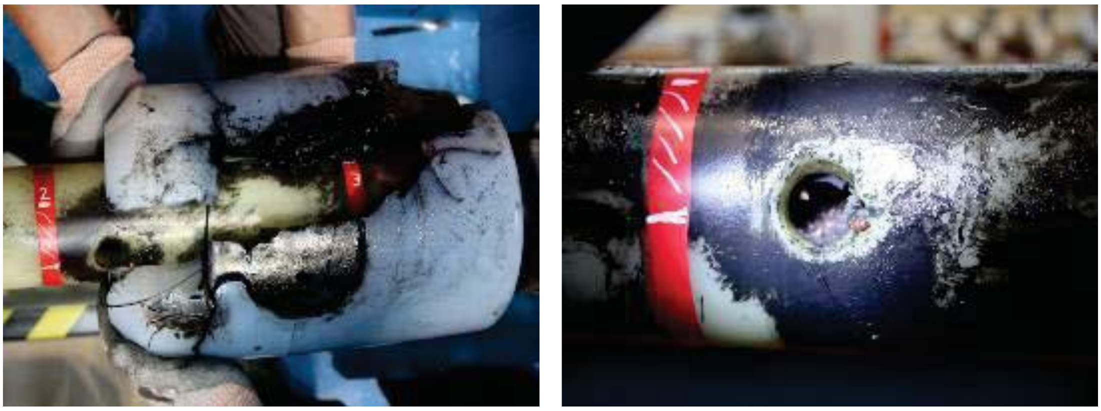

Figure 27. Failure point at the stress cone (left) and cable (right)

The inspection carried out at the factory where the terminator was produced did not indicate any obvious installation failure that could have caused it to fail. The visual analysis of the cable, stress cone, dimensions, and all other parts shows no abnormalities, and all measured values align with their specifications. All parts were installed properly and according to the procedure described in the installation instructions. The cause of failure was unascertainable, likely due to destruction during the failure process. As a result of the investigation, it was determined that the failure was caused by a unique incident and not by a general design failure of the cable or the stress cone. Furthermore, additional mechanical testing of the stress cone material and the core insulator also did not reveal any design errors. The remaining terminators installed on the mixed circuit worked without faults.

Due to the failure, the line remained switched off for over 3 months until the damaged termination was replaced, including the time for the investigation and the production of a new element. Fortunately, the repair did not require replacing the cable, as adequate slack was provided during installation.

**220 kV cable in Adlershof** [14]

In [14], an example of a fault on the 220 kV mixed circuit is presented. This circuit was put into service in 2007. It arose from a 220 kV OHL, where a smaller section was replaced by a UGC. One year after it was put into service, an explosive fault occurred at the transition point from the UGC to the OHL. This fault caused pollution and damage to neighbouring properties, unsettling the residents (see Figure 28). To reassure residents that such a type of fault will not occur again, a concrete structure was built around the crossing point (see Figure 29). It took 8 months to completely repair the affected circuit.

Figure 28. Pollution and damage to neighbouring properties caused by the explosive fault [14]

Figure 29. Implemented solution over the affected UGC–OHL crossing [14]

**110 kV Vollenhove–Kampen MXD circuit**

Due to the inhabited region (from Kampen) and the crossing of a nearby river, the affected 110kV OHL had to be constructed as a mixed circuit, comprising two cable sections, as shown in Figure 31. Both sections are around 2 km each.

The incident in 2024 occurred during the transition from the UGC to OHL on the tower, as shown in Figure 30. Two explosions on the affected phase were detected: an initial fault, followed by AR, which triggered a second explosion just 1 second later.

Figure 30. Fault in the cable section of the mixed circuit

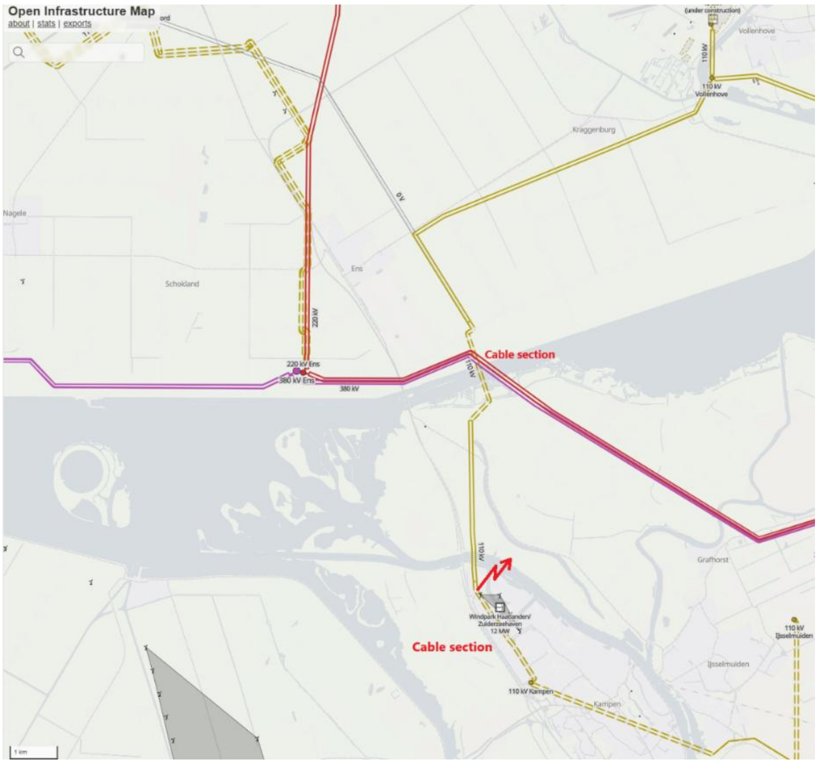


Figure 31. Affected 110 kV mixed circuit

Figure 32. Destruction of the affected circuit equipment

**Lyon 27/10/2006**

An explosion caused by the AR of a faulted cable is described in [15]. On 27 October 2006 at 10 am, an explosion occurred beneath a public road, lifting 20 m² of pavement (30 cm thick). A safety perimeter was established, nearby building occupants remained indoors, and traffic was halted. The explosion was traced to a 225 kV underground electric cable insulated with pressurised oil, which detonated when switched back on. The metal casing ruptured, forming a large crater.

The impact was as follows:

- Four people sustained minor injuries.
- Two vehicles were damaged.
- 1,000 litres of oil spilled onto the ground.
- The power line was automatically shut off.

In response:

- Valves were closed to isolate the affected section.
- Road repairs began within hours by an external company.
- A second company handled oil drainage and collection.
- The emergency phase concluded by 4 pm.

Despite the damage to the town’s 225 kV grid, which was temporarily weakened, no power outages occurred.

Even though many examples of faulted mixed circuits followed by an explosion have been demonstrated in this chapter, it should be emphasised that the number of ARs of faulted cables without a serious incident is much higher than those that have led to serious incidents.

## 3.3. Operational issues

To enhance the performance of mixed circuits, compensation of the cable reactive power might be advisable.

Shunt reactors can be installed on power lines to eliminate the effects of transmission line capacitance and thereby improve voltage in the transmission network. Since cable lines have several times the capacitance of overhead lines, their impact on network voltage is significantly greater. The influence of cable lines on voltage depends on their length and load. Lightly loaded cable lines are sources of reactive power, which causes a voltage rise at the point of cable connection. At the same time, losses due to reactive power transmission increase. To consume the excess reactive power, shunt reactors can be added near the cable lines. These shunt reactors are connected in parallel with the cable line's capacitance. To avoid sudden voltage changes when the cable line is connected to the network and thereby prevent potential equipment damage due to overvoltage, the shunt reactor can be directly connected to the cable line and energised simultaneously with it. In this case, the question concerns the extent to which the line’s capacitance should be compensated. Perfect compensation (100%) may not always be the best solution, even though this results in a balanced voltage in the unloaded line. In heavily loaded lines, it may lead to overcompensation and to the so-called zero-missing phenomenon.

Shunt reactors are constructed with air cores or with intentionally inserted air gaps in the magnetic core. As a result, the shunt reactor cannot saturate and thus is not prone to magnetising inrush current. On the other hand, a significant DC current component can be generated during switching, depending on the exact moment the shunt reactor is switched on. The largest DC component occurs when the shunt reactor is switched on at the zero-crossing. This DC component gradually decays, but it may take several seconds to disappear. If the cable line’s capacitance is fully compensated, the capacitive current generated by the cable line is equal to the current flowing into the inductor but is phase-shifted by 180°. In such a case, only the DC component of the current in the shunt reactor flows through the circuit breaker. The current flowing through the circuit breaker does not pass through zero for a certain period, and if the circuit breaker needs to be opened, it may fail.

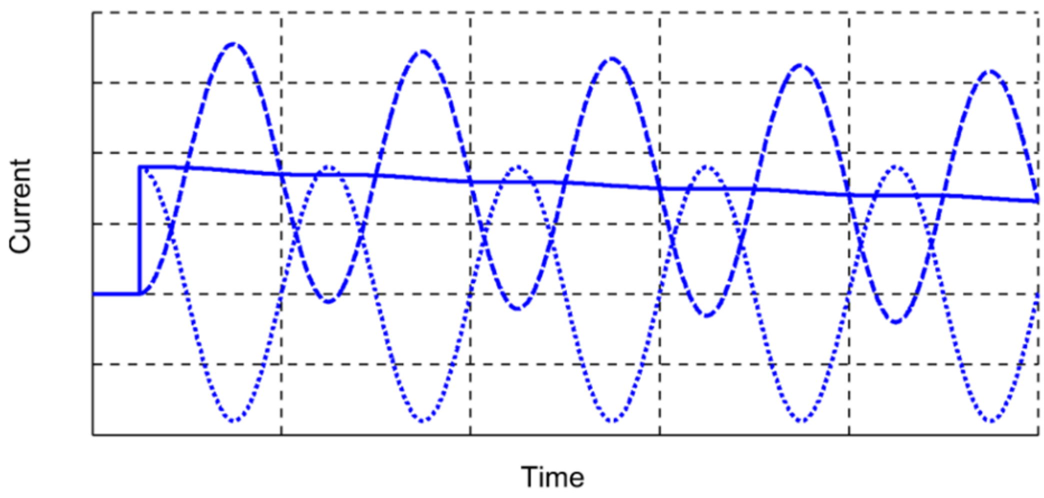


Figure 33. The current in the shunt reactor (dashed line), cable (dotted line), and their sum on a compensated line [16]

To avoid the zero-missing phenomenon, the switching should be made when the voltage is at its maximum. Consequently, the maximal switching overvoltage would occur.

The zero-missing phenomenon can also be prevented by avoiding full compensation of the line capacitance. If the shunt reactor compensates only 50% of the capacitance, the phenomenon described above will not occur. The current will begin to pass through zero from the very first period after the circuit breaker is closed. On the other hand, the influence of line capacitance on the voltage in the transmission network will not be eliminated. This effect can be reduced by using an adjustable shunt reactor or a system of multiple shunt reactors switched on gradually.

The zero-missing phenomenon, as well as switching overvoltage, can also be avoided by using a shunt reactor connected to the line via an independent circuit breaker. In such a case, it is advisable to use independent single-pole sequential switching of the line and the shunt reactor by point-on-wave switching. First, the line should be energised at the moment when the voltage crosses zero, which prevents the overvoltage. Subsequently, the shunt reactor is connected at the moment the voltage reaches its maximum, thereby preventing a large DC current component and eliminating the zero-missing phenomenon.

# 4. Challenges in protecting mixed circuits

## 4.1. Calculation of impedance

### 4.1.1. K0 factor policy

The K0 factor is the residual compensation factor used in distance relays for the calculation of fault impedance in the phase-earth loop when a phase-earth fault is recognised, as shown in the following equation:

$$Z_{Ph-E} = \frac{U_{Ph-E}}{I_{Ph} - K_0 I_E}$$

It is calculated from the positive- and zero-sequence impedances of the affected line.

$$K_0 = \frac{Z_0 - Z_1}{3Z_1}$$

The positive- and zero-sequence impedance of an OHL are in relation to the line length. This is not the case for UGCs, where zero-sequence impedance may vary nonlinearly along the cable. [15]

As shown in Figure 34, both sections of the MXD circuit exhibit different impedance characteristics. Depending on the percentage participation of certain sections, various approaches to selecting the K0 factor for MXD circuits are used. According to [2] andhe results of our questionnaire, the K0 factor is mostly calculated from the equivalent impedance of the MXD circuit. This means that the MXD circuit is represented as a single homogeneous line, with Z1 and Z0 equal to the serial impedance of the UGC and OHL sections.

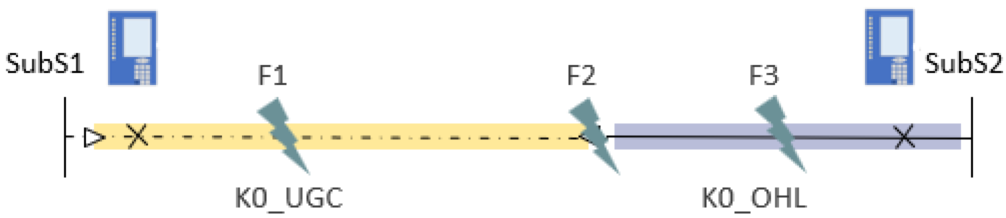


Figure 34. Graphical representation of an MXD circuit and the K0 factor dilemma

When this global K0 factor is selected, the lowest calculation error occurs for the phase-ground loop impedance of faults at the remote line end and for external faults. For internal faults such as F1 and F2, the relay installed on the SubS1 side (see Figure 34) will calculate impedance, with an additional error caused by the implementation of a global K0_MXD compensation factor.

### 4.1.2. Impact of the cable sheath earthing policy

The zero-sequence impedance of a cable depends on the material, the sheath cross-section and the sheath bonding and earthing. In the case of an earth fault, the performance of the distance relay is determined by the current-returning path. This path depends on the cable sheath properties, the type of bonding and the earthing of the UGC. [16]

In Figure 35, a phase-to-sheath fault on an MXD circuit with one side of the UGC section sheath earthed is shown. The lower part of the figure shows the equivalent diagram in symmetric components representation. Z0c represents zero-sequence impedance of the core, while Z0s represents zero-sequence impedance of the sheath, and Z0m is mutual-coupling impedance between the core and the sheath of the cable.

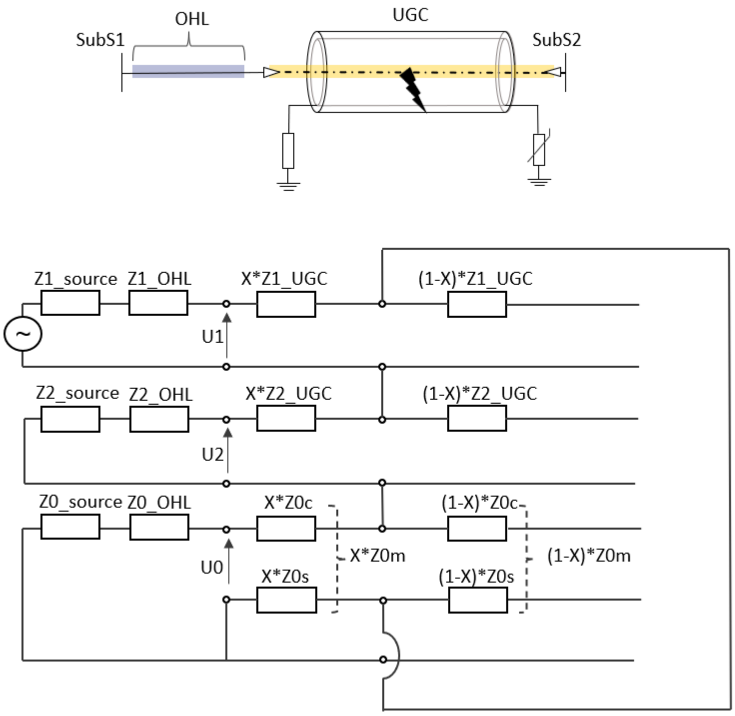


Figure 35. Phase-to-sheath fault on the UGC section for a one-sided earthed cable sheath

As shown by comparing the equivalent diagrams in the symmetric components representation for one- and two-side-earthed cable sheaths (Figures 35 and 36), the return path of the fault current differs, leading to different zero impedances of the fault.

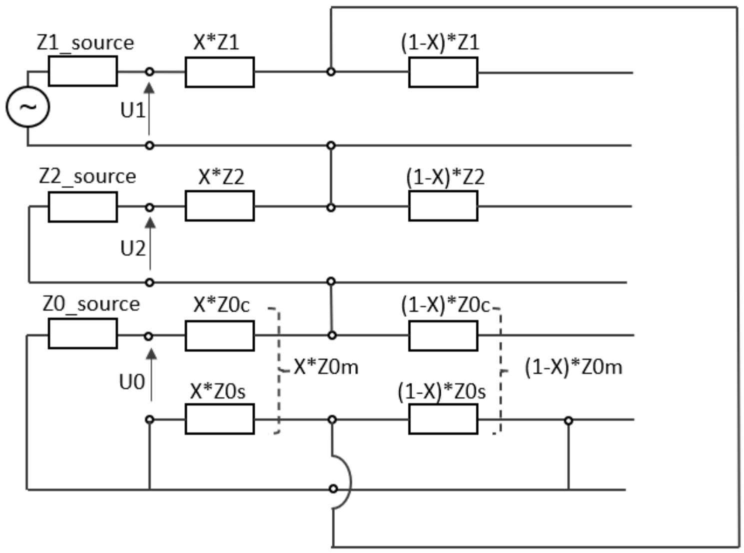


Figure 36. Phase-to-sheath fault on the UGC section for a two-sided earthed cable sheath

For simplicity of discussion, Figure 35 and Figure 36 both represent a fault core sheath without ground. For a two-sided earthed cable sheath, the impedance seen by the relay will not be linear but parabolic. For a one-sided earthed cable sheath, the impedance seen by the relay will be linear. [16]

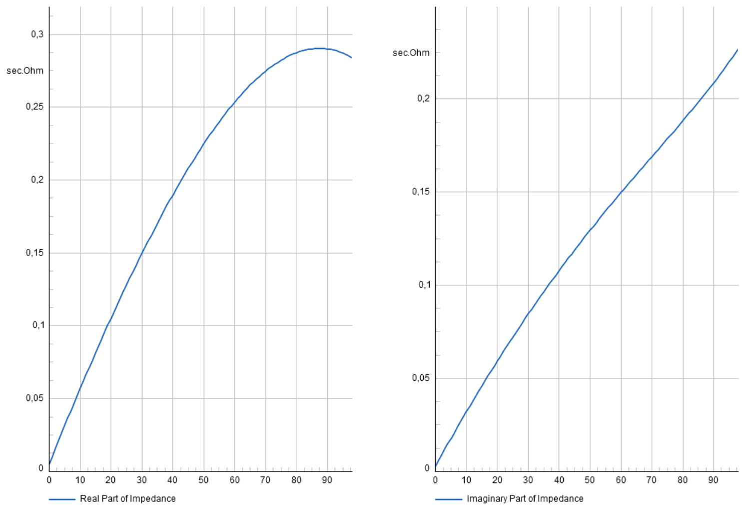


Figure 37. Impedance sweep for earth fault on the two-sided earthed sheath

Figure 37 represents simulation results of an impedance sweep for the two-sided earthed cable sheath. On the X-axis is the line length as a percentage, and on the Y-axis is the impedance in Ohms seen from one side of the cable for a single-phase-to-ground-to-sheath fault. These simulation results correspond to the calculations represented in [2].

In [2], a table comparing the series impedance of a 230 kV UGC under different earthing policies is presented. These values are also shown in Table 1 of this report.

| Circuit | Z1 (Ohm/km) | Z0 (Ohm/km) | k0 |
|---|---|---|---|
| 230 kV UGC – two side grounded | 0,032+j0,109 | 0,170+j0,075 | $0,42^{(-j87,4°)}$ |
| 230 kV UGC – one side grounded | 0,017+j0,114 | 0,165+j1,822 | $4,97^{(j3,4°)}$ |
| 230 kV UGC – cross-bonding | 0,017+j0,114 | 0,170+j0,075 | $0,46^{(-j95,9°)}$ |

Table 1. Serie sequence impedance and K0 factor from [1]

### 4.1.3. Wave propagation

A fault on a transmission line produces travelling waves that propagate from the fault location to the line terminals, with a propagation velocity determined by the line's distributed inductance and capacitance. [17] Complex propagation constant γ [1/s] is calculated according to the following equation:

$$\gamma = \sqrt{ZY}$$

Where Z is impedance, and Y represents the admittance of the corresponding line. These values differ for OHLs and UGCs, resulting in different travelling-wave propagation velocities in these sections of the MXD circuit. According to [18], the travelling wave propagates two times slower in UGCs than in OHLs.

When a travelling wave is confronted with a discontinuity, part of the incident wave is transmitted while the remainder is reflected. The amount of energy that is transmitted and reflected depends on the characteristic impedances of the line section beyond the transition point (Zt) and the characteristic impedance of the line through which the wave travelled (Zr). [17]

If Zr=Zt (no discontinuity, homogeneous line), no energy is reflected and all energy is transmitted.

If Zt=0 or Zt= ∞ (3ph fault location or open circuit), no energy is transmitted, but the travelling wave is reflected with the opposite sign.

This must be considered when applying modern protection functions related to the propagation of travelling waves.

## 4.2. AR

As described in Section 2.4, AR on faulted cables cannot be successful. For this reason, it is highly recommended to apply a selective AR function to avoid further damage. Depending on the complexity of the mixed circuit, the cable location and the cable earthing, different selective AR solutions may be applicable.

### 4.2.1. Selective AR function

As mentioned in previous chapters, selective AR allows for AR to be applied to sections of the MXD circuit where the likelihood of successful execution is high, while preventing it from being executed in sections where AR may not be successful and could lead to further issues.

In this section, we will discuss different methods for implementing selective AR. It is important to emphasise that there is no ideal solution that addresses all MXD circuit challenges; rather, there are various options, each with its own advantages and disadvantages. The decision regarding which solution is the best will be a compromise among all established goals.

**Dedicated distance protection zone**

One possible approach to achieving selective AR is to use distance protection with a dedicated distance protection zone covering the UGC section. The primary advantage of using distance protection for this purpose is that it does not require additional equipment or devices beyond what is already in place for line protection. This can significantly reduce both costs and complexity, making it an attractive solution for simple mixed circuits.

Distance relays work by calculating impedance from measured voltage and current values at the relay location. For selective AR with distance protection, various solutions may be available based on the relay location relative to the cable section and the type of mixed circuit. Some of the possible solutions will be further discussed.

The first distance protection solution is represented in Figure 3838. Here, a dedicated distance protection zone is applied only at the local end; the relay is set to cover cable detection faults within the cable section. If the fault is detected, a blocking signal will be generated, blocking the AR function. In addition, blocking signals should also be sent to relays at the opposite end. The blocking zone (Zx) comprises the covered cable section and the required safety margin.

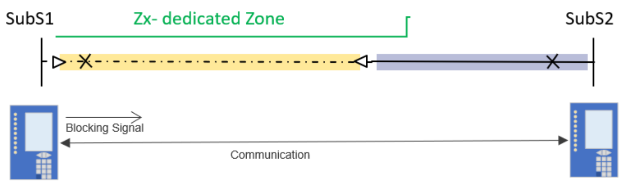


Figure 38. Dedicated distance zone on the relay at the UGC section end

A disadvantage of this method is that blocking signals will only be sent if a relay detects a fault. In case a circuit breaker at the local cable end is open, no current will flow through the distance relay of interest. This means that the blocking signal will not be generated or sent to relays on the opposite side to prevent AR.

The second method applies to distance relays located at the opposite side of the cable section. This method utilises a dedicated impedance zone to identify faults in the overhead line section, allowing the AR function to be activated. This method can be used when there is no communication between the two ends of the line protection, or as a backup if the cable end is opened. The activating zone (Zx) comprises the part of the line section minus the safety margin.

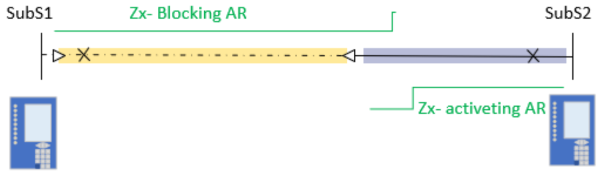


Figure 39. Dedicated distance zone on both ends of the MXD circuit

If the cable section is in the middle of the circuit, additional logic is required to detect a failure in that section.

One solution could include a communication link between protection devices.

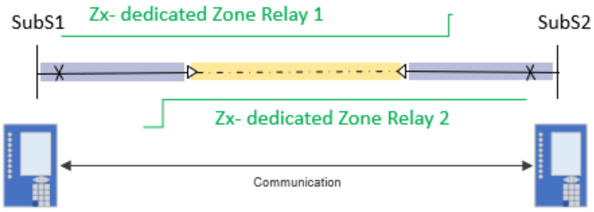


Figure 40. UGC section in the middle of an MXD circuit, including communication between protection devices

The zone (Zx) comprises one line section on the protection side, the cable section and the safety margin. This zone should be calculated separately for each side. If distance protection on one side detects a failure in zone Zx and receives information from the opposite side that the failure is also in zone Zx, then the AR function should be blocked.

Another option would be without a communication link.

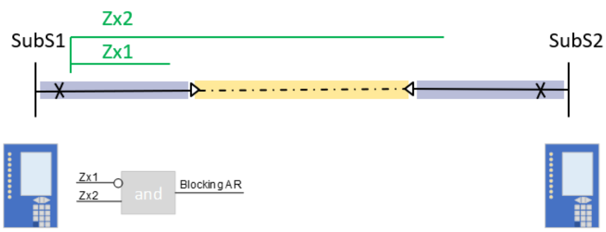


Figure 41. UGC section in the middle of an MXD circuit without communication between the protection devices

Zone Zx1 comprises one line section on the protection side, minus the required safety margin. Zone Zx2 comprises one line section on the protection side, the cable section and the safety margin. The same logic is required from the opposite side.

Distance protection typically operates in conjunction with other protection systems, such as differential protection, especially in more complex circuits. Proper coordination between these protection devices is crucial for ensuring the selective AR function works as intended. For instance, differential protection typically trips faster than a distance relay. If a fault is identified in the cable section, the AR function must be blocked to prevent the circuit breaker from reclosing and potentially causing further issues.

A key disadvantage of this method is the safety margin, which is typically around 20% for the impedance zone. As a result, the method does not achieve 100% selectivity and may not meet the required measurement accuracy, especially in complex mixed circuits. This limits the method's performance in complex mixed circuits. In summary, using distance protection to block AR can be a cost-effective solution for certain types of mixed circuits.

**Differential protection**

Differential protection can also be used to identify faults in a cable section to block the AR function. The primary advantage of using differential protection is that it provides 100% selectivity within the protection zone. The main disadvantage compared to distance protection is the need for additional equipment.

Essentially, differential protection is implemented directly over the cable section, measuring the current flow through the cable and applying a basic differential protection algorithm. If a fault is detected, a blocking signal will be generated and sent to the corresponding protection device to prevent the auto-reclosing function, as shown in Figure 42

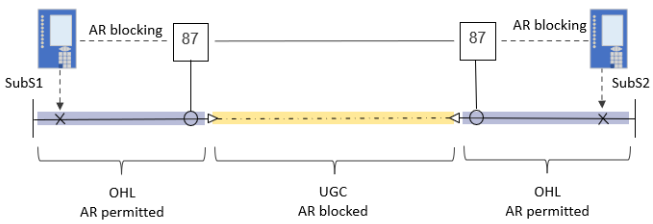


Figure 42. Application considering differential protection

There are two variations in applied differential protection solutions used by European TSOs:

1) Differential protection with conventional CTs and additional relays: This method requires differential relays, power supplies and CTs at each end of the cable section. A communication infrastructure is needed to establish communication between relays and send the blocking signal.
2) Differential protection with optical CTs: The advantage of this method over the first group is that no intelligent electronic devices (IEDs) or auxiliary power supplies are required at transition points. However, this method has limitations, such as the need for optical fibre in each cable section and a limit on the maximum length of the optical fibre cable.

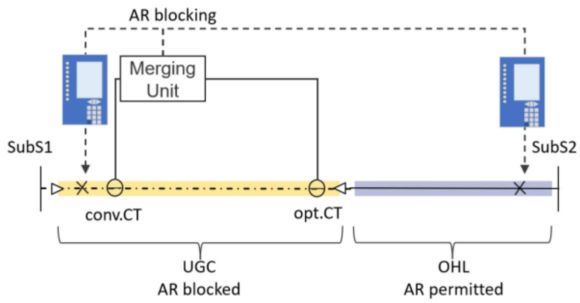


Figure 43. Variant 2, including optical CT

Differential relays detect faults in the protection zone by comparing the magnitude of the current flowing into and out of the area. The differential protection zone is defined between the measurement points. Therefore, it is crucial to carefully consider the locations of the CTs.

This approach can be applied to various mixed circuits. For each cable section, a measurement point is required at both ends. Communication between these measurement points is essential, and a blocking signal must be sent to each end of the protection mixed circuits to prevent AR. As the number of cable sections in the mixed circuit increases, so does the complexity and cost.

**High-precision fault location devices**

High-precision fault location devices, such as those using travelling-wave technology, can be used to detect whether a fault has occurred on the UGC OHL. If the fault detection device detects a fault in the UGC section, a blocking signal would be generated to prevent the AR function within the protection device.

In Figure 44, a possible solution using the double-end fault location principle is demonstrated. For more information on travelling-wave fault locator (TWFL) technology, please refer to Section 4.3. Here, two TWFL devices are implemented, one at each end of the MXD circuit, exchanging information. Each TWFL device obtains current and voltage measurement signals, enabling the travelling wave effect to be estimated with higher precision. Furthermore, the breaker auxiliary contact is wired to TWFL, providing breaker position status.

Once a fault occurs on the line, TWFL devices start detecting and informing the protection device of the fault location. Depending on the fault location, blocking logic might be implemented to prevent the AR of the affected circuit breaker.

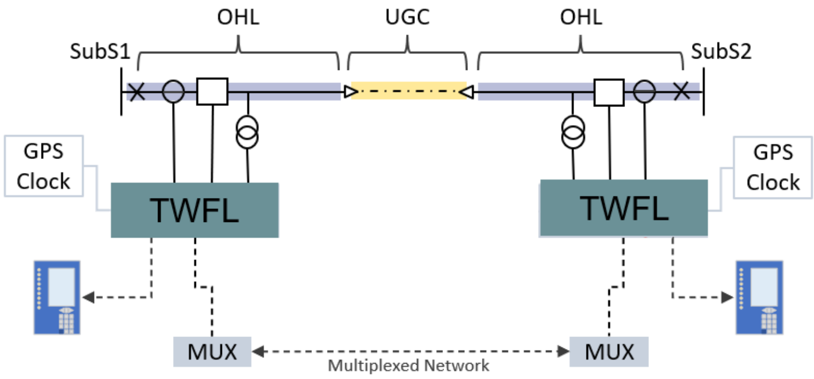


Figure 44. Application using a travelling wave fault locator

**Secondary arc detection**

This method is primarily used for adaptive AR and has been developed for that purpose. Adaptive AR means that the protection device can adapt the dead time set in the AR function. In other words, the protection algorithm adjusts the protection setting based on measured system values (voltage).

A secondary arc can be observed in the measurement of the affected phase-to-ground voltage and arises from capacitive and inductive coupling from the healthy line phases.

Figure 45 and Figure 46 demonstrate a secondary arc on the same 380 kV line. The difference between these two figures is represented in the different duration of the secondary arc. In Figure 45, a secondary arc exists for around 0.86 s, which is lower than the dead time set in the AR function. This can be seen in the change of the form of the measured voltage. Reclosing the affected faulted phase in 1.2 s, around 0.4 s after the extinction of the secondary arc, the line was returned to normal operational condition. The voltage returned to the sinus shape and the prefault value.

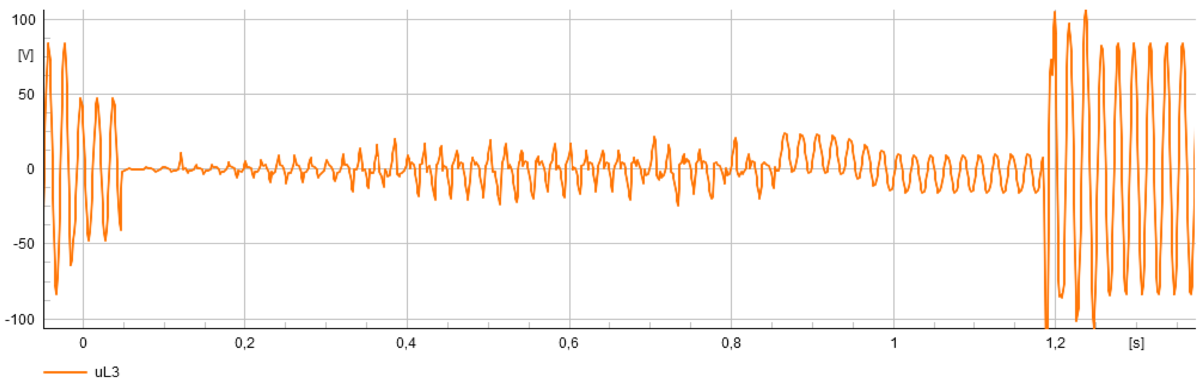


Figure 45. Successful AR due to a short secondary arc duration

Figure 46 demonstrates a case in which the secondary arc persisted at the moment of reclosing (for more than 1.2 s), and it can be seen that reclosing was not successful.

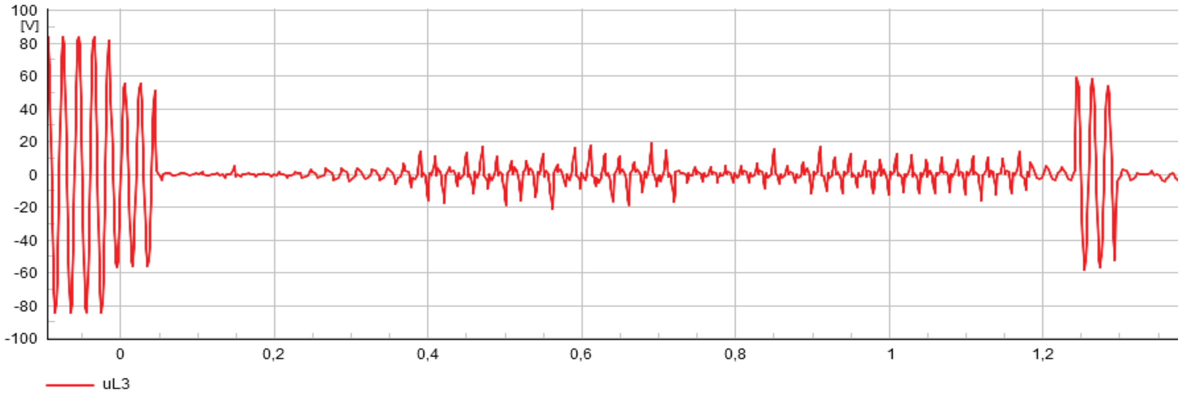


Figure 46. Unsuccessful AR due to an excessive secondary arc duration

Depending on the relay manufacturer, different algorithms can be implemented to detect the presence and extinction of a secondary arc.

In [14], an adaptive AR function based on monitoring the level of total harmonic distortion and voltage amplitude at the fundamental frequency of the affected phase voltage is described. If the total harmonic distortion is lower than the set parameter and the evaluated voltage amplitude is higher than the set parameter, the algorithm recognises no secondary arc.

Figure 47 shows how this secondary arc detection algorithm performs based on a simple example. As can be seen, the existence of the secondary arc was recognised (AWE: BEW. Sek LiBo aktiv) in cases where THD was high enough, or the measured voltage amplitude was smaller than the set value.

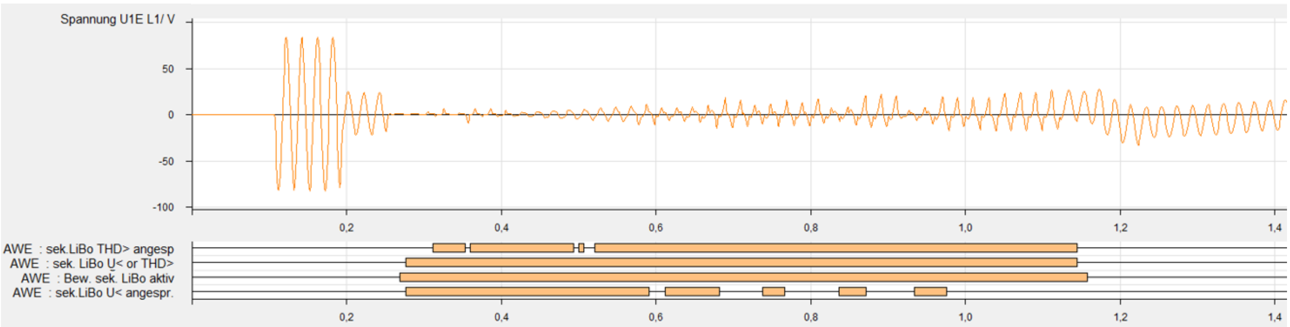


Figure 47. Secondary arc detection example

A secondary arc exists only for temporal faults, where the arc is established in ionised air. In case of a fault on the OHL, the probability of a secondary arc after the affected phase is interrupted is relatively high. In case of a permanent fault on the OHL or the UGC, no secondary arc can be expected. Knowing this fact, this phenomenon can be used to distinguish between permanent and temporary faults and to decide whether to block the AR function.

**Overcurrent protection on the cable sheath current**

Fault detection on a cable section, made up of single-phase cables earthed at one end only (the other end of the sheath is insulated from earth by a surge arrester), can be achieved by monitoring the currents flowing in the cable sheath.

Under normal operating conditions, no current can flow through the cable sheath. In the case of a fault external to the cable section, since the sheath is only earthed at one end, the current flowing through the sheath is also zero.

In the event of a fault on one of the cables, contact between the phase conductor and the cable sheath is highly probable. Therefore, the fault current or at least a non-negligible part of it, will flow through the cable sheath towards the earthed end.

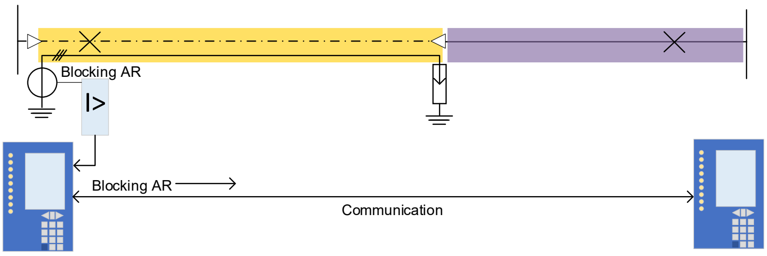


Figure 48. Overcurrent protection on the cable sheath current

Based on this current measurement, the cable section fault is detected using an instantaneous overcurrent relay. When a fault is detected on the cable section, this relay sends a binary signal to the main protection to block the automatic reclosing function. This system is never used to trip the element. The blocking signal must be sent to each end of the protection mixed circuits to prevent AR.

## 4.3. Fault location

The fault location is particularly important for troubleshooting in mixed circuits, as it helps pinpoint the exact fault, enabling a quick, targeted repair. Accurately determining fault locations can be challenging due to several factors, including mutual coupling in zero-sequence components, fault resistance, varying load conditions and nonhomogeneous system characteristics. When locating faults, two main aspects are considered: first, measuring the distance to the fault; and second, determining whether the fault lies within the cable itself or on the overhead line section of the circuit. If it is unclear whether the fault lies within the cable or another part of the circuit, additional troubleshooting may be needed, such as cable testing. The fault location can generally be determined using different methods. Some methods, such as differential relay or earth sheath protection, focus only on the second aspect and can identify cable failure, but do not provide the distance to the fault. Other methods, such as distance protection or travelling-wave technology, estimate the distance to the fault and thus provide information on both aspects. In this section, we focus only on methods that measure the distance to the fault (aspect 1 of the estimation of the fault location), using the term fault location to refer to these functions.

The fault location function in commonly used protection devices is generally classified into two categories:

Single-ended method: The fault location is determined using measurements from one terminal of the transmission line.

Double-ended method: The fault location is determined using data from multiple terminals of the transmission line, resulting in greater accuracy.

An impedance-based fault locator (single-ended method) measures voltage and current to calculate the apparent impedance and locate the fault. The fault location is calculated based on the line parameters. Some protection devices offer additional compensation techniques to minimise fault measurement errors, such as load compensation when power is injected from both sides and measurement correction for parallel lines (zero-sequence mutual coupling). However, the differing impedances of OHLs and UGCs make it difficult to accurately pinpoint faults in mixed circuits. An impedance-based fault locator can be used for simple mixed circuits (e.g., with a single underground cable section), provided measurement errors are acceptable. This limitation can be tolerated if the function is used in conjunction with other methods capable of detecting faults within the cable section.

The double-ended fault locator method uses measurements from both line terminals. Double-ended methods require communication between the two ends. Algorithms based on two ends offer significant improvements in fault location accuracy when compared to those based on a single end. Depending on the protection device applied, double-ended fault location algorithms can differ.

One example of such a double-ended fault location method uses the profile of the estimated negative-sequence voltage magnitude along the transmission line to identify the fault location. The fault location estimation based on the negative-sequence network remains unaffected by zero-sequence mutual coupling and errors in zero-sequence line impedance. It is also immune to load flow and fault resistance, with no impact from inaccuracies in the residual current compensation factor. [15] A key advantage of using negative-sequence quantities is that line-charging currents have minimal impact on fault location accuracy, since the negative-sequence voltage is much lower than the positive-sequence voltage along the transmission line. This dual approach enhances accuracy, especially for mixed circuits. [20]

In such cases, multiple line sections can be defined, allowing for separate line parameters for each section. A common approach for double-ended fault location involves using fault profiles along the line. With a known current and voltage at the ends of the line, the voltage at any point along the line (reactive impedance) can be calculated. At the fault location, the voltages calculated from both ends should match. By graphically displaying both voltage curves, as in Figure 49, the point of intersection indicates the exact fault location.

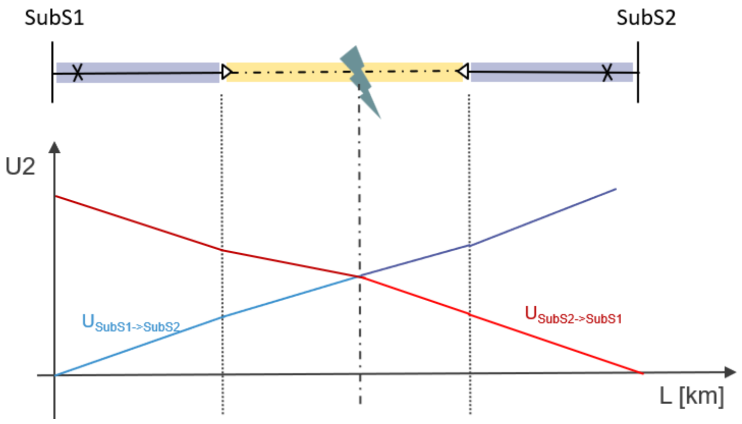


Figure 49. Graphical display of a fault location via a double-ended algorithm using U2

$U_{SubS1\text{->}SubS2}$: the voltage profile is calculated using the voltage and currents from the line-end SubS1 ($U_{SubS2\text{->}SubS1}$ line and SubS2).

Additionally, the double-ended fault location method can also be used for three-terminal lines, although it may introduce additional challenges. However, this method still provides better accuracy in such cases compared to the single-ended fault location method.

Depending on the manufacturer, if double-ended fault location determination is not possible, the impedance-based fault location method could be activated. Fault location evaluation can still be performed afterward by combining data from both sides of the line, utilising specialised post-fault analysis tools.

In scenarios where fault location determination using impedance-based methods is challenging, particularly in complex mixed circuits, the travelling-wave fault location method offers an alternative approach.

Travelling-wave fault location uses wave surges in voltage or current signals from faults to estimate the fault's position. Not only is the fault causing wave surges in the primary system, but switching will also lead to a certain level of wave surges.

Travelling-wave methods can be classified into single- and double- or multiple-ended types. In the single-ended method, the fault location is determined based on the time it takes for the travelling wave to propagate from the measurement point to the fault and then reflect back. The measurement relies on the moment the fault is initially detected and the time taken for the wave reflection to travel back to the fault and return to the TWFL device. This time difference is used to estimate the distance to the fault.

In Figure 50, the operational principle of the single-ended TWFL method is presented. When the fault occurred at t0, the travelling wave was emitted in both directions. At t1, the wave first arrives at the TWFL at SubS2. A portion of the wave reflects and travels back to the fault, where it reflects once more before returning to the TWFL at time t4. [17] Here, the distance to the fault m is calculated from the time difference t1-t4; the time wave travelled a distance of 2* m.

$$m = \frac{L}{2} \frac{t_4 - t_1}{TW\_propagation\_time}$$

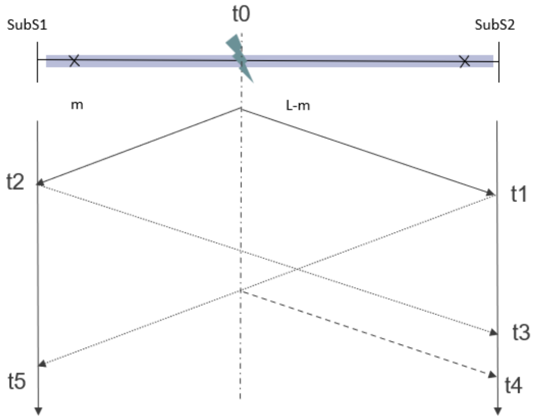


Figure 50. Operational principle of the single-ended TWFL

The double-ended travelling-wave method accurately determines the arrival times of the first travelling waves at both ends of a transmission line. By synchronising the time between the two TWFL devices, this approach enables precise distance calculation to the fault.

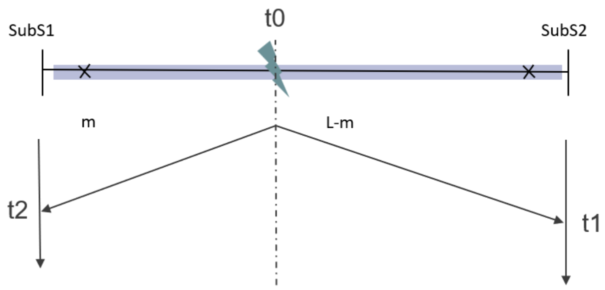


Figure 51. Operational principle of the two-ended TWFL

$$m = \frac{L}{2} \left(1 + \frac{t_2 - t_1}{TW\_propagation\_time}\right)$$

In mixed circuits, there are challenges due to differences in line structure and impedance between overhead lines and underground cables. In comparison with the homogeneous line propagation velocity of the travelling wave in the MXD line, the line propagation velocity differs in each section. This makes the fault location more difficult. Moreover, because the travelling wave reflects from each discontinuity, at MXD lines, we can expect more reflections than would be the case for a homogeneous line.

Figure 52 demonstrates a theoretical wave process when a fault occurs in a cable. After the fault occurs at t0, the initial fault-travelling wave propagates in both directions along the line. At time t1, the travelling wave has reached SubS1. On the opposite side, the initial wave reaches the joint between the UGC and OHL, enters the OHL section and changes its propagation velocity. At the same time, it will reflect on the joint, reaching the SubS1 at t4. At t2, the initial wave has reached SubS2, and a part of it has also been reflected. At t1, part of the initial wave that has reached SubS1 also reflects, then reaches the fault location and reflects towards SubS1, which is reached at t3, and so on.

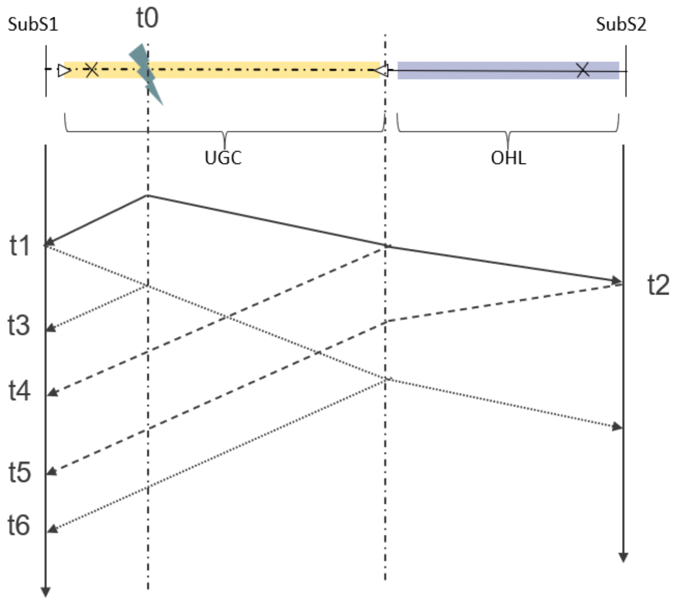


**Figure 52. Travelling wave propagation in an MXD circuit with a fault on the UGC section**

The main challenge of the TWFL based on measurements from one side is to identify the TW, which is the first reflection from the fault, among many other travelling waves (TWs) that may arrive at the local terminal. [17]

The double-ended travelling-wave fault location method provides better accuracy than single-ended methods, even in the presence of these complexities. The ENTSO-E publication, “Use of Traveling Waves Principle in Protection Systems and Related Automations”, published in April 2021, provides a comprehensive explanation of the travelling-wave principle. For this reason, this topic will not be described in detail here.

# 5. Case studies and examples of protective practices

This section will present some experiences of European TSOs in protecting MXD circuits.

## 5.1. Case 1: EirGrid

There are many mixed circuits on the EirGrid-controlled transmission system. All of the mixed circuits, except one, have a short cable section leading to stations at one or both ends. There is also one example of a mid-circuit cable section with OHL sections on either side.

Protection of the mixed conductor does not differ from the protection of the OHL, but the only difference between schemes is the use of fault location-based AR supervision for mixed circuits.

Fault location-based AR supervision schemes are in place. Reclosing is permitted on the OHL section of the circuit, but is blocked for faults detected on the UGC section. Naturally, appropriate safety margins are employed to account for inaccuracies in line length and instrument transformer measurements.

Figure 53 demonstrates the distance protection philosophy applied to the mixed circuit from the protection device on the OHL section. Here, as can be seen, a dedicated zone is set as the AR PERMIT ZONE, which is set to cover up to the remote cable section with an adequate undersetting safety margin. If this zone recognises a fault, an AR will be performed. Zone 5 is set to cover the full length of the circuit, including the remote cable section and a margin. If Zone 5 picks up without Zone_AR_PERMIT, AR will not be permitted.

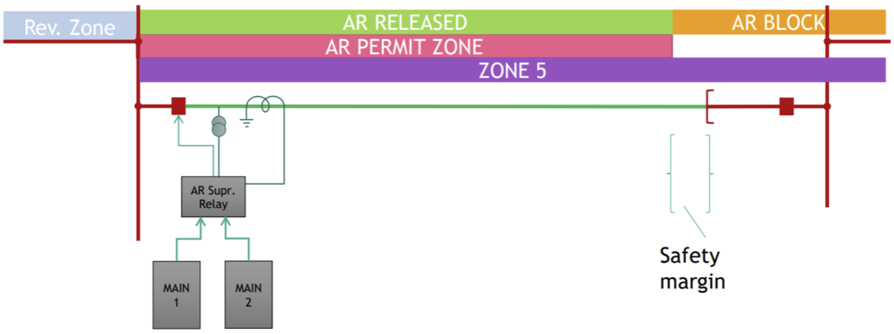


**Figure 53. Impedance supervision of AR, distance relay allied to the remote cable section**

The distance protection philosophy applied to the local cable section is shown in Figure 54. Here, Zone 1 covers the local cable section with an appropriate safety margin, while Zone 2 covers the full length of the circuit with a defined safety margin. If Zone 2 picks up without a Zone 1, AR will be permitted.

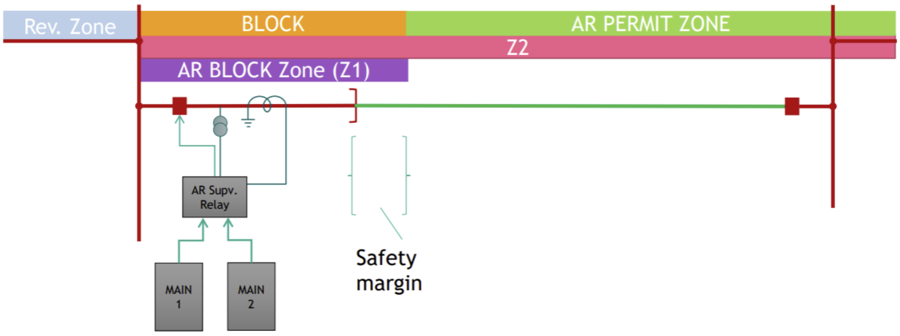


Figure 54. Impedance supervision of AR, distance relay allied to the local cable section

Applied philosophy is mostly satisfactory, given that most of our mixed circuits consist of only short UGC sections, so reclosing is only sacrificed for a short part of the OHL (required to provide a safety margin to ensure AR does not occur on the cable section due to measuring inaccuracies previously referred to).

The downside of the method is that, because the AR supervisory scheme is distance protection-based, for high-resistance earth faults on the OHL, the AR supervisory relay may not detect the fault and thus cannot permit reclosing, so AR does not occur. In a pure OHL, the directional comparison earth fault (DCEF) protection available as a supplementary function within the main distance relay permits reclosing for such a fault.

## 5.2. Case 2: Amprion

The operating philosophy at Amprion for mixed circuits concerning AR after a single-phase short circuit is as follows:

- AR is permitted for faults in the overhead line section(s).
- AR is prohibited for faults in the cable section(s).

To suppress AR for cable faults, differential protection (represented in red in Figure 55.) is set up across the cable section. If this detects an internal fault (i.e., a fault on the cable), a signal is sent to both opposite ends using telecommunication. These signals at the receiving ends ensure that the AR function is blocked at both protection devices. A cable fault is thus switched off on all poles from both ends.

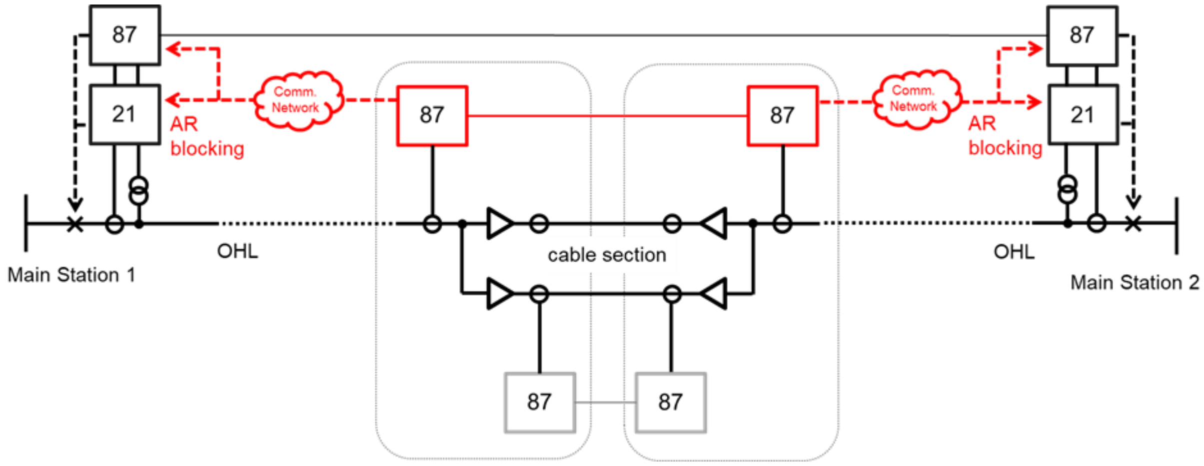


Figure 55. Simplified protection scheme for mixed circuits with an AR block

Failures in the protection or tele-protection scheme also cause the AR to be blocked at the line ends. For single-phase faults on the overhead line, single-phase AR is performed as usual.

The second differential protection, shown in Figure 55 at the bottom, is useful for distinguishing which cable system the fault is in when a second cable system is present. The faulty system can be disconnected, and the line can be put back into operation more quickly using the remaining cable system.

The concept shown above was first put into operation in 2016 for tests. At present, there are three cable sections on the circuit, each with cables ranging from 3 to 5.5 km in length. When fully completed, the line will be approximately 180 km long and comprise four cable sections totalling 15 km. The cable loading capacity is compensated by shunt reactors (not shown for simplicity).

The disadvantage of this concept is that at transition locations between overhead lines and cables, infrastructure such as power supply and telecommunications connections must be available. In the future, it is conceivable that Amprion could do without this complex concept and instead use secondary arc evaluation to differentiate between permanent and non-permanent faults. Investigations into this have already begun, but have not yet been successfully completed.

## 5.3. Case 3: REN

To ensure a reliable power supply, protection systems must differentiate between cable and overhead transmission line faults. For example, after operating for a line fault, the main protection system may initiate AR only after positive confirmation that there is no fault in the power cable. Therefore, cable differential protection provides reliable discrimination between faults in the cables or in the overhead line section.

In this particular case, in Portugal, Rogowski coil-based cable differential protection has been designed for implementation on several in-service 220 kV power cables that interface gas-insulated switchgear (GIS) substations with overhead transmission lines.

A Rogowski coil was chosen as a suitable current-measuring device due to the limited space at the point of installation. An additional advantage of Rogowski coil current sensors is significantly lower power consumption during operation. Rogowski coils are connected to devices that have high input resistance, resulting in negligible current flowing through the secondary circuit. Conventional CTs contain a ferromagnetic core that also consumes energy/power due to hysteresis losses. Rogowski coils have no core losses. In fact, an operating Rogowski coil has much smaller power loss than conventional CTs, which leads to significant savings of energy and ultimately reduced lifecycle costs. Another advantage is size: the Rogowski coil takes up much less space than a conventional CT.

A key disadvantage compared to conventional CTs is the lack of filtering for high-frequency transients, as the Cooper protection devices installed in these cases do not include a low-pass filter. Consequently, certain switching operations in the network or trips in nearby lines may cause unintended tripping of the Cooper protection, resulting in false fault indications on the cable.

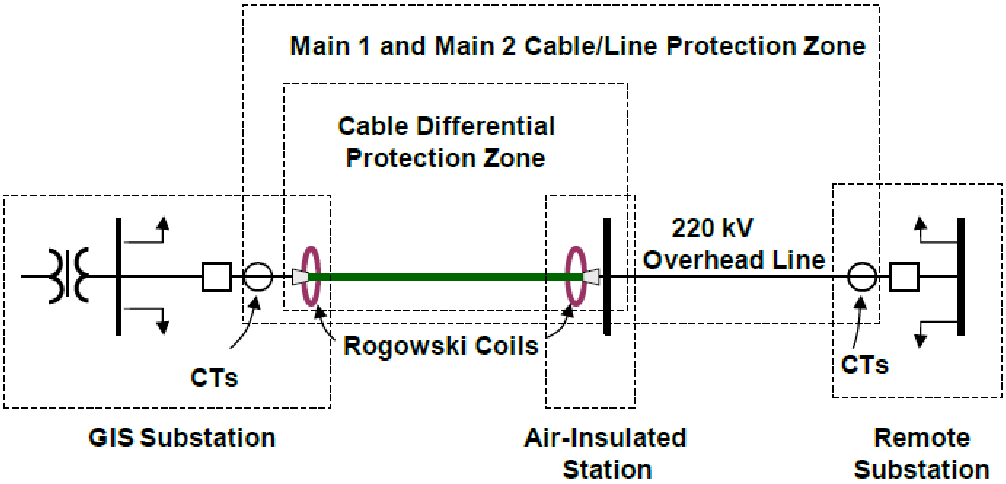


Figure 55. Differential protection solution using a Rogowski coil as a measurement device

In the existing design, the overall mix of overhead/cable lines is protected by line differential protection on Main 1 and distance protection on Main 2, with tele-protection systems. The Rogowski coil-based cable differential protection system creates an internal protection zone, as illustrated in Figure 55. If a cable differential protection trip occurs, the Main 1 and 2 protection units block reclosing into a faulted cable.

Communication between the two differential protection units (one at each end of the cable) is carried out via optical fibre.

Figure 56. Example in the substation using a Rogowski coil

## 5.4. Case 4: Swissgrid

In some substations of the Swissgrid-controlled transmission system, the connection between the OHL and the substation is provided by a cable link. When this cable remains within the substation perimeter, no specific action is taken to monitor faults that may occur on it. Otherwise, i.e., when the cable connection leaves the substation perimeter, monitoring for faults that may occur on the cable is implemented.

Fault detection on the mixed circuit and tripping of circuit breakers is ensured by the main line protection systems 1 and 2. The cable fault monitoring system does not generate any circuit breaker trip orders. This system is used only to block automatic reclosing of the protection system main 1 in the event of a fault on the cable link. The AR function is only activated in protection system 1.

The length of such cable connections is usually quite short. Therefore, the metal screen is grounded at only one end of the link. The other end of the screen is insulated using surge arrestors. Simplified monitoring of faults occurring on the cable link can then be carried out.

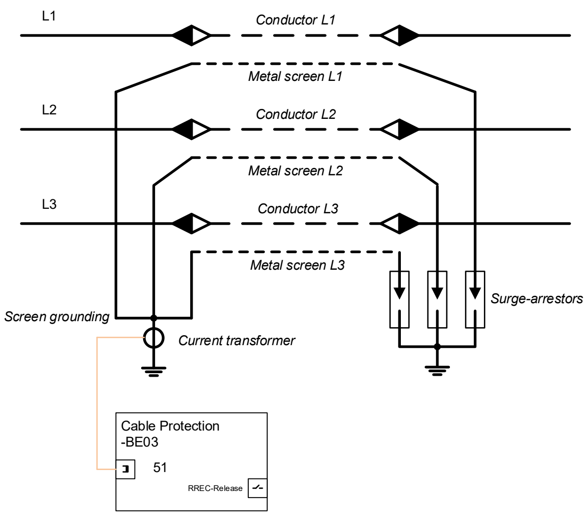


Figure 57. Simplified monitoring of faults occurring on the cable

The current flowing through the cable screens is measured at the common earth of the screens. Overcurrent protection is used to detect abnormal currents flowing through the grounding of the screens. In normal operating conditions and when external faults occur in the cable connection, no current can flow through the cable screens because the screens are insulated at one end. On the other hand, when a fault appears on one of the cables, a current will flow through this earth connection.

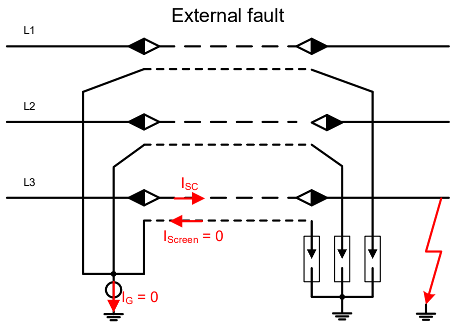


**Figure 58. Fault detection with screen-current-measurement**

To ensure safe operation of the automatic reclosing blocking system, the cable monitoring system does not emit a blocking signal but a release signal. Thus, when no fault is detected on the cable link, the protection system's main 1 at the ends of the mixed circuit are authorised to proceed with automatic reclosing.

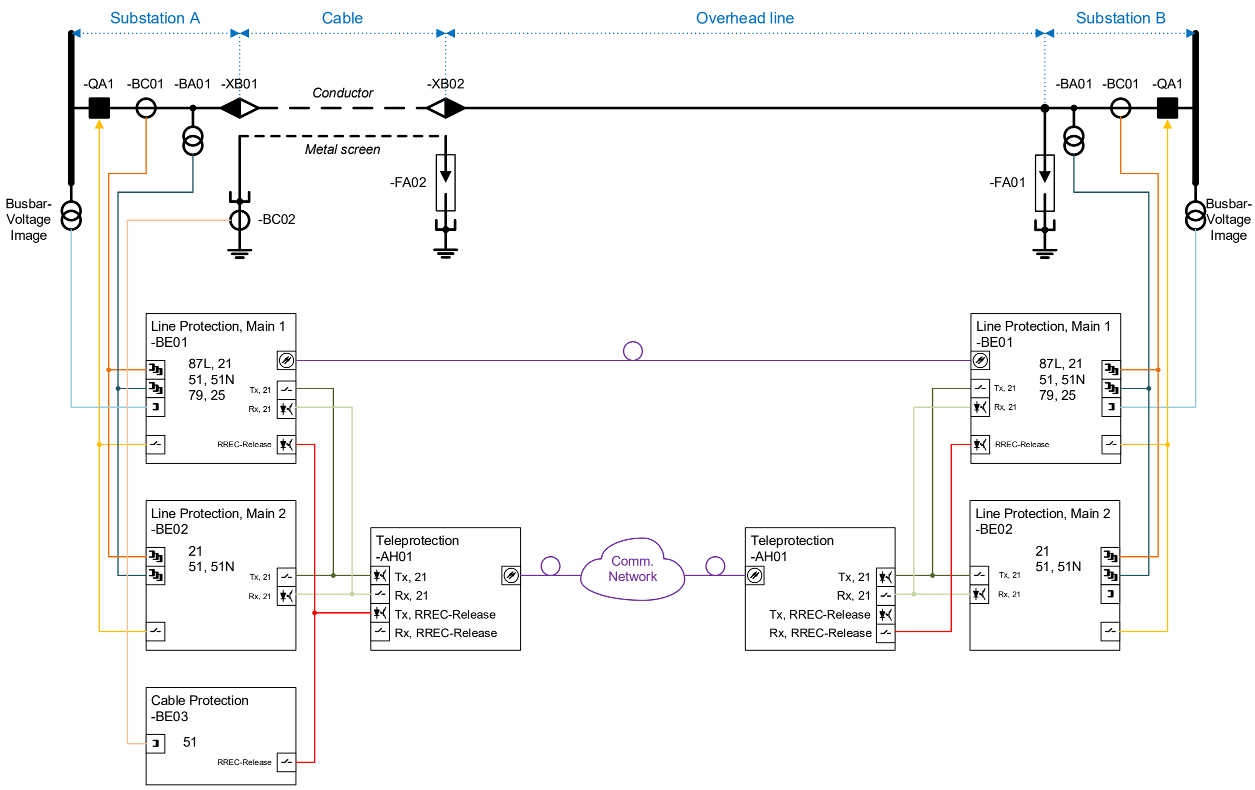

Figure 59. Complete protection system for a short cable link

The automatic reclosing release signal is transmitted to the other ends of the mixed circuit using the tele-protection system.

When the cable is long, it is no longer possible to ground the screen at only one end due to the voltages induced in the screen. In this situation, to reduce induced currents in the screens, the cross-bonding method is typically used. When cross-bonding is implemented, it is no longer possible to assume, under normal operating situations and even less so in the event of an external fault, that the current flowing in the screens is zero. The detection of faults occurring on cables can no longer be ensured by a simple measurement of the earthing current of the screens. A differential protection function between the ends of the cable link is then implemented.

To also allow supervision of cable connections installed in the middle of an overhead line, a system for measuring the currents in the cable conductors using non-conventional CTs (NCCT) is applied.

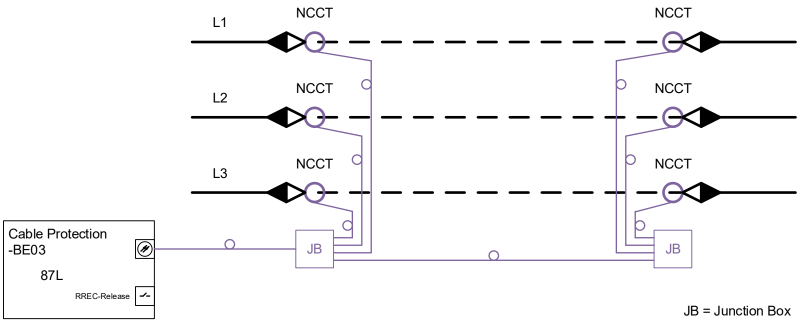


Figure 60. Differential protection for cable fault monitoring

The NCCTs are usually installed directly under the cable terminals. The transmission of current measurement values is ensured via a fibre-optic link that can transmit signals over distances of up to 50 km without the need for a repeater. The system is therefore passive at the aero-underground transition level. There is no need to provide any power supply for these measuring systems.

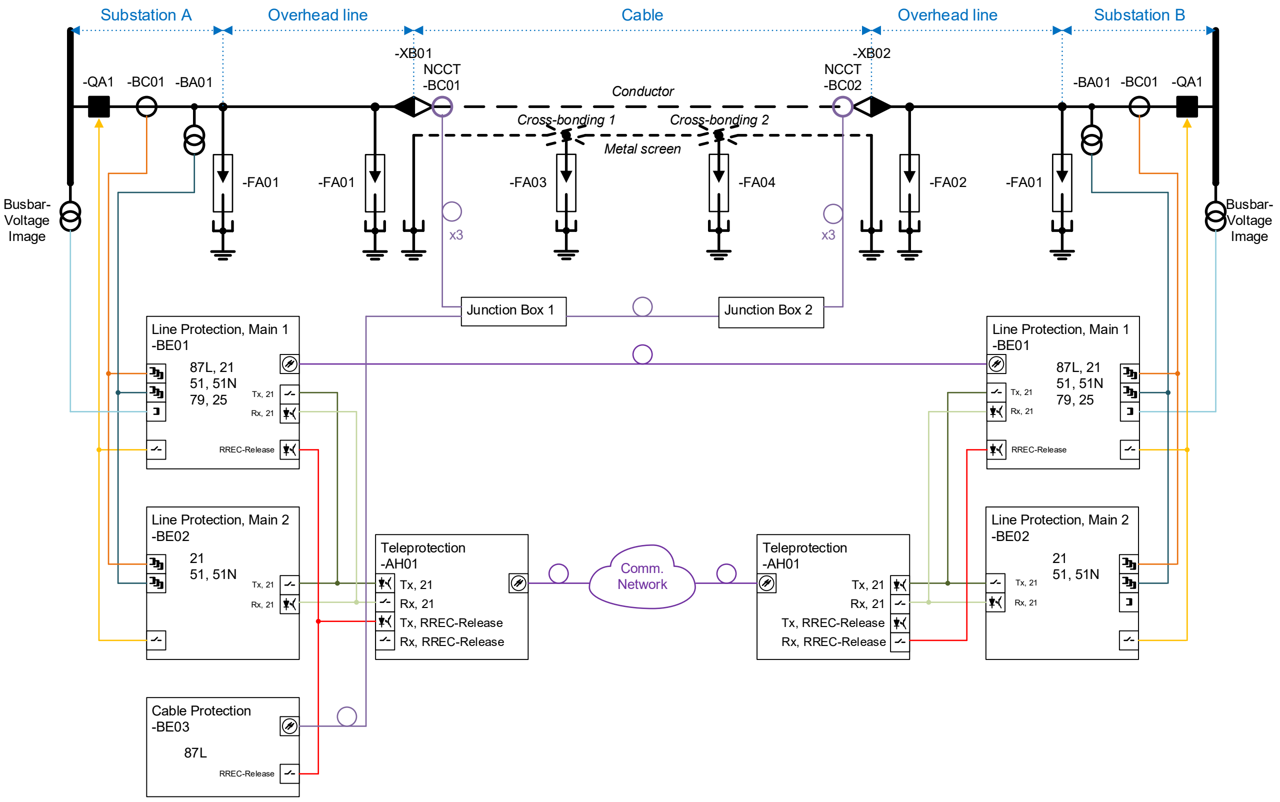


**Figure 61. Complete protection system for a long cable link**

The cable supervision system using differential protection is installed in one of the substations at the end of the mixed circuit. The transmission of the automatic reclosing release signal to the other ends is ensured by the tele-protection system.

## 5.5. Case 5: Terna

This example refers to an infrastructural work of major strategic interest for Terna due to the construction of a new 380 kV north–south Italy connection (which will be added to the three existing ones) and to the reorganisation of the network because it overlaps and replaces a pre-existing 220 kV OVH of greater extension (and therefore of greater environmental impact) but of limited capacity.

The power lines built crossing areas close to the city of Florence, which are urbanised and landscape protected, require the burying of two sections of the line, namely the incoming and outgoing ones from the GIS station of Tavarnuzze, with connections to the overhead lines for SS Casellina and GIS SS S. Barbara in two UGC OHL transition stations.

The northern line connects the SS Casellina and SS Tavarnuzze, comprising 1.7 km of cable and 8 km of overhead. The connection point between the cable and overhead sections is at the cable/air transition station in Fontelupo.

The southern line connects the Tavarnuzze and Santa Barbara power stations and comprises 1.3 km of cable and 29 km of overhead. The connection point between the cable and overhead sections is at the cable-air transition station at Le Rose.

The overhead sections are made up of aluminium-steel braided conductors with a cross-section of 3 x 800 mm2, which, according to the CEI 11-60 standard, corresponds to a capacity of 2,955 A in the cold period. The cable power lines entering and leaving the Tavarnuzze power station have the same characteristics and are composed of double triads of single-pole cables with flat-laid spacing, copper cross-bonding shields, extruded XLPE insulation, and 2,500 mm² copper conductors. Each cable triad has a capacity of 1,500 A.

Table 2 summarises the characteristics of the two power lines:

| Line | Overhead section | | | Underground cable section | | |
|---|---|---|---|---|---|---|
| | Leight (km) | Type/section (mm²) | Current ratio (A) | Leight (km) | Type/section (mm2) | Current ratio (A) |
| Casellina–Tavarnuzze | 8 | Alloy/steel T585 (3x 800) | 2,955 | (2x) 1.7 | Copper (2 x 2,500) | 2 x 1,500 |
| Tavarnuzze–S.Barbara | 29 | Alloy/steel Ty585 (3x 800) | 2,955 | (2x) 1.3 | Copper (2 x 2,500) | 2 x 1,500 |

Table 2. Casellina/Tavarnuzze/S.Barbara substation link type of mixed-line section

The choice of the double cables for the underground sections of the 380 kV lines is a consolidated choice of Terna that is systematically applied to all the lines of the extra-high voltage (EHV) primary transmission grid and is determined essentially by the following factors:

1. The need to guarantee the maximum continuity of operation of the cable lines in the event of a fault, considering that this eventuality would entail unavailability of the entire connection, which can be estimated at between 4 and 5 weeks.

2. The need to ensure that the cable part of the mixed lines has a current capacity equivalent to that of the overhead part, given that the maximum size cable used to date is the 2,500 mm² Cu cable.

Regarding the first point, it should be noted that if a cable breaks down for any reason, such as perforation by excavations, corrosion, water penetration into the insulation, construction defects, faulty assembly of joints and terminations, etc., the repair of the cable takes a long time and requires the intervention of highly specialised workers.

For this reason, the EHV cable power lines are always designed in double line, and, at the same time, it is required that each line be easily sectioned at the ends so that, if one of them fails, it is possible to exclude the faulty line and resume operation in a short time with the healthy one.

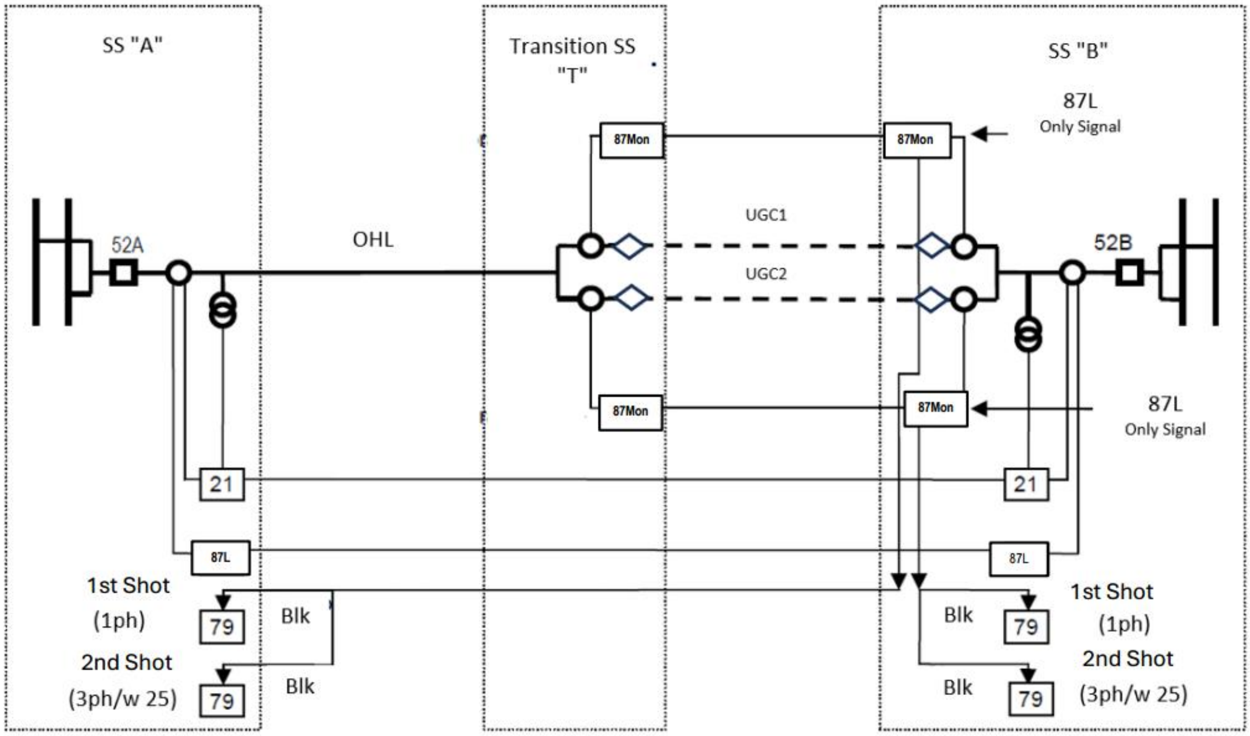


Figure 62. Protection system for a mixed line with automatic disconnection of a faulty cable

With reference to Figure 63, since the two lines described have identical configurations, they will be recalled in the following for simplicity as the generic line A–B, where A and B also identify the two SS end bays.

The intermediate transition substation will instead be identified as T (SST).

A fully redundant double protection system is used (as per the standard for an EHV grid) to protect the entire A–B mixed line, comprising:

- Distance protection with a remote protection scheme with zone acceleration (21) - Main 1.

- A line differential protection with integrated reserve distance function (87L/21) - Main 2.

The line is also equipped with a first-shot single-phase AR without synchronism controls and a second-shot three-phase AR with synchronism controls to ensure service continuity following transient faults.

On the two cable sections, there is a fault detection system capable of discriminating the cable, if necessary, affected by a fault, using an additional differential device called the monitoring device

(87Mon). The function of the latter device is to indicate the presence of faults in cable sections by providing information to operators and the automatic system for disconnecting the faulty cable.

**Faulty cable detection and discrimination logic:**

In order to take out of service only the cable connection affected by the fault, it is first necessary to identify the location of the fault with certainty. Accordingly, it is necessary to determine whether the fault is in the OHL section or in the cable and, in the latter case, whether it affected cable 1 or 2.

Whatever the location of the fault, both the distance line (21) and differential (87L) protections will trip quickly with the opening of the switches at the ends, but only the monitoring devices (87Mon) can report whether one of the two cables has been hit. If so, since it is a permanent fault, the automatic reclosing cycle of the line is blocked, avoiding unnecessary stress on the cable section and the system.

The differential monitoring equipment, in addition to the main function of recognising the faulty cable, is equipped with other ancillary functions used for the safe operation of connections, such as the detection of the presence/absence of current in cable connections and the transmission of signals between the ends of the cable connection by optical fibres.

**Automatic faulty cable disconnect function:**

The automatic faulty cable sectioning function is based on the six basic steps illustrated below:

1. A cable is uniquely recognised as faulty if the following conditions are met at the same time:

- Tripping of the circuit breaker with opening of the 52L circuit breakers at the ends of the EHV line due to the tripping of the line protections (21 and/or 87L) or other protections available (busbar protection, 50 breaker failure, GIS internal protection, 63 SF6, RX remote trip).

- Tripping of the differential device for monitoring the cable (87Mon) or other protections relating to the cable section (low oil level for cable bushing, CT cable SF6 low pressure, high cable temperature).

2. At the same time, the block command to AR and the open switches position are given. The order is given by the "remote alarm" logic implemented in the 87Mon devices.

3. At this point, the logic controls the ”dead line”( off on the three phases of the line voltage). The check is performed at both ends of the cable.

4. Once this verification phase has been passed and the time necessary for the discharge of the voltage due to the cable capacity has elapsed, the logic commands the opening of the disconnectors of the fault cable at both ends (in SS transition).

5. In the transition station, upon receiving the "automatic disconnecting logic" command, the logic verifies the ends of the cable and ascertains the absence of current in the SST through the cable monitoring protection and commands the opening of the disconnectors of the faulty cable.

6. At the end of the opening disconnectors operation, the logics of the station (B) and the transition station (T) place the disconnectors of the failed cable in the open locked state.

At the end of this fully automatic sequence of operations, it is certain that when the line is open, the faulty cable section is isolated and sectioned from the rest of the system.

If the 87Mon differential monitoring devices of both cables are tripped, they are disconnected and placed in a permanently blocked state.

If an 87Mon differential monitoring device is activated while the other is in an abnormal state, the faulty cable is isolated and blocked, but the automatic reclosing function will not be activated. The switch can still be closed manually by the operator.

The logic of this function is summarised in Figure 63.

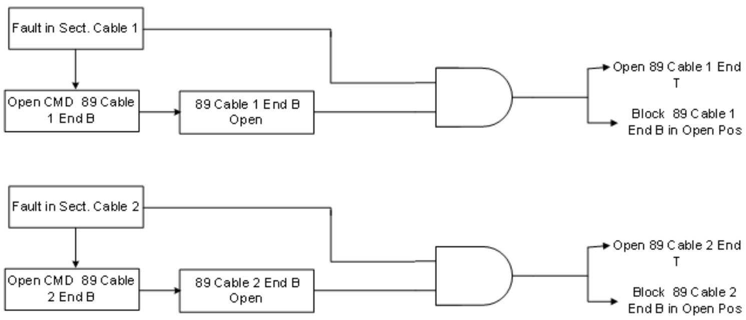


Figure 63. Automatic faulty cable disconnect logic

**Automatic reclosing function**

At this point, it is possible to resume service through the healthy cable, which, thanks to the automation and control system, can be carried out automatically without operator intervention.

The operations of the automatic reclosing logic can be summarised as follows:

1. Automatic control of the signals acquired by the system to confirm that the previous faulty cable disconnection has been successfully completed.

2. Closing control of the switches at the ends of the line, which will take place through the automatic reclosing three-phase devices (79. 2$^{nd}$ S) according to the prearranged programme:

- Voltage launches at one end of the line and parallels at the other end with synchronism control.

- The unblocked closing command to the local switch 52B is given directly, while to the remote switch 52A it is sent through a telereclosure (TR) signal by FO links.

- If the sequence is successful, service will be restored on the cable not affected by the fault. In all other cases, including when both cable sections are faulted, the procedure is blocked and the line remains open.

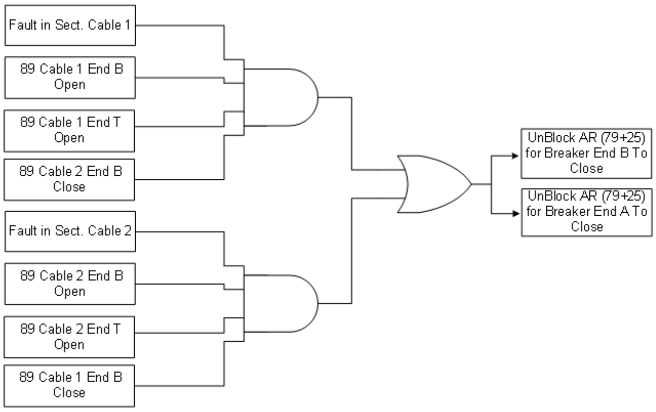


**Figure 64. Automatic reclosing logic**

## 5.6. Case 6: RTE

There are many mixed circuits in France. RTE protects the lines with impedance protection and differential protection (cable and line). RTE has also used optical detection for several years, but only as an indicator to avoid reclosure.

The main difference appears between short (cable < 25km) and long (cable > 25km) mixed lines.

For the short line, the following are used:

- Distance protection
- Differential OHL protection
- An optical differential system or overcurrent protection on the cable sheath current to distinguish between cable and OHL lines and disable the reclosure system to avoid a reclosure on a cable fault. The optical differential system cannot be used to trigger the breaker.

For the long line, the following are used:

- Distance protection
- Differential OHL protection
- Differential cable protection on the cable section. This differential protection is installed due to some issues (as described in Chapter 4) with the distance protection on the cable linked to the OHL. Therefore, RTE decided to install a dedicated cable for differential protection to complete the differential OHL protection. The installation of this protection requires

installing a power supply on the cable-aerial connection pylon. This power supply can be autonomous (powered by solar panels) or provided by the distributor.

**Concerning the reclosure:**

We consider that the re-energisation of mixed lines is generally applicable and that this involves installing discrimination devices between cables and lines to avoid reclosure on the cable. However, in certain cases (e.g., very short cables), the question of implementing these devices arises. The subject is currently being considered by RTE.

The discrimination devices can be implemented in three modes:

**Full optic differential mode**
In this case, the scheme represented in Figure 65 is used.

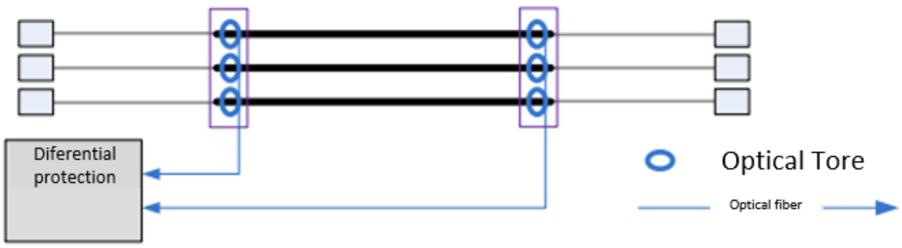


Figure 65. Full optical differential mode

In this case, the SDO FCT is optical toroidal, as shown in Figure 67.

Figure 66. Fibre is wrapped around the cable

In this case, the SDO–MU–CFD protection will not trigger the breaker but only disable the reclosure. The reclosure disable is transmitted by a communication device between the two stations.

**Mixed differential mode**

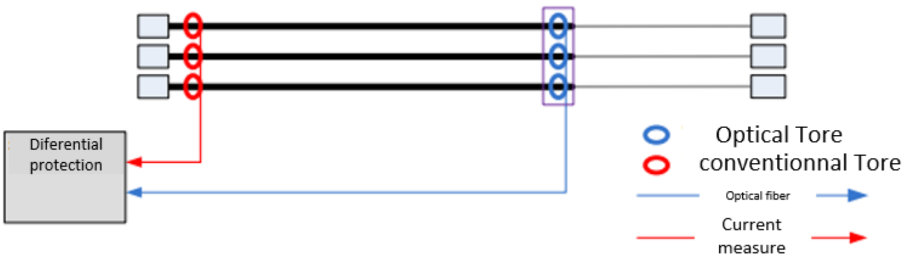


Figure 67. mixed Differential mode

In this case, a conventional current transformer is used at the SDO input.

In this case, the SDO–MU–CFD protection will not trigger the breaker, but will only disable reclosure. The reclosure disable is transmitted by a communication device between the two stations.

**Overcurrent earth mode**

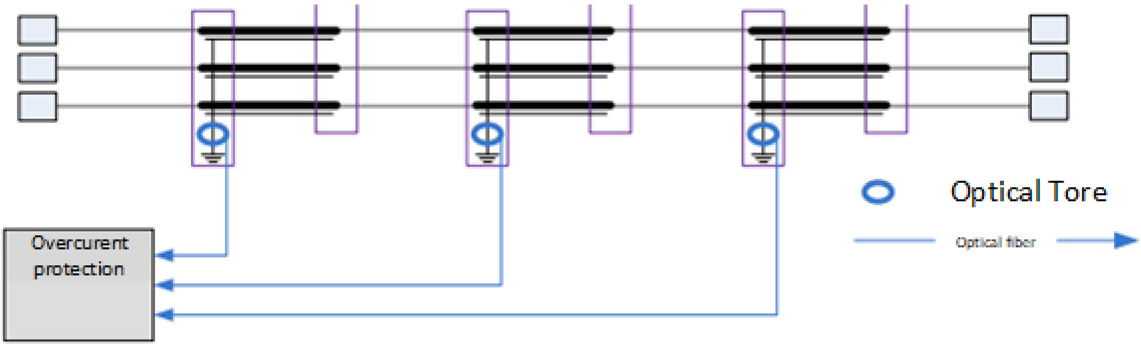


Figure 68. Overcurrent earth mode

This case will only work if there is exactly one link to the earth for each cable.

In this case, the SDO–MU–CFD protection will not trigger the breaker but will only disable reclosure. The reclosure disable is transmitted by a communication device between the two stations.

# 6. TSO questionnaire

A questionnaire was completed by TSOs that are either represented within the ENTSO-E SG Protection Equipment subgroup or were contacted by it. The aim was to gather insights into the use, operational challenges, reliability and maintenance of mixed circuit protection systems. The questionnaire was divided into three main groups:

- Implementation of mixed overhead-cable circuits
- Experience of faults in the mixed circuits
- Protection scheme and settings

Table 3 lists all TSOs that have participated and completed the questionnaire. At the end of the questionnaire-answering phase, we received 24 responses from TSO members of ENTSO-E.

| *NR* | *TSO (country)* | *NR* | *TSO (country)* |
|---|---|---|---|
| 1 | APG (AT) | 13 | RTE (FR) |
| 2 | ESO (BG) | 14 | Energinet (DK) |
| 3 | EMS (RS) | 15 | TenneT (NL) |
| 4 | ELIA (BE) | 16 | TenneT (DE) |
| 5 | Statnett (NO) | 17 | Amprion (DE) |
| 6 | EIRGRID (IE) | 18 | Terna (IT) |
| 7 | EAC (CY) | 19 | TransetBW (DE) |
| 8 | MAVIR (HU) | 20 | Fingrid (FI) |
| 9 | PSE (PL) | 21 | CEPS (CZ) |
| 10 | Swissgrid (CH) | 22 | SEPS (SK) |
| 11 | RED Eléctrica (ES) | 23 | REN (PT) |
| 12 | HOPS (HR) | 24 | Ukrenergo (UA) |

**Table 3. TSO questionnaire participants**

## 6.1. Mixed overhead-cable circuits implementation

This questionnaire part focuses on gaining an overview of different implementations of mixed circuits. It should provide background information on the topics discussed in Chapters 2 and 3, including the Mixed circuits implementation.

**Q1.1 Are there any mixed circuits in your network, or are you planning to implement some?**

The first question asked TSOs whether they have mixed circuits in use, or if they do not have any, whether they will get some in the near future.

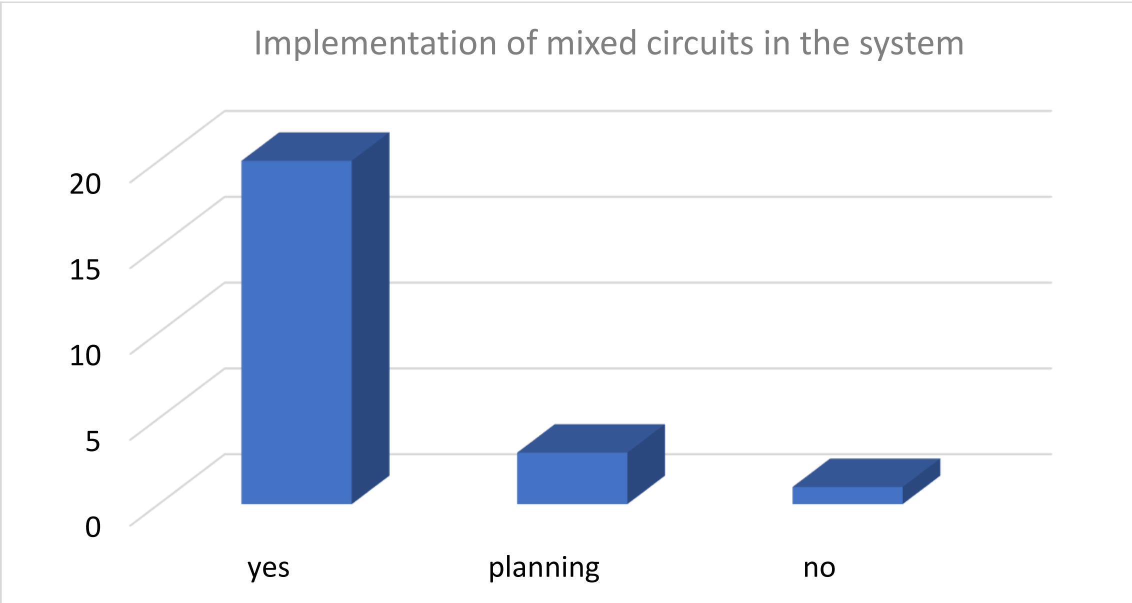


Figure 69. Distribution of answers to Q1.1

Twenty of 25 answered that they already have experience with MXD circuits in their networks. In three TSOs, MXD circuits are in the planning phase, and only one responded that they do not have and are also not planning to implement any soon. This means that in the years to come, an overwhelming majority of TSOs will have mixed circuits implemented in their system.

**Q1.2 What do you consider under mixed circuits, and what are your criteria (minimum length, minimum percent, etc.)?**

This question should elicit different views on the term 'mixed circuit' as used by TSOs. It should be recalled that TSOs in Europe have different structures due to their historical development, as reflected in the TSO AC voltage levels used in the system. While some TSOs cover only 220 and 380 kV, others also cover higher voltages, such as 500 kV or lower voltages, such as 110 or 60 kV.

The main goal of this question is to derive a mutual definition of this term.

A graphic representation of the distribution of the answers is difficult, although two main statements can be recognised: one group for which each OHL/UGC circuit outside of the substation is considered a mixed circuit, and another where the length of the OHL to UGC is crucial to decide whether the circuit is mixed or not.

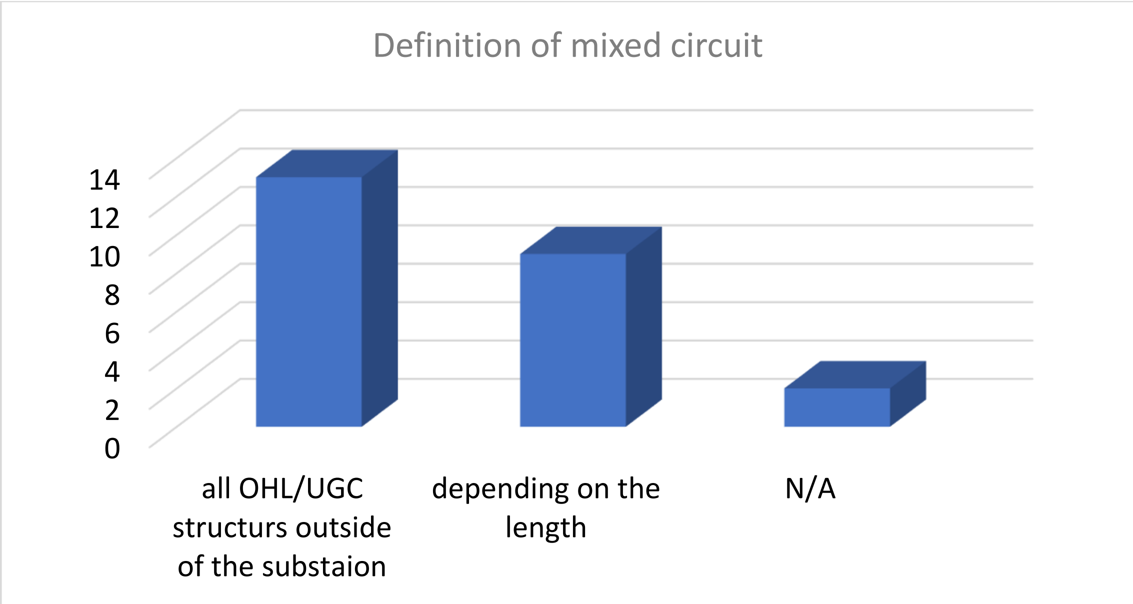


Figure 70. Distribution of answers to Q1.2

From a protection perspective, a circuit can be considered mixed as long as it contains sections outside OHLs and UGCs and its protection scheme differs from the standard line protection applied to a pure OHL or UGC.

**Q1.3 How are mixed circuits distributed in your power network depending on the voltage level?**

It was expected that mixed circuits would be implemented mostly at lower voltage levels for several reasons: lines at lower voltage levels are implemented closer to consumers and populated areas than those at higher levels, and the total number of these lines is higher than that of higher-voltage lines.

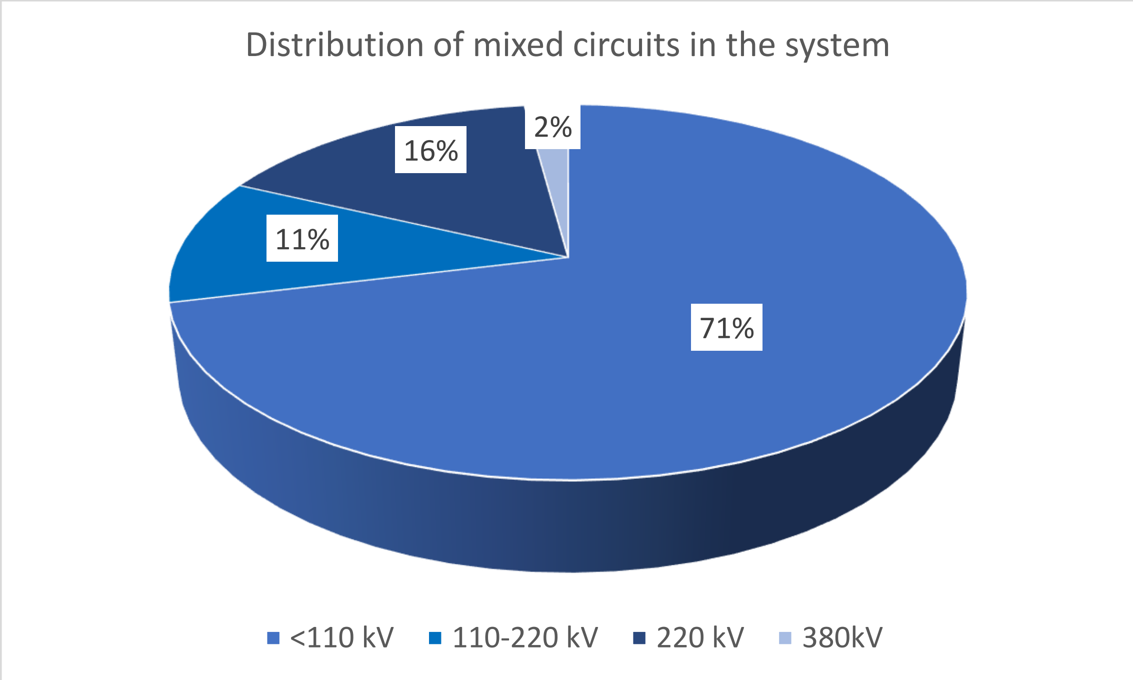


Figure 71. Distribution of answers to Q1.3

From the answers received, this assumption was confirmed, so it can be said that as the voltage level increases, fewer mixed circuits are implemented. The reported answers also show that around 30% of all implemented mixed circuits were at voltages above 110 kV.

**Q1.4 What is the topology of the mixed overhead-cable conductor in your network? (Is the cable section in the middle or at the end of the line? Do you have cable sections implemented in a multi-ended circuit?)**

Most implementations of mixed circuits are simple, containing one UGC section on one side and OHL on the other. Mixed circuits of complex topology comprising more UGC sections are in the minority.

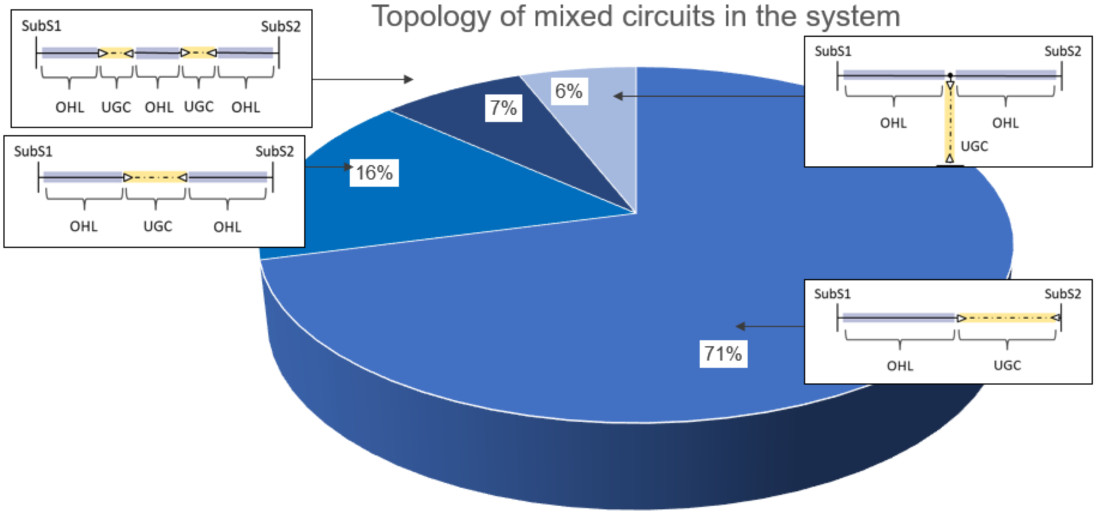


Figure 72.Distribution of answers to Q1.4

**Q1.5 Do you compensate the reactive power by shunts or other equipment in the mixed overhead-cable circuit?**

Cables have different electrical characteristics from overhead lines. This question focuses on the compensation of reactive power in the mixed circuits themselves.

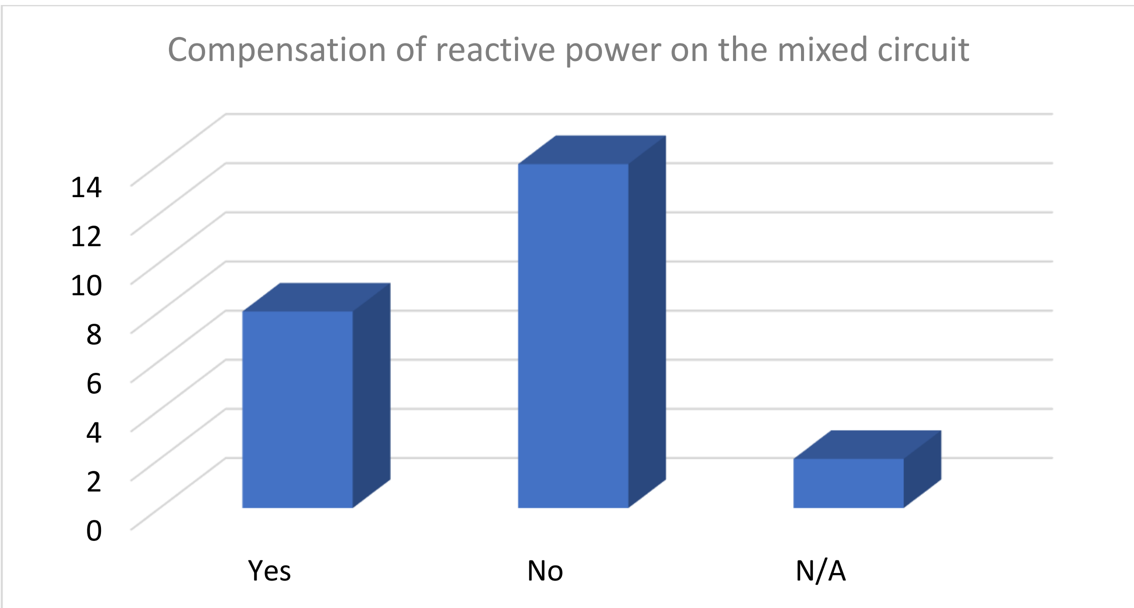


Figure 73. Distribution of the answers to Q1.5

As shown, 14 of 24 participants responded that there is no compensation for reactive power on the mixed circuit itself. This can have two main reasons: one is the length of the cable section, as reactive power compensation is not considered for short cables; the other is that, if compensation is needed, it is mostly done in the nearby substation rather than on the line itself.

Eight participants responded that they do consider compensation. This is mostly not a general approach; the decision to compensate reactive power on the mixed circuit is evaluated on a case-by-case basis.

**Q1.6 What earthing policy do you have for earthing the cable shield: one-sided earthing, both-sided earthing, cross-bonding…?**

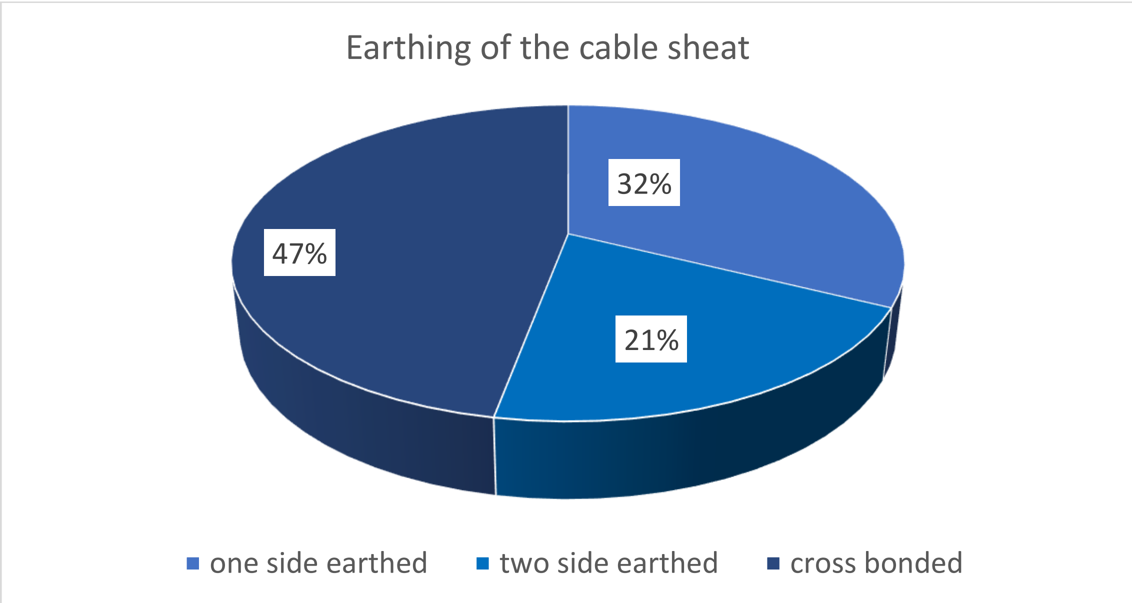


Figure 74. Distribution of answers to Q1.6

Depending on the length of the cable section, different earthing policies have been implemented. While the sheets of short cable sections are practically all one-sided earthed, longer cable sections are mostly cross-bonded or two-sided earthed. This means that if mixed circuits are implemented with only short cable sections, the TSO will have only one side-earthed cable section in its system. On the other hand, if the UGC sections are longer, the TSO might implement two or even all three earthing policies.

## 6.2. Faults in mixed circuits

The questions in this section of the questionnaire support the discussion in Section 3.2 on Experience with faults.

**Q2.1 Have you experienced faults in the cable section of mixed conductors? Did your protection react as expected?**

From this question, we can see not only the experience but also the frequency of faults in the cable sections.

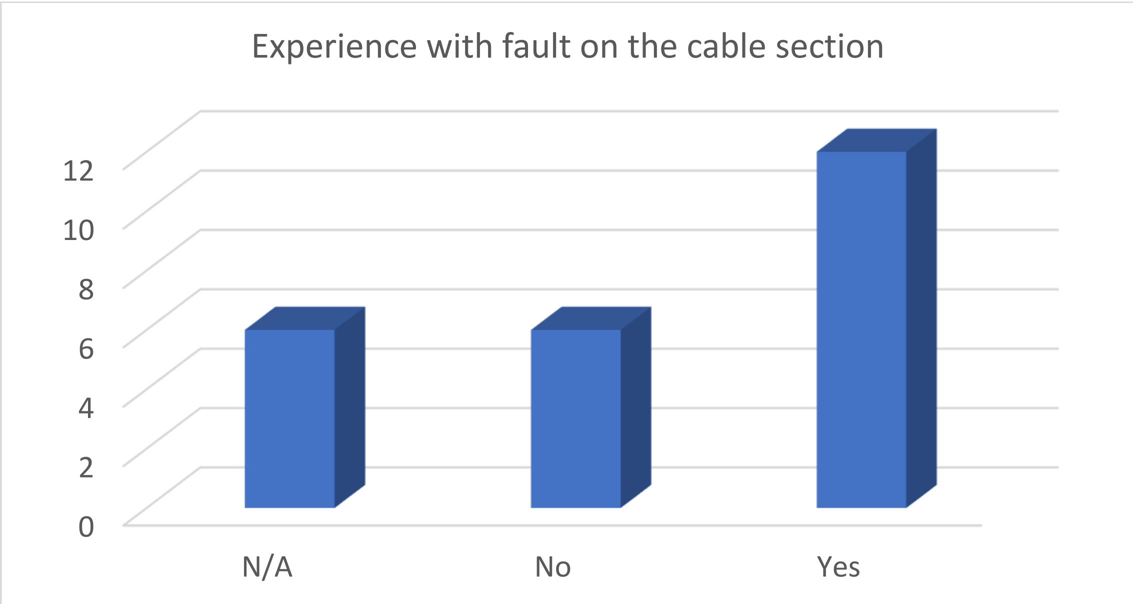


Figure 75. Distribution of answers to Q2.1

Half of the responses were positive, indicating that 12 of 24 TSOs had experienced a fault in the cable section. Six had not experienced any fault in the cable section, and the rest did not have mixed lines implemented or did not respond.

In all cases, protection reacted as expected. There was one example where protection did not react as expected. This was a special protection scheme used in the early days to protect one of the first mixed circuits at a European TSO. The issue causing the malfunction has been resolved.

**Q2.1.1 Where do the faults occur mostly (in the middle of the cable section, at the ends, on the joints or at the terminal points)?**

Independent of the voltage levels that TSO covers, all TSOs that have experienced faults on the cable section mentioned these terminal and joint points as the most frequent locations where faults have occurred.

External faults, such as those caused by human activity or environmental issues, are not dominant in the middle of the cable section. This is also dependent on the voltage level and how close the affected cable section is to urban areas or other parallel infrastructure.

**Q2.2 Have you experienced reclosing on a faulted cable section?**

Of the 12 TSOs that reported experiencing faults on the cable, 10 had reclosed on the faulted cable.

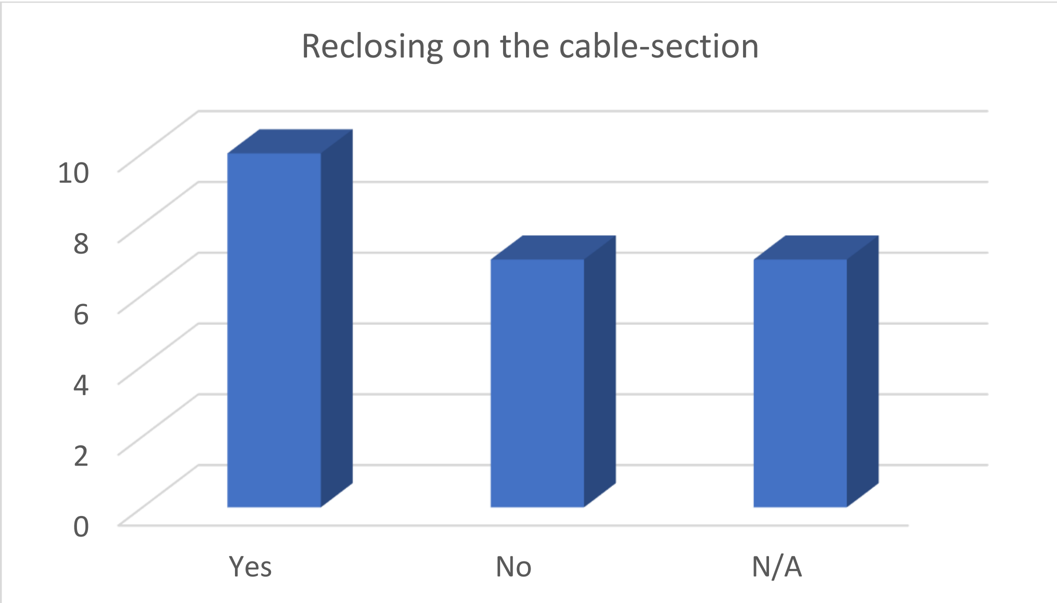


Figure 76. Distribution of the answers to Q2.2

**Q2.2.1 What were the consequences of reclosing you experienced (thermal and mechanical damages, explosion, further problems in the system…)?**

Most of the answers indicate that no significant issues were encountered during the reclosing. Reclosing on the faulty cable has led to thermal and mechanical damage to the affected element, as expected.

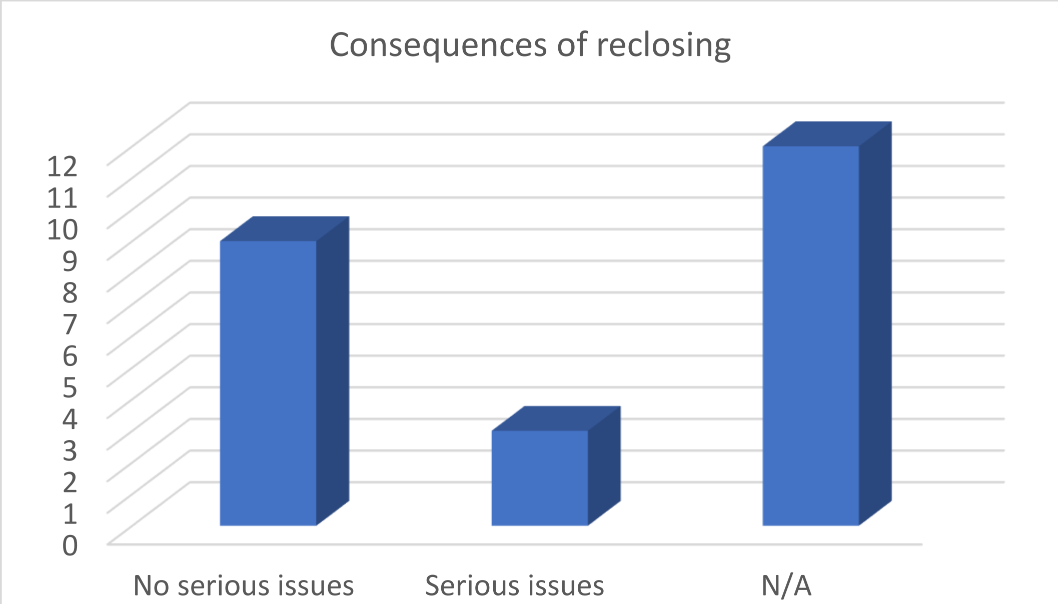


Figure 77. Distribution of answers to Q2.2.1

Three TSOs reported serious issues. One issue was not as much about reclosing as about the external cause of the fault (an anchor from a ship causing damage to three one-phase cables). Reclosing occurred, but the primary fault had already caused such destruction that the effects of reclosing most likely did not contribute much. The other examples have been presented in Section 3.2.

## 6.3. Protection scheme and settings

The questions in this chapter should provide us with an overview of protection schemes applied to mixed circuits in European transmission systems, as well as guidance on selecting specific protection settings.

**Q3.1 Do you apply a specific protection scheme for mixed circuits?**

The answers to this question provide us with an overview of how many TSOs in Europe are applying specific protection schemes to mixed circuits.

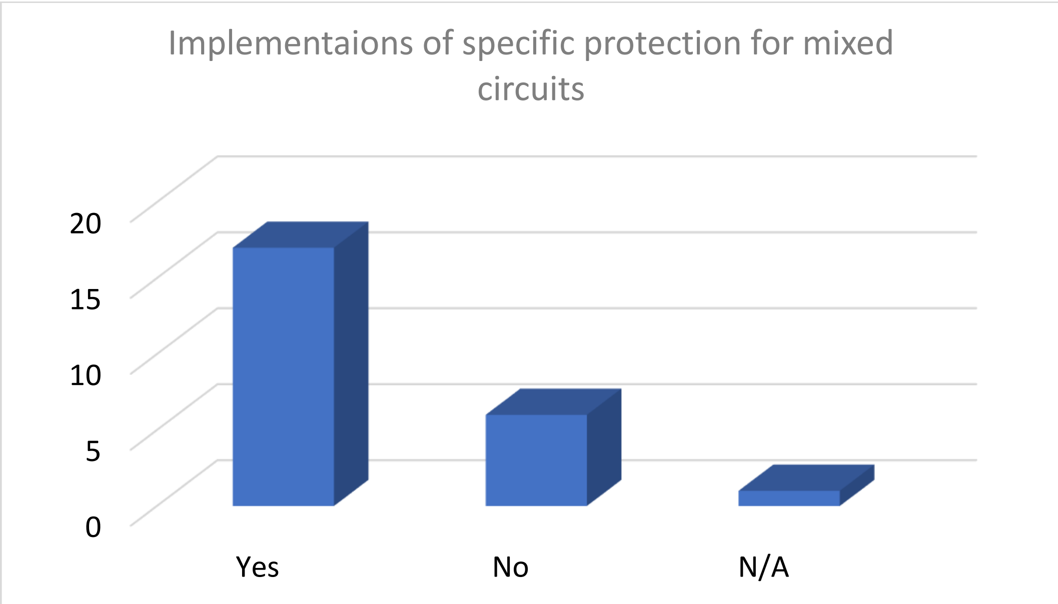


Figure 78. Distribution of answers to Q3.1

As can be seen, around 70% state that the protection scheme for mixed circuits differs from that applied to a pure OHL or UGC. However, this does not automatically mean that 70% of TSOs always apply this MXD circuit-specific protection scheme. In many cases, the decision to apply the MXD circuit protection depends on additional factors, e.g., the presence of CTs at transition points, the length of the UGC section, and the importance of the line for system stability.

25% stated that no specific protection scheme was applied. In this case, UGC sections are mostly protected the same way as OHLs, or, in fewer cases, mixed circuits are protected with the same scheme as UGC for their entire length.

**Q3.2 How much does the protection scheme of mixed conductors differ from the standard applied line protection scheme?**

The majority highlight that the protection scheme for a mixed conductor includes blocking AR for faults in the UGC section. For this, different methods have been applied, including one in which differential protection over the cable section was used solely to generate the blocking signal. Some also reported using differential protection applied over the cable, but in addition to the blocking signal, the differential protection relay was also generating a tripping signal.

One TSO also mentioned that overvoltage protection had been implemented in the 420 kV MXD circuits. This was done in cases where long lines are energised from a single station, and there is insufficient connected reactive compensation.

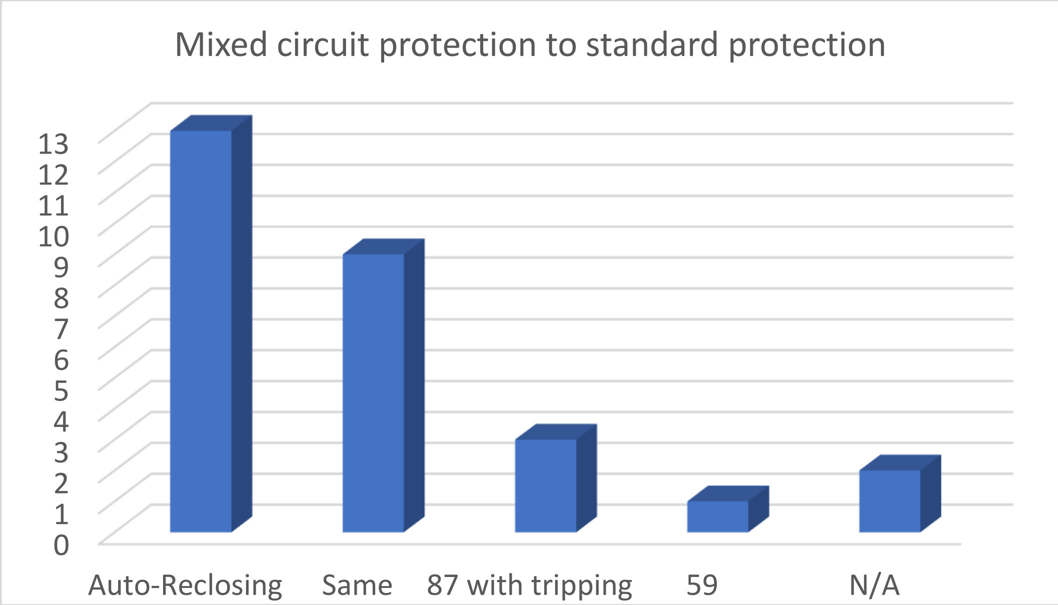


Figure 79. Distribution of answers to Q3.2

**Q3.3 Can you share a simplified scheme of the protection system (attaching the diagram in a different file)? Sensitive data that might be included in the attached diagram (substation names, protection device manufacturers, etc.) will not be published or used in any form by this report.**

Some of the answers to this question are used as the basis for Chapter 5

**Q3.4 How do you treat the AR function in the mixed overhead-cable lines protection scheme?**

Depending on the structure of the MXD circuit, TSOs may have more than one option for how AR is handled in the system.

Most answered that they do apply or are considering applying selective AR. AR is treated differently depending on the length of the UGC and OHL sections.

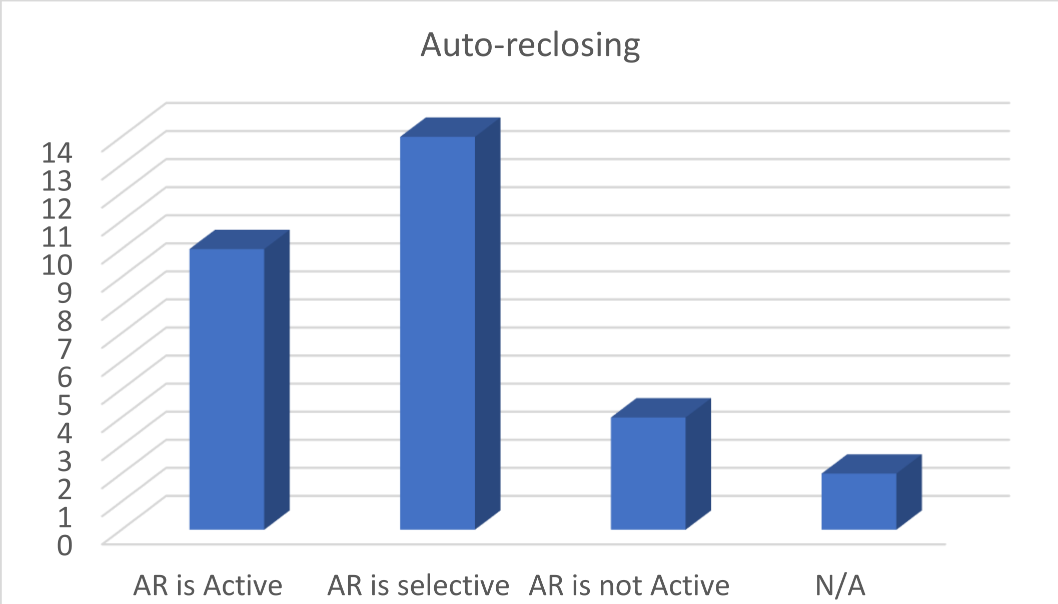


Figure 80. Distribution of answers to Q3.4

**Q3.4.1 Do you perform or are you considering applying a selective AR (AR function that is active for faults on an overhead line and blocked for faults on a cable section)?**

The vast majority stated that they apply, or are considering applying, selective AR. Comparing these answers to the answers to question Q3.1, "Do you apply a specific protection scheme for mixed circuits?", it can be seen that here one "yes" was added. This is because one TSO does not apply a specific protection scheme to MXD circuits in its network, but the MXD circuit interconnections to neighbouring TSOs are protected by selective AR.

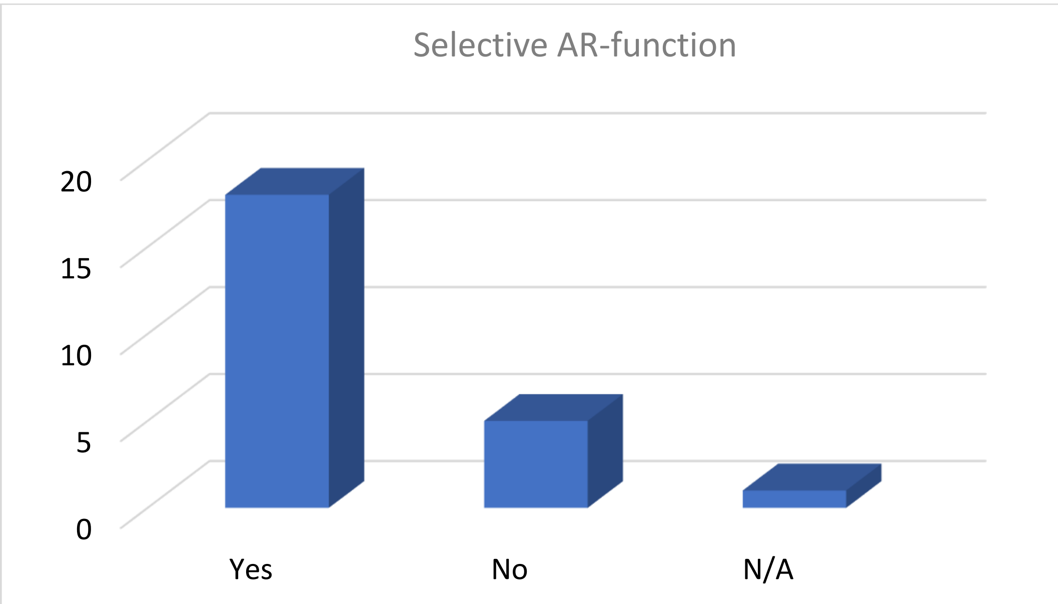


Figure 81. Distribution of answers to Q3.4.1

All TSOs that answered that the specific protection scheme was applied or will be applied to the MXD circuits are also implementing selective AR.

**Q3.4.2 How is the selective AR being implemented? Please describe your applied system(s).**

As in many cases, the answers show that more than one method is applied, depending on the length of the UGC section, sheath earthing and available primary equipment, etc. The majority reported implementing differential protection in the UGC section, which detects a fault on the cable and generates a blocking signal. The second most commonly used option is a dedicated distance zone over the cable section. Some also reported using travelling waves or other technologies for exact fault location, and several reported using overcurrent protection that uses cable sheath current measurements as its input.

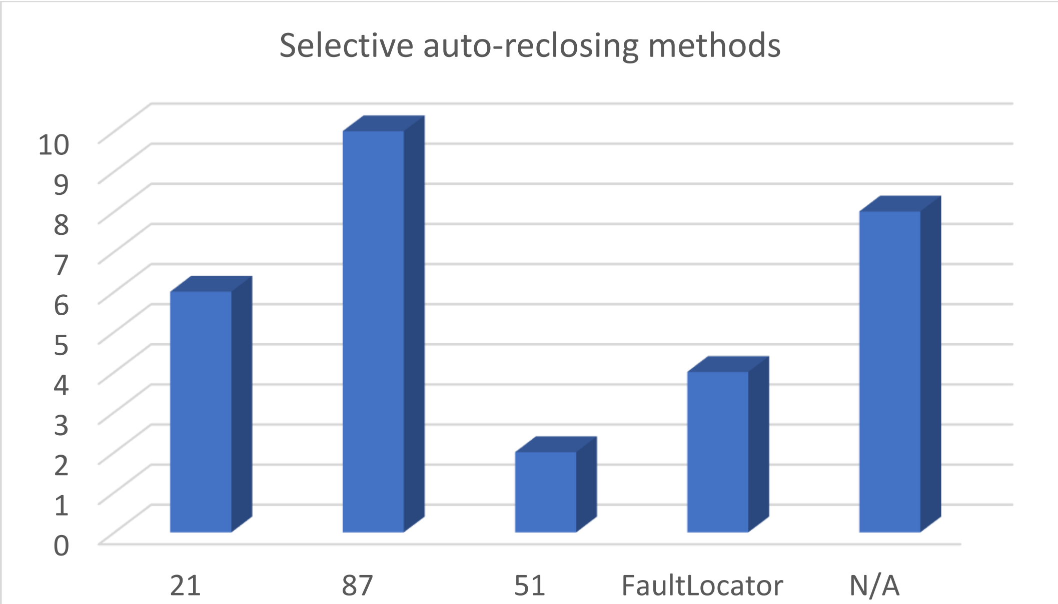


Figure 82. Distribution of answers to Q3.4.2

**Q3.4.3 How satisfied are you with the applied method? Please describe the benefits and disadvantages.**

Only one TSO replied that they were not satisfied with the performance of the applied method used in the early phases. This was also one of the first MXD circuit implementations in Europe at a high-voltage level at that time. Meanwhile, the issue was resolved.

All answers received point towards a high satisfaction rate with the applied methods.

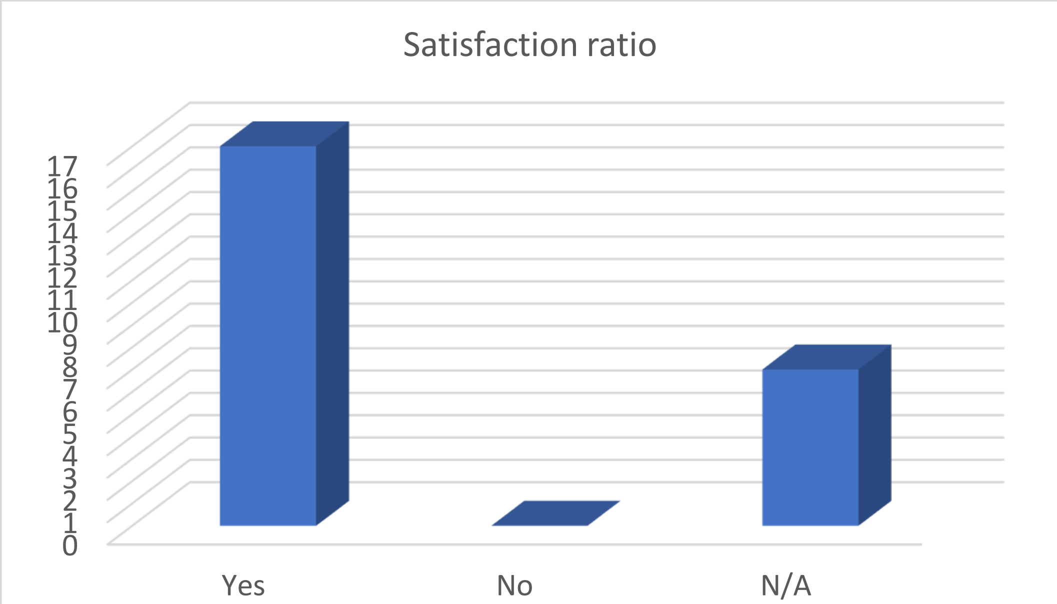


Figure 83. Distribution of answers to Q3.4.3

**Q3.4.4 In comparison with the pure overhead lines, do you set different dead times for the AR function on mixed overhead-cable lines? If yes, why?**

Twelve of 24 TSOs reported that they do not set dead time differently for the MXD circuits, and that dead time is the same for all lines in the system. Four reported that there is a difference in the duration of the dead time, caused by the extinction time of the secondary arc. Some perform additional electromagnetic transient (EMT) analysis to determine the minimum dead time, and some conduct primary tests and select a longer dead time according to their experience.

One TSO reported that the applied dead time is different depending on the localisation of the cable. The goal was to reclose first on the OHL part and then on the UGC section to avoid overvoltage due to switching.

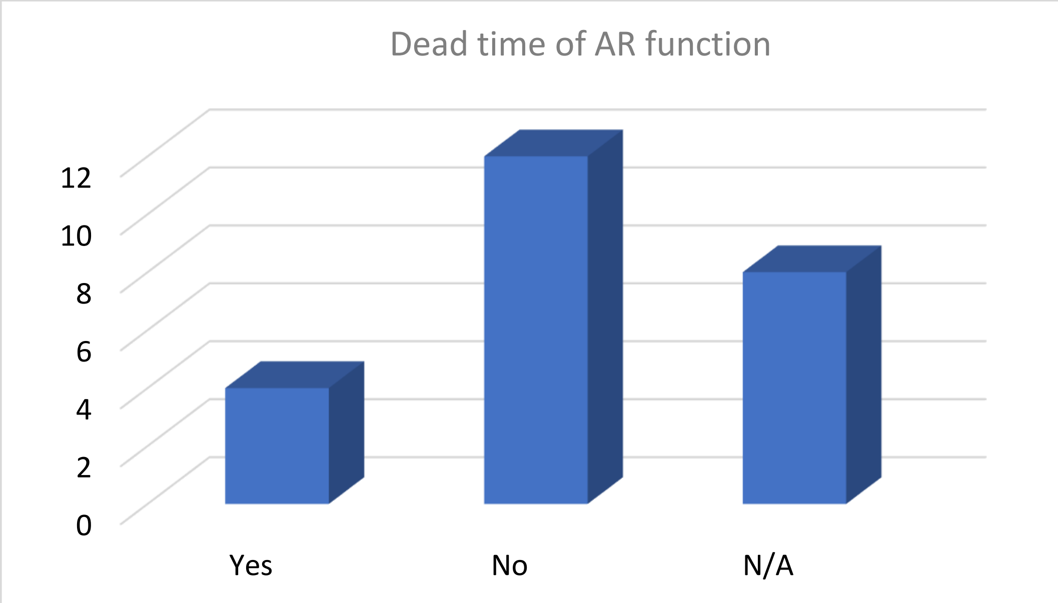


Figure 84. Distribution of answers to Q3.4.4

**Q3.5 In case no AR or no selective AR was implemented, what do you do after the protection operation to be certain that the fault did not occur on the cable section?**

All answers received point in the same direction. Procedures can differ among TSOs, but the first available date from the fault locators and fault event recorders is evaluated. If it is not possible to precisely distinguish where the fault occurred, a detailed investigation would start, including an on-site visual inspection and final measurements on the cable.

**Q3.6 How do you discriminate the fault location (whether it is on the cable or overhead section)?**

Fault locators are primarily used to discriminate between fault locations. These are either implemented in protection devices as distance protection functions or are separate devices, such as those based on travelling-wave technology.

The second most dominant fault location option is based on the same infrastructure as that used for selective AR. Comparing it with the previously described option, this one does not provide a precise fault location but only indicates whether the fault occurred in the UGC or OHL section.

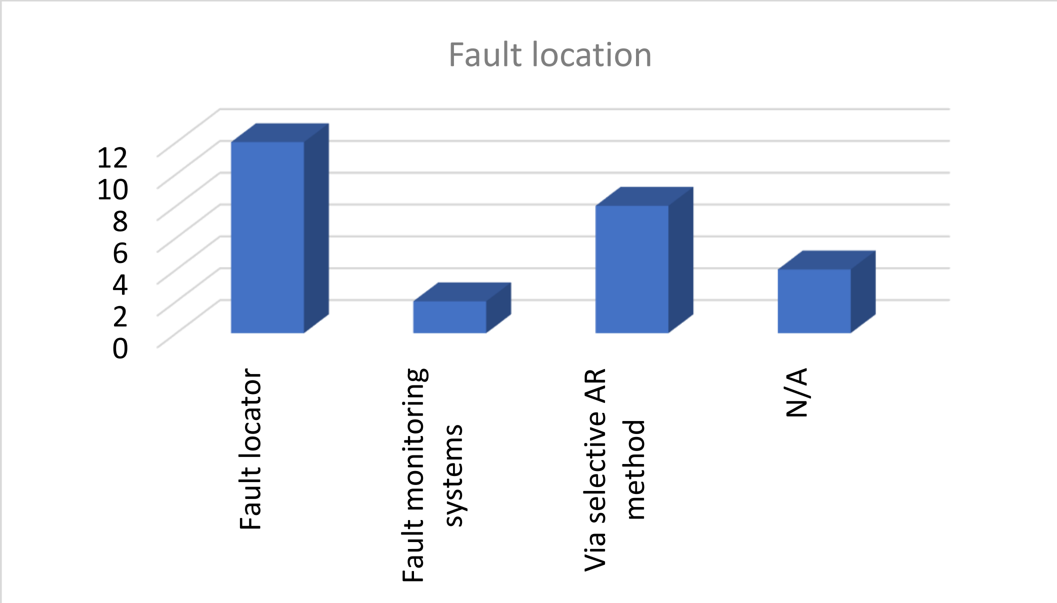


Figure 85. Distribution of answers to Q3.6

**Q3.7 How do you set the zero-sequence component factor K0 for mixed overhead-cable lines?**

There are several approaches to selecting the K0 factor for distance protection.

K0 OHL: Due to the short length of the UGC section and its limited impact on the total impedance of the total MXD circuit, some TSOs report applying a K0 factor of the same value as for OHLs.

K0 composite: First, the total impedance of the MXD circuit is calculated. Once the total impedance is known, the K0 factor is estimated.

K0 measurement: Here, the MXD circuit impedance is measured to obtain the circuit's total impedance. After the total impedance is measured, the K0-factor is calculated.

K0 average: K0 factors for each section are calculated separately, so that later on, an average value can be estimated.

K0 setting separately: Only those protection devices are applied that allow entering the K0 factor for each section separately.

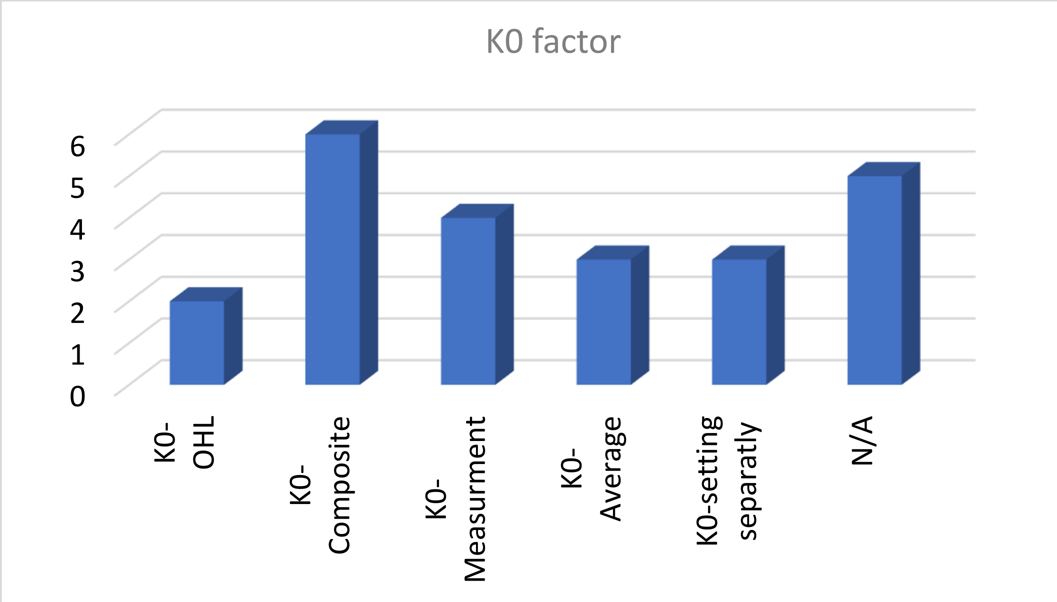


Figure 86. Distribution of answers to Q3.7

As shown, the K0 composite method was most often used, while the K0 OHL method was least used.

**Q3.8 Do you implement overload protection functions considering the cable section?**

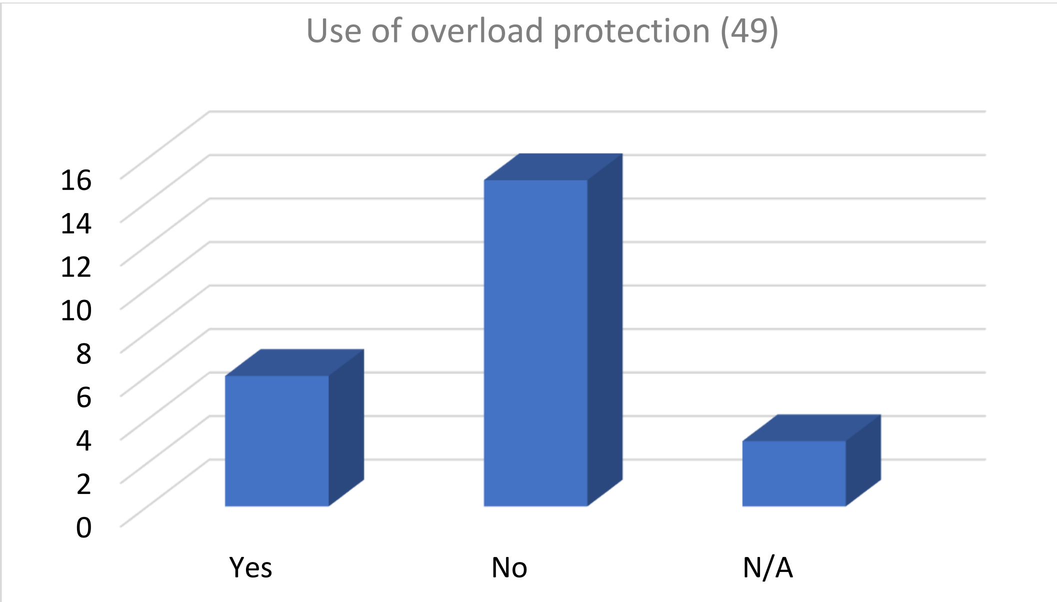


Figure 87. Distribution of answers to Q3.8

The majority reported that overload protection (49) is not being implemented for cable sections. Six TSOs reported that overload protection is applied as an additional protection function on the UGC section of the MXD circuit.

**Q3.9 Do you apply point-on-wave switching to mixed conductor lines? What is the reason for doing so?**

Answers to this question have been used as a basis for the discussion in Chapter 4.

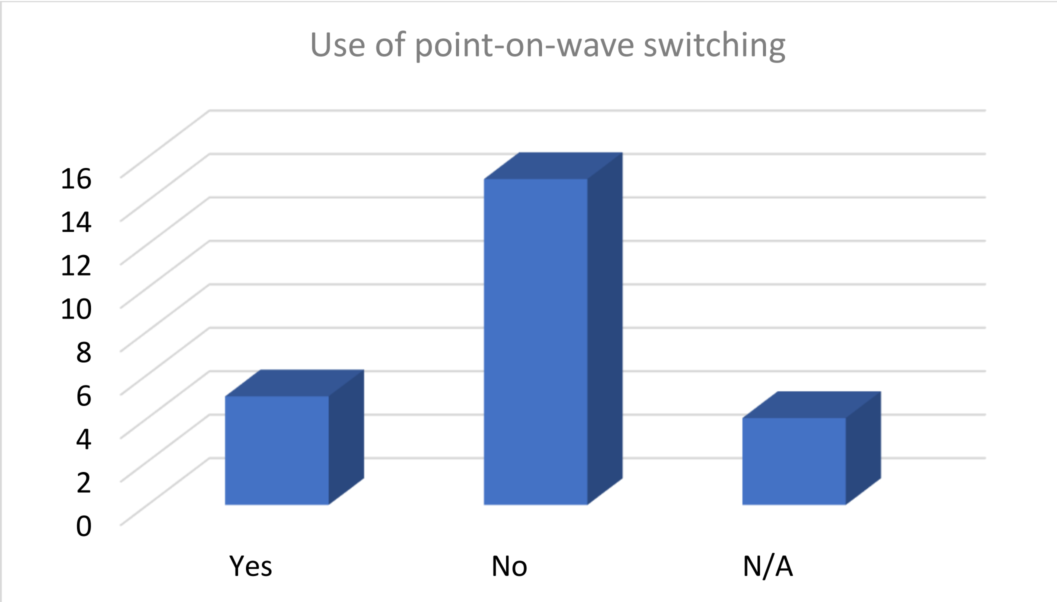


Figure 88. Distribution of answers to Q3.9

The majority answered that they do not apply point-on-wave switching to MXD circuits. This is mostly due to the short length of the UGC sections implemented in MXD circuits. Those that implement point-on-wave switching do not do so automatically on all MXD circuits, but only on those where it is necessary. Applying point-on-wave switching has transient overvoltages in focus.

# 7. Conclusion

Mixed conductors that combine overhead lines with underground or submarine cables play an important role in modern transmission systems. Their unique configurations help overcome challenges posed by terrain, environmental constraints and urbanisation.

Due to their heterogeneous electrical characteristics and operational complexities, mixed conductors require specialised protection strategies. Addressing these challenges is crucial to preventing faults and ensuring the smooth operation of the electrical grid.

Proper protection of mixed conductors is essential for maintaining the reliability and stability of electrical systems. Faults in these circuits can lead to significant disruptions, affecting the overall performance and safety of the power network.

Implementing tailored protection schemes and accurate fault location techniques is necessary to address the unique challenges posed by mixed conductors. This ensures that any issues are quickly identified and resolved, minimising downtime and maintaining system integrity.

Ongoing research and development in mixed conductor protection are essential to keep pace with the evolving demands of modern transmission systems. Investing in innovative solutions will help enhance the reliability and stability of electrical networks.

Future research in this area should focus on developing innovative protection strategies that can adapt to the evolving demands of modern transmission systems. This includes exploring advanced fault detection and isolation techniques, enhancing the accuracy of impedance calculations, and improving selective AR mechanisms. Additionally, further studies on the impact of environmental factors on mixed conductors, along with the development of robust simulation models, will contribute to a deeper understanding of their behaviour under various conditions.

Investing in research and development will not only enhance the reliability and stability of electrical networks but also pave the way for more efficient and sustainable energy transmission solutions. By addressing the challenges posed by mixed conductors, we can ensure a resilient, secure power grid for the future.

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