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Availability and Risk Assessment of 380 kV Cable Systems in Transmission Grids

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SUMMARY

Aspects like pressure of public opinion, impact on natural reserves, the crossing of canals, rivers and densely populated areas force the TSO's to search for innovative solutions in developing the transmission grid. As a result, it is expected that the application of extra high voltage AC XLPE cable systems in transmission systems on land will strongly increase in the coming years. Currently, TenneT TSO B.V. in the Netherlands is constructing a 10 km long, double circuit cable system with two cables per phase, which is unique in the world. To investigate the behaviour of such long cable lengths in transmission grids, TenneT started a long term research project. The necessary information was gathered by universities and three other European TSO's.
It is shown that long cable lengths impose a high risk in transmission grids due to the failure rate and repair time. The failure rate depends amongst other on the quality assurance procedure, which should guarantee that first of all quality is built-in. However, this high quality of the cable systems should be maintainable and quickly restorable in case of failure.
Precautions can be taken to reduce the impact of a failure e.g. by the application of explosive free terminations or by taking measures for reduction of the total outage time on component or system level.

KEYWORDS

Extra high voltage cables, XLPE, Risk Assessment, Failure Frequency, Outage Time.

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INTRODUCTION

To strengthen the Dutch electrical extra high voltage (EHV) transmission system, TenneT TSO B.V. will build in addition to the existing 380 kV overhead line (OHL) ring two new 380 kV double circuit rings in the western part of the Netherlands, the Randstad380 project, with a transport capacity of two times 2635 MVA. In this way, TenneT will be able to provide sufficient transport capacity for the new conventional power plants, off-shore wind parks, but also to connect the Dutch network with the HVDC link to Great Britain in a reliable way. Due to the fact that the new transmission system has to cross rivers, canals, densely populated areas and natural reserves, one solution is to apply extra high voltage cables in the new systems. Almost 15 years ago, the first XLPE 380 kV cable system has been installed. Since that date, several 380 kV cable systems have been installed worldwide, however, most of them as sea-cables. Therefore, the total amount of installed circuit kilometres on land is still very limited and very young.

As a result, there is uncertainty about the failure rates for EHV XLPE cables and accessories. More specifically, the available statistics in international literature is limited with a large spread in the results. Compared to overhead lines, the current experience with EHV cables shows a significantly higher unavailability rate specifically due to the long repair times. As a result, the application of long cable lengths imposes a risk to the business values of TSO's. To investigate the behaviour of long cable lengths in transmission grids, TenneT started a long term research project. The necessary information was gathered by universities and three other European TSO's. The first topics to be studied are the expected failure rate, its implication on the TSO's risk position and measures to reduce the risk for EHV cables on land and will be discussed in this contribution.

RETURN-OF-EXPERIENCE

In order to calculate the risk for the company, the failure consequences and failure rate are two important input parameters. To understand the failure consequence and failure rate, knowledge available at other TSO's regarding cable failures and repair times was investigated.
As a result, only 8 failures were identified in 380 kV XLPE cables on land in Europe, so statistical analysis is delicate but it was possible to calculate a most likely failure frequency range, see table 1 [1].

Table 1: Failure rates of XLPE 380 kV cable systems based on the return of experience and from Cigré Technical Brochure 379 [2]

	Minimum failure rate	Maximum failure rate	Cigré failure rate
	[100 comp.years] or [100 cct.years]		
Cable	0,079	0,120	0,133
Joint	0,016	0,035	0,048
Termination	0,092	0,168	0,05

The experience has shown that only a small part of the total cable outage time is the repair time of the cable itself. In particular, the total outage time depends strongly on other aspects like getting approval to enter the premises, failure investigation and best method to repair, arranging the proper permissions to start working, cleaning the area, availability of skilled personnel, spare parts, etc. The experienced minimum outage time for 380 kV XLPE cables in Europe was as low as 2 weeks in one case, but got as high as 9 months in another case.

To conclude, the experience showed a rather large spread in the maximum and minimum failure rates and maximum and minimum total cable outage time. The next section uses this information to assess the risk position of a TSO to include a certain amount of cable length in the system.

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RISK ASSESSMENT

Due to the redundancy in the Dutch system, the failure of one circuit will have no impact on the security of supply. However, during the repair time of the failed circuit, a failure of the second parallel circuit might have a catastrophic impact to the business value security of supply. The failure rate of two parallel cable circuits can be calculated as follows:

$$\left.\begin{aligned} FF_{two\ cable\ circuits} &= U_{cable\ 1} \cdot FF_{cable2} + U_{cable\ 2} \cdot FF_{cable1} = 2 \cdot U_{cable} \cdot FF_{cable} \\ U_{cable} &= \frac{FR_{cable} \cdot Total\ outage\ time\ [h]}{8760} \end{aligned}\right\} \Rightarrow$$

$FF_{cable} = \sqrt{\frac{FF_{two\ cable\ circuits} \cdot 8760}{2 \cdot Total\ outage\ time\ [h]}}$, in which FF stands for Failure Frequency and U for Unavailability.

The risk position is based on the failure frequency and impact. In this contribution, the impact is set to catastrophic. Then it is possible to determine the transition from one risk position to the other risk position by taking the different failure frequencies of failure of both circuits as constants as well. Then for each failure frequency, it is possible to determine the relation between the total outage time and the failure frequency of a single cable circuit. This is summarized in figure 1. It shows that the risk position can be improved, either by reducing the total outage time, by reducing the failure frequency or both.

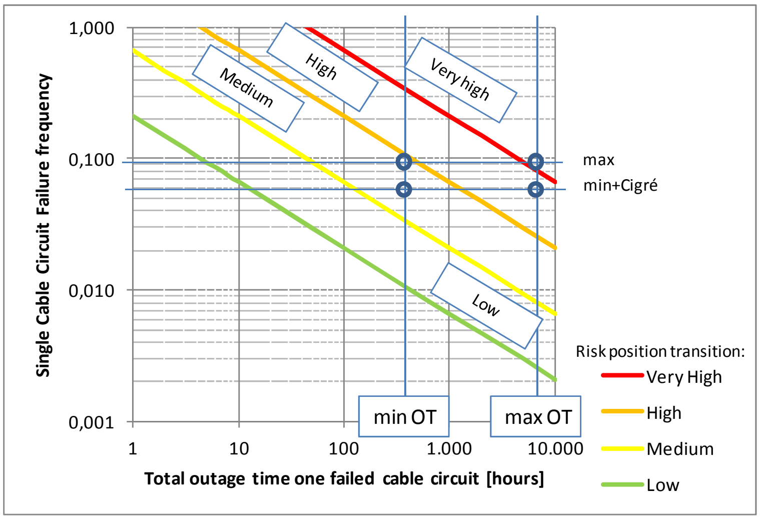

Figure 1: Relation between total outage time to repair one failed cable circuit, the failure frequency of one single cable circuit and the risk position of a TSO if the impact on security of supply is catastrophic.

IMPACT REDUCTION

The impact of a cable system failure depends on the different TSO business values: Quality of supply, Environmental, Financial, Safety, Compliance, Customers and Reputation. Interruption of the power delivery has impact on the quality of supply. Moreover, an exploding termination will lead to safety issues, see figure 2. If the failing termination is oil filled, the oil will be spilled in the environment. Moreover, the explosion might damage other components close to the termination which will clearly lead to longer repair time and higher costs.

Figure 2: Failed 380 kV cable termination.

Therefore, the explosive free termination is increasingly being used. This technical solution is necessary mainly for terminations installed in towers at the transition from overhead line to cable. Often these towers are placed near houses, other

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buildings, streets or places with presence of people, so that it is necessary to avoid any injuries to persons or damages to properties due to the explosion of terminations. Since the explosive free termination technology is fairly recent, it is important to make some considerations about the different technological solutions for their realization. The ultimate goal is to avoid dispersal of debris in the explosion. An explosion of the termination is usually caused by an overpressure due to an internal short circuit. Therefore it is necessary to insert a weak element, like a rupture disk, in the mechanical structure of the termination that will allow the evacuation of the insulating oil at overpressure in the termination.

The aspects that may affect the behaviour of the rupture disks are the following:

- The energy really developed inside the termination following the oil fire depends on the arc duration and length, because with them also the volume of oil involved by the fire increases; furthermore it depends on the type of insulation oil used by the manufacturer;
- The peak value of the current during the short circuit depends on the circuit asymmetry; therefore for testing purposes the laboratory uses the best closure timing in order to obtain the higher current peak value with a minimum arc trigger voltage taking into account the circuit characteristics;
- Building technology and material used for the rupture disk;
- Mechanical stress type that causes the rupture disk breakage (for example they can be bolts giving in for shear stress, or a thin wall that has to break at the incision)
- Given the difficulties associated with the design of rupture disks, and especially to ensure the repeatability of the behaviour of the termination following the explosion, close attention must be paid to the execution of the testing and assessing its performance.

To prevent spreading of the burning oil leading to severe damage to other equipment, a grit-bed underneath a 380 kV cable termination can be applied, see figure 3.

The previous examples showed measures for impact reduction on component level. An example of impact reduction by taking circuit restore or repair actions seen on a system reliability level will be discussed in a later paragraph.

Figure 3: Grit-bed under a 380 kV cable termination to prevent spreading burning oil.

QUALITY ASSURANCE

The use of the new XLPE cable technology requires an integrated quality assurance management. First of all, quality should be built in by correct specification, testing and installation of the cable system. Then, quality should be maintained using the proper maintenance activities. In case of failure, it should be possible to restore the required quality. Figure 4 summarizes these 3 steps in green (quality built-in), orange (maintain quality) and red (restore quality) colour respectively.

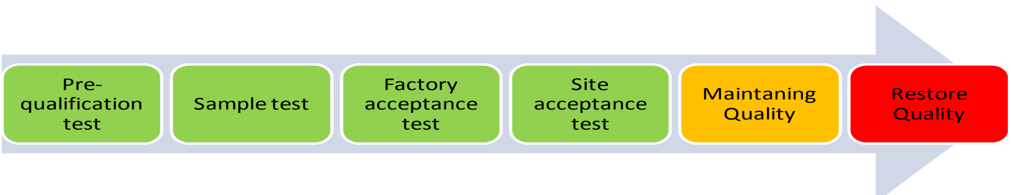

Figure 4: Structure of the quality management system. The green blocks lead to quality built-in the cable system and should be aimed for. The orange block contains actions to maintain quality during operating the cable system. The red block contains methods to restore the quality after a failure.

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Quality built-in

Making sure quality will be built-in in the cable system, cable details and appropriate testing should be specified. As an example, with respect to cable terminations, it is important to work on the aspects that cause the failure in the early age of the component, just after the installation. So it is important to have more detailed installation procedures in which the most critical activities, like welding or connecting, are defined. Besides procedures, more and more attention has to be given to personal qualification of the workers [3]. One of the most critical parts of the termination is the compression bolt on the top of the termination. Sometimes it is made of two different materials in order to join the copper cable conductor with the aluminium conductor out of the termination. This bimetallic connection can be very critical from a thermal point of view leading to a reduced reliability. For this reason some TSO's decided not to accept it and asked the supplier to make it inside the termination. As a result, some manufacturers adopted a copper compression bolt with a silver coating. Naturally no bimetallic bolt is necessary for aluminium conductor cable so that this problem does not exist. With regard to the installation activities, the composite termination is lighter and easier to install compared to the porcelain one. This aspect allows a reduction in assembly time which is of great importance especially in the case of a fault recovery.

For the installation of a 380 kV XLPE cable system in Berlin, the requirements regarding the tests arose from the CIGRE recommendations [4], but were tightened in agreement with the producers, as there was no experience available with the new technology, see table 2.

Table 2: Different test conditions for 400 kV XLPE cable

Test	Part	IEC 62067	Berlin Requirements
Type Test	Mechanical Test	25 (d+D) + 5%	20 (d+D) + 5%
	PD Test	1.5 U_0	2.0 U_0
	Noise Level	< 5 pC	< 2.5 pC (acceptable), < 1 pC
Prequalification	Prequalification Test	equal	equal
Test during Manufacturing		-	Every 5 km manufacturing cables , 30 m test loop with joint
	Heating Cycles	-	90°C , 2 cycles
	A.C. Voltage withstand Test	-	2.0 U_0 24 h
	Lightning Impulse Test Hot	-	1425 kV 10 pos/10 neg
	PD Test	-	2.0 U_0
Routine Test	• PD Test	1.5 U_0	2.0 U_0
	• Noise Level	< 10pC	
	• A.C. Voltage withstand test	2.0 U_0 1 h	2.0 U_0 10h, Hot Set Test
Commissioning Test	• Heating Cycles	-	
	• A.C. Voltage Test	1.7 or 1.0 U_0	400 kV 15 min
	• PD on all accessories	-	345 kV, 45 min, no visible PD

A producer who applies changes to the design of his installation after the prequalification should submit these to a qualification test along with the type testing [5]. After installation, the whole cable system was submitted to a heating test to simulate operational conditions. Over a period of approximately 3 weeks, the cables were heated up with nominal current during 8 hours and cooled during 16 hours. The insulation test of the 400 kV cable installation with 1.7*U0 = 400 kV was only conducted afterwards for 15 minutes after which the voltage level was reduced to 345 kV. During the voltage withstand test, a partial discharge measurement was performed and a jointing error was detected. This would have led to a system failure in the long term. After this non-destructive testing, a new joint was installed.

Besides the different tests before installation, also between each installation step a sheath test should be carried out. This test indicates even small damages e.g. from handling. If such faults are undetected this can be the beginning of a major problem later on. For the design of the cable system the spacing of the phases is of major importance. Spacing can be done in trefoil as well as in flat formation. The advantage of backfilling the space between cable phases is the increased resistance against burning and heat influence, see figure 5.

The easiest way to protect a cable system would be the installation in a deep tunnel (property of the utility), far away from installations of other utilities. Tunnels are expensive and may be a problem for employees during maintenance and repair work if there is more than one cable system installed (magnetic field exposure and high voltage influence to be considered). Cables in trenches can be protected against third parties damages by using coloured concrete slabs on three sides around the cable block (left, right, above). To avoid contact with other "low level utilities" the depth of laying should be deeper than all other installations.

Figure 5: thermal influence between two phases after a fault at a 110kV cable.

Maintaining Quality

In service, preventive inspections and maintenance can help in preventing failures. For example, a daily check of the cable route is recommended to prevent uninformed and unauthorised digging resp. other work near the cables. Utilities doing so prevented damages and avoided outages of important cable systems. After commissioning of the cable-system periodic measurements of the cable sheath shall be carried out. Damages from small impacts which were not detected earlier will appear surely after some years. Damages from third parties can be detected easily with such measurements and can be prosecuted if recorded and reproducible. A major repair can be avoided if the problem is found at an early stage.

To prevent damage on cables as shown in figure 6, it is important to inform third parties before digging about the position of the cables. Normally if someone wants to dig, prior to this the owner of a property has to be asked for permission and for details about existing infrastructural facilities in the ground. If the property is under state or town ownership, the third party can be forced to respect and to take care of other important installations in a better way. It is therefore advisable to lay cables in public ground as much as possible.

Figure 6: damage at a 380kV cable from digging work.

Restoring Quality

After a failure of a cable system, the quality should be restored as quickly as possible. Therefore, a company´s internal fault detection crew must be available 24/7 for a first investigation in case of an outage. For the next step an internal fault clearing service is necessary to localise the area of electrical problems (also 24/7 on duty). Permissions for access to properties and for work have to be organised in time long before, so the work may not be stopped in the wrong moment.

It is advisable to keep contact with the cable/system supplier and to guarantee the quick availability of jointers. After some years (decades) experienced jointers for the cable system in question may be retired and possibly nobody is available in case of emergency. A contract with the cable deliverer over years can help to reduce the reacting time - for a certain price. It is important to have a well skilled digging contractor at hand to open any kind of trench for investigations. Well skilled and experienced workers will not create more damages during the opening of the block.

For shorter repair times, quick access to the cable system should be provided in order to investigate the reason for the outage. Therefore the backfill material should not be not too hard so it can be removed with wooden wedges (preferably: very weak concrete or similar). Joint houses with access from outside make inspections easier. In case of additional joints (for repair) the joint house has to be enlarged. A magnetic sheath around the cable block to reduce the magnetic field makes any repair more difficult and more time intensive.

Spare parts normally are ordered and delivered together with the cable system to have it on stock from begin on. It should be checked if the supplier of the cable system changed his name and/or ownership. After some years of a new name and new company products, the spare parts may lose actuality and cannot be used any more. In any case it shall be checked periodically if the spare parts can be used. A pool of spare parts to be used by different utilities for similar or equivalent systems could reduce the amount of pieces in stock and reduce the storage time. There is no experience with such a pool on 380 kV XLPE level known so far.

GRID AND CIRCUIT AVAILABILITY AND RELIABILITY

As discussed before, the reliability of an underground cable system can be improved by reducing the failure frequency and the repair time. In this section, it is shown that the configuration of the cable system can contribute in the reliability as well.
In this study, the configurations as shown in figure 7 are considered. Configuration 0 is the reference scenario, a double circuit overhead line. Configuration b is the base configuration of the double cable circuit. In order to have the same transmission capacity as the overhead line, two individual cables are needed per circuit phase. In case of a cable failure, one circuit is taken out of operation. Because each circuit phase consists of two individual cables, it may be an option to (manually) isolate the failed cable only. The failed circuit can then remain in service at half its capacity. The reduced capacity may be acceptable in system operation if the line's loading is not too high. In figure 7, this option is shown as configuration b.

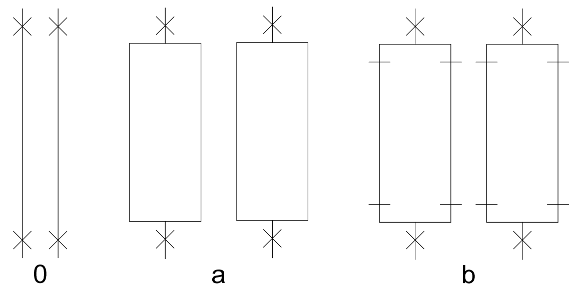

Figure 7: Different configurations for double circuit systems. 0 = double overhead line circuit, a = double cable circuit, b = double cable circuit with the possibility to isolate a failed cable. The "X" represents circuit breakers, the "-" represent disconnecting options.

For the calculations, the maximum failure rates of table 3 are used. For 10 km of overhead line, a failure rate of 0.022 failures/system.year is assumed. The repair times will be 1000 hours for the cable system and 24 hours for the overhead line. The manually switching time in configuration b is assumed 24 hours. The results are shown in table 3.

Table 3: Reliability results of different system configurations. Time to failure, recovery time and probability of having only one circuit available (10 km route length).

Configuration	time to failure of one system	recovery time of one system	probability one system available
0 (2 OHL systems)	22.7 years	24 hours	1.2e-4
a (2 cable systems, 2 cables per phase)	8.3 years	1000 hours	1.4e-2
b (2 cable systems, 2 cables per phase, with reduced capacity)	8.3 years	≈24 hours	≈3.3-4

From table 3, a comparison between underground cables and overhead lines can be made. It can be seen that for the cable system configuration a, a single circuit failure happens more often and the recovery time is longer than for the overhead line. Consequently, the cable system is significantly less reliable than the overhead line.

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Suppose that in case of a failure, the failed cable can be isolated and the double circuit can continue to operate with one-and-a-half circuit. Although this does not reduce the time to a single circuit failure, the recovery time can be reduced significantly. As a result, the reliability of the cable system, however with reduced capacity, becomes comparable with the reliability of the overhead line.

The option to isolate the failed cable only and continue operation with one-and-a-half circuit is dependent on the load flow though the system. In addition, the configuration of the network is of influence as well. It makes difference whether the cable system is situated between two substations or is embedded in a longer transmission line. If the expected loading of transmission lines is relatively small, this option may be acceptable. It must be studied in more detail whether this option is acceptable in system operation.

CONCLUSION

Aspects like pressure of public opinion, impact on natural reserves, the crossing of canals, rivers and densely populated areas forces the TSO's to search for innovative solutions in developing the transmission grid. Results of investigations on the behaviour of long cable lengths in transmission grids were presented in this contribution. The following can be concluded:

- It is shown that long cable lengths impose a higher risk in transmission grids than overhead lines due to the failure rate and repair time;
- Quality assurance is important to guarantee low failure rates, i.e. the first focus should be to have the quality built-in;
- The cable system should be designed in such a way that quality is maintainable and can quickly be restored in case of failure.
- Impact reduction can be achieved e.g. by the application of explosive free terminations or by taking measures for reduction of the total outage time on component or system level.
- The reliability of a double cable circuit can be improved by isolating the failed cable only in case of a failure. The system can then continue operation with one-and-a-half circuit and reduced capacity. It must be studied in more detail whether this option is acceptable in system operation.

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