Slim cables, compact cross-bonding and corrected distance protection

Citation for published version (APA):
Steentjes, N. G. H., Pellis, J., Rossum, van, J. C. M., van Riet, M. J. M., & Kersten, W. F. J. (2004). Slim cables, compact cross-bonding and corrected distance protection. In *Proc. Cigré Session 2004, 29-30 August 2004, Paris, France* (pp. B1-112-1/11). CIGRE.

Document status and date:
Published: 01/01/2004

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 08. Feb. 2024

21, rue d'Artois, F-75008 Paris
http://www.cigre.org

B1-112

Session 2004

SLIM CABLES, COMPACT CROSS-BONDING AND CORRECTED DISTANCE PROTECTION

N.G.H. Steentjes
Nuon Tecno.
(The Netherlands)

J. Pellis,
Eneco Netbeheer b.v.
(The Netherlands)

J.C.M. van Rossum
Pirelli Cables and Systems.
(The Netherlands)

M.J.M. van Riet *
Nuon Tecno.
(The Netherlands)

W.F.J. Kersten
Eindhoven University of Technology.
(The Netherlands)

Keywords: Cables, Cross-bonding, Distance Protection.

Abstract

In the Netherlands, high voltage connections will increasingly be realized using cables as it is very difficult to get permits for overhead lines. Pirelli and Nuon are continuously improving the design and production of the cables for increased reliability and capacity as well as lower costs. To this end, the present XLPE insulated cable has been optimized using a thinner primary insulation and lead sheath. The layout of production has been improved to lower manufacturing costs.

Cable capacity has been improved by the choice for a thinner lead screen as well as increased use of cross-bonding. A cross-bonding box has been developed that allows capacity to be increased significantly at limited additional costs. The distance protection of cables has been revised to correct the calculation error caused by the return current in the screen. It is shown that adequate correction can be achieved using a real value which depends only on cable characteristics. This considerably eases implementation into new and in existing systems.

Standardizing the cable grid system

High voltage power cable systems are essential components in modern infrastructure. Their installation requires considerable investment which is why cable systems must be capable of economical and reliable operation for at least 40 years. Polymeric cable systems have some clear advantages such as higher current ratings, greatly reduced maintenance (no hydraulic system) en simple and less worker dependent installation techniques.

For the last decade, electricity boards have merged to become more competitive. This had lead to a situation where different grid philosophies may be present within one company. This leads to more complex purchasing procedures, smaller and more expensive production batches, more costly emergency stock and the possibility of failures due to different protection philosophies.
For these reasons, a project was started to standardize the cable system. The optimisation focuses on 50 kV, 110 kV and 150 kV voltage classes. The following subjects where studied:

* maarten.van.riet@nuon.com

- Cable design improvement.
- Cross-bonding box redesign.
- Cable system standardization.
- Distance protection of the cables.

Cable design improvement: the slim cable concept

Part of the standardization is the selection of a limited number of HV cables with the basic designs and test requirements according to HD 632/A1 section 4 part K [ref. 7]. The selected conductor cross-sections are 1x400 mm^2 Alrm, 1x1200 mm^2 Alrm and 1x1200 mm^2 copper Milliken.
Remark: Alrm is the Dutch abbreviation for 'aluminum round solid'.

The conductor cross-sections were selected based on historical experiences and desired current carrying capacities. Solid aluminium conductors, cross-sections up to 1200 mm^2, are widely applied in the Netherlands for the last two decades [ref. 1,2,6]. The advantages of these conductors are easier installation techniques, lighter cable construction and water tightness. Larger conductor cross-sections are not economical due to skin effects. In cases of unfavourable thermal condition or when an increased capacity is needed, a 1200 mm^2 copper Milliken conductor is used.

The cable insulation is XLPE, applied by triple layer extrusion. The metallic sheath is a lead alloy (½ C). A lead sheath is preferred because of its corrosion resistance, low eddy current losses, water tightness, well known jointing techniques, short circuit capabilities and good service record.
The lead alloy sheath is reduced in cross-section and is suitable for the following single phase short circuit currents (at 70°C initial start temperature):
- single phase short circuit current 150kV grid ≤ 15 kA / 0.5 sec.
- single phase short circuit current 110kV grid ≤ 10 kA / 0.5 sec.
- single phase short circuit current 50kV grid ≤ 10 kA / 0.5 sec.

	50kV cable		110kV cable	150 kV cable	
	400 mm^2 Alrm	1200 mm^2 Alrm	1200 mm^2 Alrm	1200 mm^2 Alrm	1200 mm^2 cu Milliken
Conductor [mm]	21.7	38.4	38.4	38.4	43.6
Nominal Insulation thickness [mm]	11.0	10.0	15.0	17.0	17.4
Lead alloy sheath [mm]	1.6	1.6	1.6	1.6	1.6
PE outer-sheath [mm]	4.0	4.0	4.0	4.8	4.8
Cable diameter [mm]	63	77	88	94	101
Identification	Batch no. and cable length no. - year, date, time - type identification – meter marking				
Cable weigh [kg/m]	6.3	10.0	12.5	12.9	22.0
Length* [m]	>2500	>2500	2170	1740	1430
Length** [m]	>2500	>2500	2300	2180	1720

▪* transportation by truck, drum dimensions (HxW): 4200x2700 mm
▪** transportation by boat, drum dimensions (HxW): 4200x3500 mm

Photo 1: cable cross-section new and old.

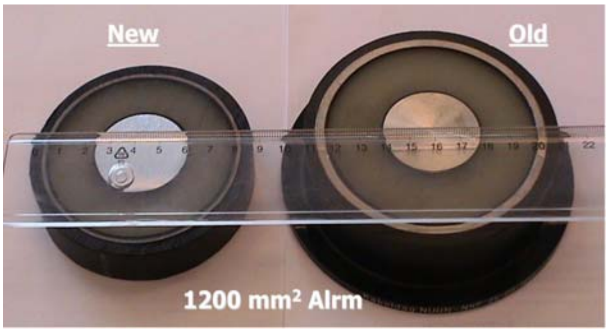


Table 1: cable constructions and their main characteristics.

Between cable core and lead sheath a water swellable tape is applied as most cables in the Netherlands are installed nearby the water table. This underlines the need for longitudinal water tightness. The Outer sheath will be black PE for its good mechanical and electrical properties.
Also, cable identification has been standardized. The cable identification will be at intervals of 1 meter, marked with a laser on the PE outer sheath. It will contain information about cable production batch number, type identification, cable meter marking and date and time of production. The slim cable design is characterized by simple and light construction, usage of well proven materials, cost effectiveness and being fully submersible. As dimensions, construction and

materials of the conductor, conductor screen, insulation, insulation screen and outer sheath are within the limits as set forward by earlier type tests and earlier long duration tests, no further tests were required. Based on the single phase short circuit currents, the minimum required nominal lead sheath thickness is 1.6 mm. This reduced lead sheath thickness was beyond Pirelli Cables and Systems N.V. known limits, at that time. Since cable cost reducing is one of the main targets, Pirelli Cables and Systems N.V. modified the production facilities in order to produce reduced lead sheath thickness. Also, production efficiency has been increased by placing the lead sheathing extruder in tandem with the outer sheath line with a 180° loop (see photo 2). This required the control systems of both previously independent production lines to be linked.

Photo 2: 180° loop between lead extruder (right) and outer sheath line (left)

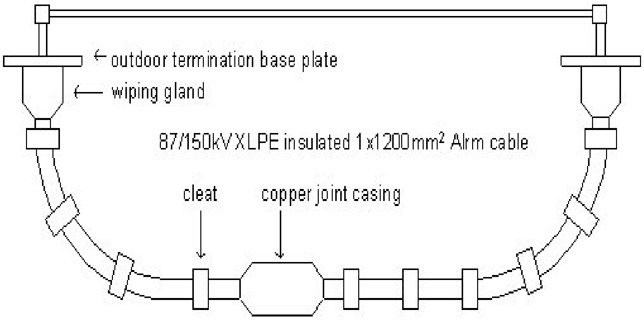


Figure 1: setup for accessories compatibility

A XLPE insulated 87/150kV 1x1200 ^{2} Alrm cable was produced after the production machinery modifications had been completed. This cable was subjected to tests:

- Bending test according to HD632/A1 part 4 section K.
- Longitudinal water tight test according to HD632/A1 part 4 section K.
- Lead quality assurance tests according to internal Pirelli procedures. These quality tests incorporate segregation tests, the crystal size determination test, the tensile and elongation tests.
- Accessories compatibility test as shown in figure 1.

Figure 1 shows the test set up: a 87/150kV 1x1200 mm^2 Alrm cable with 1.6 mm lead alloy sheath is rigidly fixed in a frame and subjected to a 100 heat cycles (8 h / 16 h, max. conductor temperature 95-100 °C). After the heat cycles no cracks or any other deformation was seen on the cable lead sheath and the plumbed joints. The lead sheath of a 400 mm^2 Alrm 50 kV cable and a 1200 mm^2 Alrm 150 kV cable were subjected to a short circuit test to measure temperature rise. These tests were performed in December 2003. Photo 3 shows the test objects. The lead sheath temperature and plumb joints temperatures are recorded by six thermocouples, which are connected to a data logger.

Photo 3: the cables at KEMA High Power Lab.

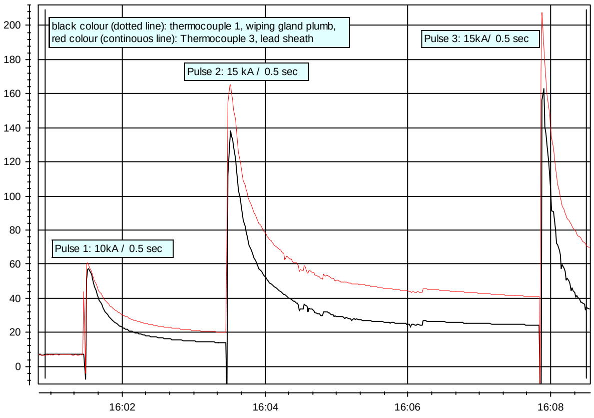
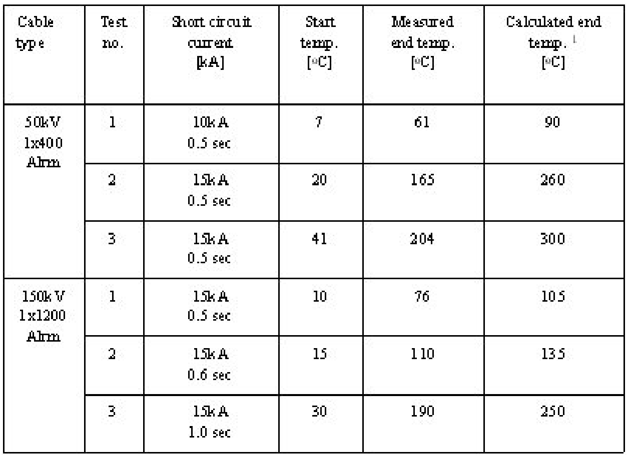


Figure 2: temperature rise of lead sheath of a 150 kV cable during three short circuit tests.

Figure 2 shows the measured temperature rise on the lead sheath for the 150 kV cable. Table 2 shows the actual measured temperature on the lead sheath during tests. Also shown is the calculated non-adiabatic temperature of the lead sheath after the short circuit test according to IEC60949 using the actual sheath thickness.



Cable type	Test no.	Short circuit current [kA]	Start temp. [°C]	Measured end temp. [°C]	Calculated end temp.[1] [°C]
50kV 1x400 Alrm	1	10kA 0.5 sec	7	61	90
	2	15kA 0.5 sec	20	165	260
	3	15kA 0.5 sec	41	204	300
150kV 1x1200 Alrm	1	15kA 0.5 sec	10	76	105
	2	15kA 0.6 sec	15	110	135
	3	15kA 1.0 sec	30	190	250

Table 2: measured and calculated temperature rises of lead sheath.

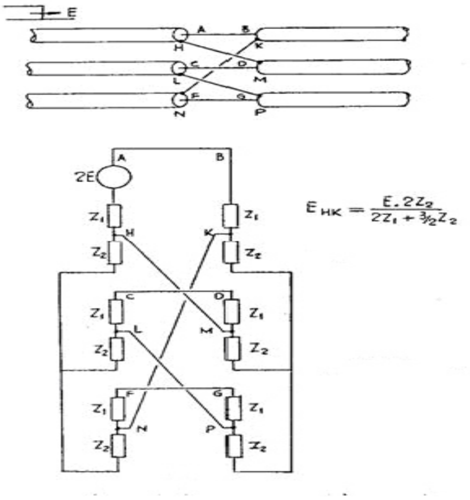


Figure 3: model to calculate overvoltages on sheath interruptions in a cross-bonded cable system.

As can be seen in table 2, the calculated lead sheath temperatures after a short circuit current, are pessimistic: the actual measured temperatures are 20% - 35% lower. Furthermore, the wiping gland plumb measured temperature after a short circuit test is 20%-30% less than the measured lead sheath. Tests show that both temperatures are not critical. The lead sheath cross-sections of the 50 kV 1x400 mm^2 Alrm conductor cable and the 150 kV 1x1200 mm^2 Alrm conductor cable are both capable for withstanding the required single phase short circuit current.

Cross-bonding surge arresters

In the Netherlands surge arresters are used in cross-bonded cable systems to protect against impulse overvoltages larger than 75 kV across the sheath interruption, or larger than 40 kV sheath to earth. To obtain a more efficient 150 kV cable system with cross-bonding, it was investigated to determine the necessity of the surge arresters. To this end, calculations of impulse voltages and measurements on an existing 150 kV cross-bonded cable system have been carried out.
Figure 3 shows the model used in calculations [ref. 11]. The theory is based on the propagation of travelling waves through lines and cables. The model is used to calculate the overvoltage on the first sheath interruption (e) as a response to an incoming impulse voltage (E). This is shown in equation (1). Z_1 is the wave impedance between conductor and earthing screen, Z_2 is the wave impedance between earthing screen and soil. Z_1 can be calculated using the cable parameters.

$$e = \frac{2 \cdot Z_2}{2 \cdot Z_1 + 1{,}5 \cdot Z_2} E \qquad Z_1 := \frac{60}{\sqrt{\varepsilon_r}} \cdot \ln\left(\frac{r_2}{r_1}\right) \qquad \text{Eq. (1)}$$

ε_r : relative permittivity of the insulation material

r_1 : outer radius of conductor screen

r_2 : outer radius of insulation

For a 150 kV 1200 mm^2 Alrm cable it can be calculated that Z_1=24.6 Ω. Calculation of Z_2 is more complicated. It is influenced by the construction of the outer sheath and the type and condition of the surrounding soil. This value can vary depending on the conditions in the cable track. To calculate overvoltages on the sheath interruption it is only important to know the value of Z_2 at this place. If the soil has low resistively (e.g. is wet) then Z_2 can be estimated by assuming that only the outer sheath is present as insulation. In this case, for the same cable, Z_2=4.9 Ω. If the soil is not a good conductor, then theoretical values up to 300 Ω can be derived. Figure 4 shows the calculated overvoltage across the first sheath interruption as a response to an incoming impulse voltage (E), as a function of Z_2. The data shown is for a 1200 mm^2 Alrm 87/150 kV XLPE cable (Z_1 = 24,6 Ω).

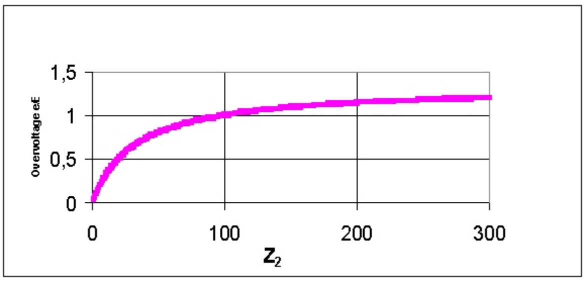


Figure 4: calculated overvoltages across the first sheath interruption

[Ref. 11] provides an overview of overvoltages across the first sheath interruption (e) as response to incoming impulse voltages (E) as measured in the field. Values between 30 % and 60 % are mentioned.

On-site measurements

Measurements were performed on the cable connection between Diemen and Amstelveen (the Netherlands). Its length is 13.5 km. A test car, normally used for fault location, was used to provide an impulse voltage between conductor and earth screen at Diemen. At the first and second cross-bonding location, voltage measurements were carried out. At Amstelveen the conductors were connected and short-circuited to earth. The type of cable in this connection is 1200 mm^2 Alrm 87/150 kV XLPE (same as used in the calculations).

When the impulse voltage was applied to one of the phases at Diemen, the other two phases were not connected to earth. In the cross-bonding boxes voltages between different points could be measured. For safety reasons it was decided to measure between a point in the cross-bonding box and earth. So to determine the voltage across the sheath interruption, two measurements were necessary which were later added. Figure 5 represents the results corresponding to impulse voltages applied to phase red at Diemen. The graphs of measurement 1 show the injected impulse voltage at Diemen, the graphs of measurement 2 show the sheath-earth voltage in the first cross-bonding box and measurement 3 shows the voltage between the same points at the second cross-bonding box. The first and second columns contain the same results, but for different time bases.

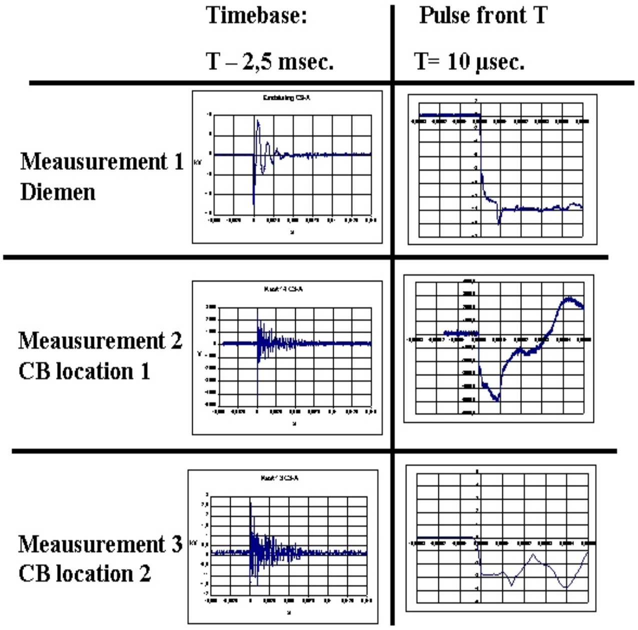


Figure 5: results of voltage measurements

The measurements were repeated to obtain the voltages at all points in the cross-bonding boxes. From these, it can be concluded that:

- An impulse voltage of 16 kV between conductor and earth screen gives an overvoltage of 10 kV (62,5%) across the sheath interruption at the first cross-bonding location and 5 kV sheath to earth (31 %). At the second cross-bonding location, overvoltages of 7.5 kV (47 %) and 4 kV (25 %) were measured.
- If the relationship between the amplitude of the input impulse voltage and the amplitude of the overvoltages at the sheath interruptions is assumed to be linear, then an impulse voltage of 650 kV at Diemen would result in an overvoltage of 406 kV across the first sheath interruption. This exceeds the maximum allowed voltage across the sheath interruption (75 kV).

Clearly, surge arresters will be necessary in 150 kV cross-bonded cables systems to prevent damage to sheath interruptions due to impulse overvoltages.

Cross-bonding box redesign

The accessories to be applied in the NUON grid are Pirelli Cables and Systems N.V. ‘Click-Fit accessories’ [ref. 2] which are fully in accordance to HD632/A1 (2002). These accessories are maintenance free, easy to install and are widely applied worldwide with a good service record. An accessory that was subjected to modification is the cross-bonding cabinet because presently these cabinets are vulnerable to accidents and vandalism, require water tight constructions, earthing rods for proper operation and regular inspection.

Based on experiences, a new cross-bonding box is to be maintenance free, not requiring earthing rods and must not have to be dismantled when the outer sheath is being voltage tested. The box must meet all relevant requirements according to HD632/A1 for 110 kV and 150 kV cables.
In order to meet the requirements, the sheath voltage limiters are connected in parallel over the sheath interruptions, so no earthing point is required at the cross-bonding box location anymore. Figure 6 shows the new concept in comparison with the existing situation.

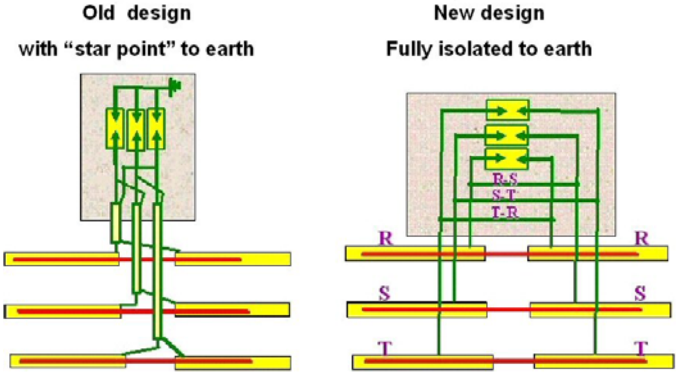


Figure 6: cross-bonding old & new concept.

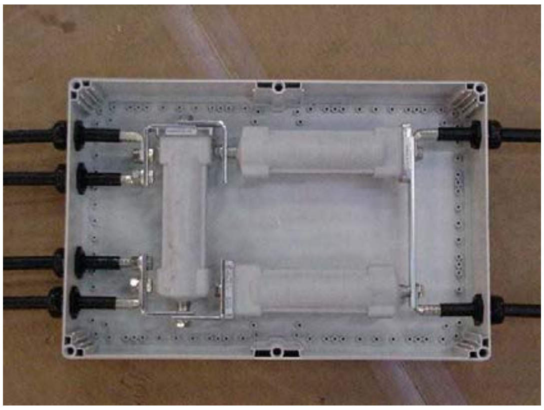
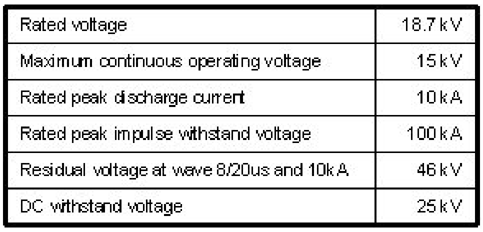


Photo 4: inner layout of the cross-bonding box, before filling with an epoxy resin.

The sheath voltage limiters are housed in a polyester box which is completely filled with a epoxy resin, resulting in a watertight, maintenance free cross-bonding box. Photo 4 shows the inner layout of the box. Cross-bonding is achieved by bonding leads. Table 3 shows the sheath voltage limiter characteristics.

Table 3: sheath voltage limiter characteristics



Rated voltage	18.7 kV
Maximum continuous operating voltage	15 kV
Rated peak discharge current	10 kA
Rated peak impulse withstand voltage	100 kA
Residual voltage at wave 8/20us and 10kA	46 kV
DC withstand voltage	25 kV

The cable outer sheath can be tested with 10 kV / 5 min. without disconnecting the cross-bonding box. In case the cross-bonding box is damaged, it will be removed by cutting thebonding leads outside the box. A new box will be installed by jointing the bonding leads with upgraded low voltage single phase joints. Before delivery, the cross-bonding box was subjected to the following qualification tests while submerged in water (1 meter depth):

- Voltage tests:
  - 10 kV AC /1 min between bonding leads and water tank.
  - 20 kV DC / 1 min between bonding leads and water tank.
  - 40 kV impulse 10+ / 10- between bonding leads and water tank.
- Thermal cycling test: during 5 days, the water tank was filled repeatedly with ice water (0^oC) and hot water (40^oC).

All tests were successfully completed. The first boxes are installed and are presently in service.

Cable system standardization

A standard trench design gives a rough indication about the cable circuit performances in the pre-engineering stage. Therefore, a standard trench layout is designed for all HV grids. Figure 7 shows the standard cable laying configuration for the NUON high voltage cables. More detailed calculation can be performed when site visits are performed and actual soil parameters are measured.
The cables are installed in touching trefoil due to expected limitations on magnetic field magnitude at the surface. The soil conditions for calculation purposes (in case no other information is available) are a thermal resistivity of 0.7 K.m/W and a maximum allowable outer sheath temperature of 50°C (largely determined by the prevention of moisture migration in the soil).

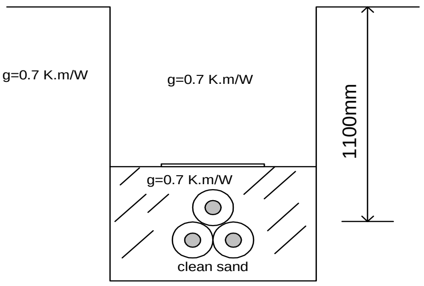


Figure 7: standard trench design HV grid NUON.

Voltage class [kV]	conductor	Metal sheath bonding	$T_{outer\text{-}sheath}$ [°C]	$T_{conductor}$ [°C]	$I_{continuous}$ [A]	$P_{continuous}$ [MVA]
50	1x400 mm^2 Alrm	Solid	50	66	545	47
		Cross-bonded		66	545	47
	1x1200 mm^2 Alrm	Solid		61	905	78
		Cross-bonded		61	930	81
110	1x1200 mm^2 Alrm	Solid		63	910	173
		Cross-bonded		64	945	180
150	1x1200 mm^2 Alrm	Solid		65	920	239
		Cross-bonded		66	955	248
	1x1200 mm^2 Cu 'Milliken'	Solid		63	1170	304
		Cross-bonded		65	1255	326

Table 4: current ratings with respect to the metal sheath bonding method

Table 4 shows the continuous current rating according to IEC60287 [ref. 8,9] for all NUON standard cables for solid bonded systems and cross-bonded systems. Based on the calculation results, the standard metal sheath bonding for the 50 kV, 110 kV and 150 kV high voltage grids will be.

- 50 kV : solid bonded.
- 110 kV: cross-bonded with the redesigned cross-bonding box.
- 150 kV: cross-bonded with the redesigned cross-bonding box.

The standard system designs will be applied in the initial stage of new XLPE cable link projects. However, if during the engineering stage the standard system design does not meet the functional requirements, further system optimisation will be implemented. These include the usage of backfill soil, cable installation in flat formations and application of different cross-section within one link with the aid of transition joints.

Table 5: comparison of present and new design.

Item	Present Systems			New optimized System designs		
Cable	50kV gird	110 kV	150 kV	50 kV	110 kV	150 kV
Conductor	240 Alrm 400 Alrm 1200 Alrm 1200 Cu 1600 Cu	800 Alrm	400 Alrm 800 Alrm 1200 Alrm 1000 Cu 1200 Cu	400 Alrm 1200 Alrm	1200 Alrm	1200 Alrm 1200 Cu
Insulation and screens	Different thickness for same conductor size within one voltage class			Uniform thickness for same conductor size within one voltage class		
Metal sheath	- Lead alloy sheath with different cross sections within one voltage class - copper wires screen (50kV only), with and without water barrier) and different cross section within one voltage class			Lead alloy sheath with uniform cross section for each voltage class		
Outer sheath	- different thickness within one voltage class. Applied colors: black and red.			Uniform thickness for all conductor sizes cables within one voltage class. Applied color: black		
Cable identification	- no uniform text, applied with embossing on the outer sheath			Uniform text applied with laser		
Accessories	50kV	110kV	150kV	50kV	110kV	150kV
Bonding lead	Different bonding lead cross sections: 70mm2, 95 mm2, 150mm2, 185mm2			One bonding lead cross section: 95mm2		
Main accessories	Many different joint, outdoor termination and metal enclosed termination types due to cable mixes.			Limited number of joints, outdoor terminations and metal enclosed terminations.		
Cross bonding box	Conventional design, subjected to maintenance			-	Maintenance free, unearthed and direct buried cross bonding box.	
System	50kV	110kV	150kV	50kV	110kV	150kV
Cable laying configuration	Close trefoil	Close trefoil	Close trefoil, flat formation		Close trefoil	
Metal sheath bonding	Solid bonded, cross bonded	Cross bonded	Solid bonded, cross bonded	Solid bonded	Cross bonded	

Table 5 summarizes the optimized cable system versus the present situation for the NUON high voltage grid. As shown in the table, the optimisation has lead to a limited number of cables designs and hence accessory designs. This leads to improved and cost effective logistics. Introduction of the new cross-bonding box has lead to reduced maintenance for cross-bonded cable systems.

Corrected distance protection

The high voltage cables under consideration are one phase cables. Here, a fault will generally be a single phase to earth fault caused by either internal failing or external damage. Distance protection can be applied to detect and locate such faults.

Principally, distance protection uses a measurement of voltage and current to calculate an impedance. This impedance is a measure to the location of the fault which may result in an operation of the circuit breaker. However, the single phase fault current will partly flow in the screen of the faulted cable. Part of the voltage being measured is the voltage drop caused by the current in the screen. In the slim cable design, the lead screen is very thin and thus has a resistance much higher than the inner conductor. This causes a significant error in impedances resulting in strongly reduced selectivity of the distance protection.

Figure 8 schematically shows a single phase cable under consideration. Also shown are the currents in conductor, screen and earth. It is assumed that at a distance L, an earth fault has occurred**.**

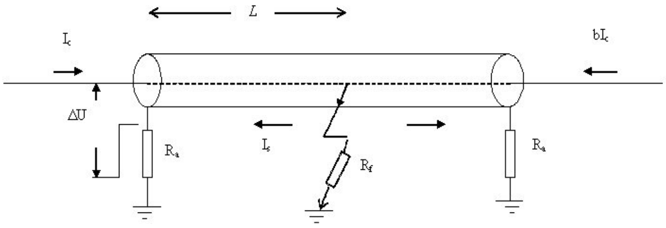


Figure 8: current flows in a cable during a single phase fault.

Considering that the cable may be part of a mesh-type grid, the fault current flows from both ends and returns via the screen and earth. From the cable end under consideration, the measured voltage ΔU is given by equation (2).

$$\Delta\underline{U} = \underline{I}_c \cdot L \cdot \underline{Z}_c + \underline{I}_s \cdot L \cdot R_s. \qquad (2)$$

Where: I_c conductor current [A]
I_s screen current [A]
Z_c impedance of inner conductor and isolation per unit of length [Ω/m]
R_s resistance of the screen per unit of length [Ω /m]
L distance to a single phase fault [m].

As the current distribution in the screen depends
relation between the measured voltage $\Delta\underline{U}$ and th
impedance $\Delta\underline{U}/\underline{I}_c$, as seen by the distance protect ilt.
Arranging equation (2):

$$\Delta\underline{U} = L \cdot \underline{Z}_c \{ \underline{I}_c + \underline{I}_s \cdot R_s / Z_c \} = L \cdot \underline{Z}_c \, \underline{I}_{corr} \qquad (3)$$

So $$L \cdot \underline{Z}_c = \Delta\underline{U} / \underline{I}_{corr} \qquad (4)$$

Where: $\underline{I}_{corr} = \underline{I}_c + R_s/\underline{Z}_c \cdot \underline{I}_s$
the “corrected current” [A]

If the impedance calculation is based on the corrected current, the impedance will be proportional to the distance to the fault. This requires measurement and addition of conductor current and screen current. The contribution of the screen current to the corrected current depends on the ratio $R_s/\underline{Z}_c$. This so called correction factor has a complex value and depends only on cable characteristics.

In order to determine the non-linearity of the impedance measured in the conventional way and to prove the applicability of the corrected impedance measurement, cable circuits have been modelled by the computer program ATP. One-phase faults have been simulated for various types of cables, earthing conditions of screens and fault resistances to ground. Here results are shown for a 1200mm^2 Aluminium cable with 18 mm XLPE primary insulation, a 1.6 mm lead screen and 5 mm outer PE cover. The length of the cable is 9 km., metal sheaths are solid bonded (both ends of the cable).

In the first configuration the screens are bonded and grounded at both ends. Figure 9 shows the impedance of the cable when a fault occurs somewhere along its length. The parameter shown is factor b, indicating the relation between the single phase fault currents from both cable ends. When the impedance measurement is not corrected, a significant error occurs in the measurement. This error increases as the amount of current originating from the other end of the cable increases, as would be the case when the fault location is at that end of the cable. The lower line in figure 9 shows the measured impedance when the measurement is corrected in accordance with equation (4).

Figure 9 clearly shows that the corrected impedance measurement is linear for all fault locations along the length of the cable and is independent of parameter b. Calculations that were performed to study the influence of the resistance of the fault to ground R_f and the grounding resistance R_a yield similar results. These show that the correction is independent of the screen current distribution, as the actual screen current at one end is used. The factor $R_s/\underline{Z}_c$ holds a complex value which significantly complicates implementation of the proposed correction. Most protection equipment, even modern ones, simply do not have the possibility to correct the distance calculation using another set of currents.

It was studied whether it would be acceptable for the correction factor to be a real number equal to its absolute value. In that case a summation current transformer could be used to add the (weighted) screen current to the phase current and the resulting current can then be fed into the existing protection equipment. This option would allow corrected distance protection to be implemented in existing circuits at limited expense.

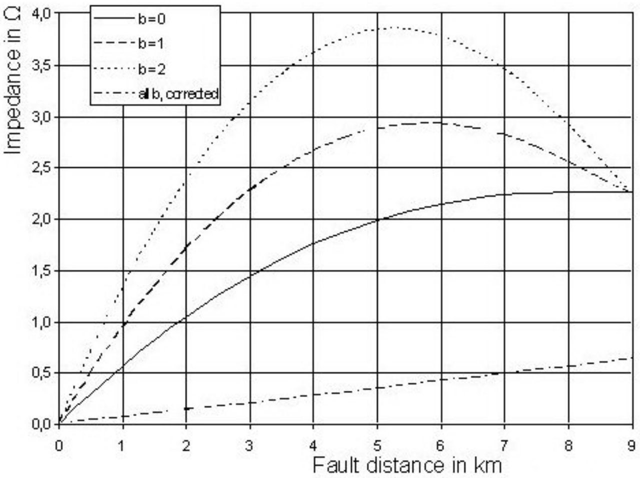


Figure 9: calculated cable impedances with solid bonded sheaths.

Calculations confirm that the complex value of the correction factor may be approximated by its absolute value. The deviation of the calculated impedance is within 6% of the impedance obtained with the complex value ($8{,}36 \angle -62{,}2^\circ$ for the cable under consideration). However there is a large error in the phase angle of the impedance. This however is less relevant.

The corrected impedance measurement suggested above can simply be applied in configurations where the screens are grounded at both ends. If however the screens are sectionalized and cross-bonded at intermediate points, it depends on the location of the single phase fault, which screen carries the fault current.

So it requires measurement and comparison of the screen currents at cable end, selecting the largest screen current and adding this current to the faulted phase current. In distance relays with only 4 current inputs, the comparison, selection and addition have to be performed outside the relay by means of a special device. This greatly complicates implementation.

In order to estimate the linearity and accuracy of the corrected impedance measurement, a cable circuit with cross-bonded screens has been modelled. The circuit consists of two so-called major sections, where each major section has three cross-bonded minor sections of equal length. At cable ends the screens are bonded and grounded. At the junction between the two major sections, cross-bonding of the screens may either be continued or the screens may be bonded together and even grounded. The first configuration is called continuous cross-bonding (figure 11), the second configuration sectionalized cross-bonding (figure 10).

Figure 10 shows the impedance in case of a single phase fault in a sectionalized cross-bonded system of slim cables. The lower lines in figure 10 show the impedance when the conductor current is corrected by the largest screen current, applying the modulus value of the correction factor. The correction is only adequate for faults in the first major section where the largest screen current can be selected. This is not the case for faults in the second major section as the return current is equally distributed over the screens in the first major section, due to the bonding of the screens at the junction between the two major sections.

However, if the screens are continuously cross-bonded the largest screen current can be selected for faults along the whole length. Figure 11 shows the conventionally measured impedance in case of a single phase fault in a continuous cross-bonded system of slim cables as well as the corrected impedance, applying the modulus value of the correction factor.

The corrected impedance is nearly proportional to the distance to the fault. However, implementation is complicated as a selection device is required which selects the largest screen current to be used for correction.

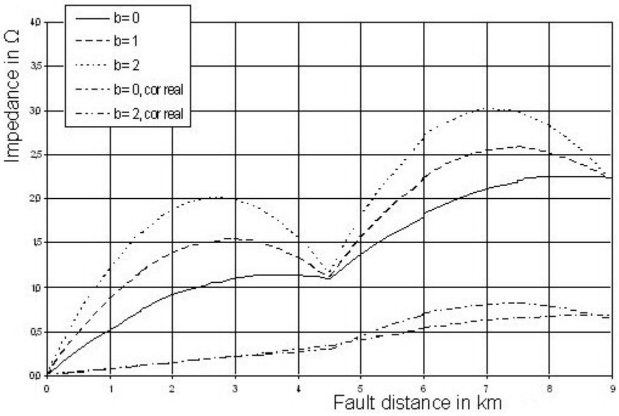


Figure 10: calculated cable impedances with sectionalized cross-bonding of two major sections.

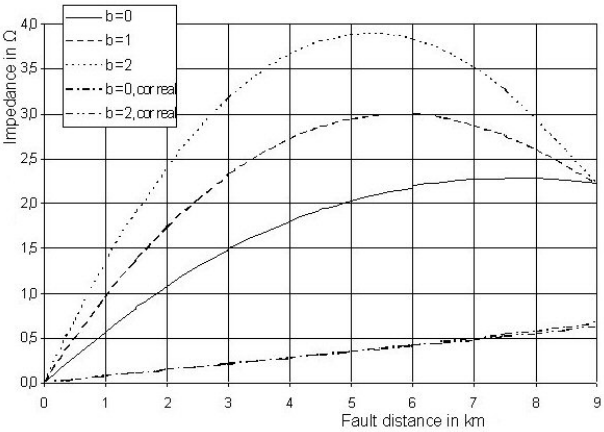


Figure 11: calculated cable impedances with continuous cross-bonding of two major sections.

For obvious reasons, there is unwillingness to use this type of active selection components in the secondary circuits of a current transformer. When protection equipment becomes available that allows for current correction by screens currents, either by hardware or by software, this method can be implemented in cross-bonded systems as well.

Conclusion

The paper describes work that has been performed to optimize the use of high voltage cables in a mesh type grid. The cable itself has been optimized, making it lighter, easier to install, more cost effective (approximately 10% on cable system investment costs) and increasing its capacity. This has been achieved primarily by limiting the thickness of the lead alloy sheath.

To further increase the capacity of a cable link, the implementation of cross-bonding has been re-evaluated. The necessity for surge arrestors at a cross-bonding site has once again been shown both by calculations and measurements.
In conventional systems, relatively complex cabinets were used to house these arresters and provide earthing. In this paper, a new unearthed compact cross-bonding box is presented.

To further increase the reliability of cable protection in a mesh type grid, the inaccuracies of distance protection was studied. It is shown that a relatively straightforward correction method can be used to increase protection accuracy. The correction is achieved by adding the weighted sheath currents to the respective conductor currents. This method can relatively easily be implemented in existing cable systems. In cases of cross-bonded systems, a complication arises with the selection of the sheath current. These complications can easily be addressed in the future, when more advanced protection relays become available.

Literature

[1] G.P. van der Wijk et al, An Intelligent HV power cable system, Cigre 1996, paper 15/21/33-11.

[2] H.M.J. Willems et al, A new generation of HV and EHV extruded cable systems, Cigre 1995, paper A.1.6.

[3] Granadino R. et al, Undergrounding the first 400kV transmission line in Spain using 2500mm2 XLPE cables in a ventilated tunnel', Jicable 2003, paper A.1.2.

[4] Mikkelsen S.D. et al, New 400kV underground able system project in Jutland (Denmark), `Jicable 2003,
paper A.4.3.

[5] R.G. Schroth et al, EHV XLPE cables, experience, improvements and future aspects, Cigre 2000, paper 21-104.

[6] H.T.F. Geene et al, Comparison of thermal effects on XLPE insulated medium voltage cables with solid and stranded aluminium conductors, Cired 1991.

[7] HD632 S1/A1, July 2002, 'Power cables with extruded insulation and their accessories for rated voltages above 36kV (Um=42kV) up to 150kV (Um=170 kV).

[8] IEC60287-1-1 (November 2001), Electric cables – calculation of the current rating – current rating equations (100% load factor) and calculation of losses.

[9] IEC 60287-1-2 (November 2001), Electric cables – calculation of the current rating – Thermal resistance.

[10] IEC 60949 (1988), Calculation of thermally persmissible short-circuit currents, taking into account non-adiabatic heating effects.

[11] Skipper, D.J.: The design of specially bonded cable circuits (part II), Electra No 47 (1976).

[12] Guide to the protection of specially bonded cable systems. Electra 128 1990), pp. 47- 61, Cigré WG 21.07.

[13] W.F.J. Kersten, J.H. Stevenhage. Non-linearity of short-circuit impedance of PE power cables. IEEE Conference on Power Cables and Accessories 10 kV to 180 kV, London, 1986,Conference Publication nr. 270 pp. 26-30.

[14] The design of specially bonded cable systems. Electra 28 (May 1973), pp. 55-81, Cigré WG 21.07.