International Conference on Electricity Distribution

# Test Recommendations for Ground Screen Power Cable Connections

Working Group 2017-1

**Working Group**

# Final Report

# Test Recommendations for Ground Screen Power Cable Connections



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# Table of contents

Members of the Working Group ..... 3
List of Abbreviations ..... 6
Summary of the report ..... 8
1 Introduction ..... 9
1.1 Background and Scope of the Working Group ..... 9
1.2 Structure of the Final Report ..... 9
1.3 Background and Scope of the Working Group ..... 9
2 Cable Screens and Metallic Laminate Design Types for the Distribution Network ..... 11
2.1 Distribution Cable Types ..... 11
2.1.1 Paper cables ..... 11
2.1.2 Polymeric cables ..... 12
2.2 Distribution Cable Accessories ..... 12
2.3 Metallic Screen Connection Designs ..... 13
3 Reported Service Failures Due to Thermal Overheating at Screen Connections – Cases ..... 16
3.1 Case 1: Missing Laminate Grounding ..... 16
3.2 Case 2: Screen Interconnection and Wrong Installation of 630 $mm^2$ XLPE Cable ..... 17
3.3 Case 3: Wrong Dimensioning of 630 $mm^2$ XLPE Cable ..... 18
3.4 Case 4: Al Screen Fault of 630 $mm^2$ XLPE Cable ..... 18
3.5 Case 5: Al Screen Fault of 630 $mm^2$ XLPE Cable ..... 19
3.6 Case 6: Al Screen Fault 1200 $mm^2$ XLPE Cable ..... 21
4 Test Recommendations for Screen Power Cable Connections ..... 23
4.1 Flowchart Diagram for Testing ..... 24
4.2 Test Screen Currents ..... 25
4.3 Test Setup ..... 26
4.3.1 Test Objects ..... 26
4.3.2 Voltage Measurement Point ..... 27
4.3.3 Equalization points ..... 28
4.3.4 Test Circuits ..... 28
4.4 Resistance Measurements ..... 32
4.4.1 Instrument Accuracy ..... 32
4.4.2 Measurement Intervals ..... 33
4.4.3 Resistance of The Reference Cable ..... 33
4.5 Temperature Measurements ..... 33
4.6 Heat Cycle Test Programme ..... 33

4.7 Short-Circuit Test Programme ... 34
4.8 Assessment of Results and Acceptance Criteria ... 35
4.8.1 Visual Inspection ... 35
4.8.2 Screen Connection Device Temperature ... 35
4.8.3 Contact Resistance ... 35
4.8.3.1 Contact Resistance Factor ... 35
4.8.3.2 Initial scatter $\delta$ ... 37
4.8.3.3 Resistance factor changes $Y_A$ and $Y_B$ ... 38
4.8.3.4 Resistance factor ratio $\lambda$ ... 38
4.9 Test Report ... 39
4.10 Evaluation of Changes and Modifications in a Prequalified System ... 40
5 References ... 41

## List of Abbreviations

| Symbol | Unit | Description |
|---|---|---|
| $\alpha$ | $K^{-1}$ | Temperature coefficient of resistance at 20°C |
| d | mm | Length between two screen connections on a piece of cable |
| d' | mm | Length between adjacent screen connections |
| I | A | Direct current flowing through a connection during resistance measurement |
| $I_{NC}$ | A | Alternating current necessary to maintain the reference cable conductor at its equilibrium temperature |
| $I_{NS}$ | A | Alternating current necessary to maintain the reference cable screen at its equilibrium temperature (chosen in Table 4-1) |
| $I_{RS}$ | A | Direct current flowing through the reference cable screen during resistance measurement |
| k | | Connector resistance factor |
| $k_n$ | | Connector resistance factor at $n^{th}$ heat cycle (n=0-500) |
| $\ell_{cs}$ | mm | Length of metallic screen being a part of the current path between voltage measurement points |
| $\ell_j$ | mm | Length of screen connection device |
| $\ell_{RS}$ | mm | Length of reference cable screen between measurement positions |
| $\ell_{RS}$ | mm | Length of reference cable |
| R | Ω | Measured resistance between voltage measurement points, corrected to 20°C |
| $R_j$ | Ω/m | Resistance of connector, corrected to 20°C |
| $R_r$ | Ω/m | Measured screen resistance on reference cable between measurement points, corrected to 20°C |
| $R_{r\theta}$ | Ω/m | Measured screen resistance on reference cable on reference cable between measurement points |
| $s_0$ | | Standard deviation |
| $t_1$ | min | Heating time |
| $t_2$ | min | Time necessary for the screen connection devices and the reference conductor and screen to cool to a value equal to or less than 35°C |
| U | V | Potential difference between measurement positions while current I is applied |

| | | |
|---|---|---|
| $U_{RS}$ | V | Potential difference on metallic screen between measurement positions on reference cable while current I is applied |
| $Y_A$ | | Change in resistance before short-circuit |
| $Y_B$ | | Change in resistance after short-circuit |
| $\delta$ | | Initial scatter of screen connections |
| $\theta_{RC}$ | °C | Temperature of the reference cable conductor determined in the first cycle |
| $\lambda$ | | Resistance factor ratio of screen connections |
| $\overline{K_0}$ | | Mean value of connector resistance factor at cycle 0 |

## Summary of the report

This technical brochure addresses the issue of cable failures where the failure sites are close to or at the accessories as joints and terminations. The reported failures most often involve large cable cross-sections, including high conductor currents and induced currents in the metallic cable screens. The root cause for the failures addressed in this technical brochure is local overheating due to a too high contact resistance of the metallic unit connecting the ground screens of the cable with the earthing wires of the joint / termination. The polymeric cable materials have a limited maximal temperature, and the overheating can cause melting of the thermoplastics and over time oxidation of the insulation system in the cable and accessory. Melting of metallic cable screen members into the cable core (insulation screen) has also been observed. Some of the failures are due to incorrect installations of the metallic connecting devices.

There are yet no international standardized test protocols for ground screen connections that addresses their ampacity. The root cause analysis indicate that it is the long term and high cyclic current loading of the connections that over time generate the failures.

This brochure includes several cases where cable failures have occurred due to local overheating at screen connections, or installation where very high currents are involved (yet not failed). Large conductor cross-sections (≥ 630 $mm^2$) are often involved, resulting in very large induced currents (>100 A) for solid bonded metallic screens. The ampacity of the involved metallic connections is questioned.

The number of combinations of different cables, accessories and metallic screen connection designs are huge. For example, a ground screen connection could include either an aluminium or copper laminate in addition to the copper screen wires of the cable. These metallic members must be properly connected. The brochure gives some examples of cable and connection designs, but do not cover all the possible design types and combinations that are available today.

The proposed test of metallic ground screen connections includes thermal cycling and short-circuits applied to the test loop. Further work is required to establish well proven acceptance criteria.

*Sverre Hvidsten, Convenor of the Working Group, July 2021*

*Kristian Solheim Thinn, Secretary of the Working Group, July 2021*

# 1 Introduction

## 1.1 Background and Scope of the Working Group

Severe service failures due to improper laminate and screen connections of power cables are occurring in the distribution and transmission networks, but also in offshore wind farms. Such failures are often associated with very high repair costs, interruption of delivered power and even personnel safety issues when the cable failure occurs in for example a substation. As the cable and accessories often are produced by different manufacturers, the compatibility of different designs is also an issue. This is generally not covered in the installation manuals.

Severe failures are often located close to power cable accessories such as joints and terminations but have also occurred at random positions along the cable route. Today no qualification tests or standards exist to test the ampacity of the screen connections systems. The actual ampacity of the metallic screen connection devices is therefore generally not known or assessed.

Information from analysis of failed cable systems, test reports and on-going research projects have been used to propose the qualification test procedures for metallic screen connections in joints and terminations given in this brochure. This test program can be used by suppliers and distribution system operators to assess the ampacity in existing and new screen connection designs as well as the combination of accessories and cables from different manufacturers.

## 1.2 Structure of the Final Report

The final report of the Working group consists of the following main parts:

i) Cable Screens and Metallic Laminate Design Types for the Distribution Network (Section 2)
ii) Reported Service Failures due to Thermal Overheating at Screen Connections (Section 3)
iii) Test Recommendations for Power Cable Screen Connections (Section 4)

The first part gives an overview with examples of different designs of distribution network cables with focus on the type of ground screens, cable joints and different metallic screen connections.

The second part includes reported failures with root cause due to local overheating at or near metallic cable screen connections. The failures reported are examples from different countries.

The final part includes the test recommendation for power cable screen connections. The test recommendation includes guidelines for sample number and preparation, and temperature and resistance measurements.

## 1.3 Background and Scope of the Working Group

During normal operation (symmetrical current load at power frequency), currents are induced in the cable screens due to the magnetic field resulting from the conductor currents, in addition to the capacitive charging currents. The magnitude of the induced currents depends on the installation geometry (flat or trefoil), the magnitude of the conductor currents, and the metallic screen design (i.e. geometry and electrical conductance of the screen elements).

In addition to normal operation, the cable screens must be able to carry transient currents originating from induced voltages during short-circuit and ground fault conditions [1].

Currently there are no international standards for specification of test procedures to determine the ampacity of screen connections for different cable system designs. Furthermore, product information from the suppliers indicates that basis for design and test criteria is not uniform, and tests are not performed reflecting relevant operation and fault scenarios [1].

This document is partly based on standards and recommendations from:

- IEC [2-7]
- CENELEC [8, 9]
- CIGRÉ [10]

During the lifetime of a medium and high voltage cable system in electricity distribution or industrial networks, the screen connections will be subjected to induced currents. The screen connection's ability to handle the induced currents should be tested in advance of installation, preferably in a qualification test for such accessories.

The objective and area of interest for of this document and the working group has been to propose qualification tests for screen connections in medium voltage cable systems covered by IEC 60502/CENELEC HD620 ($U_m$ < 42 kV). The working group is of the opinion that the same testing philosophy could be adapted to LV, HV and EHV cable systems as well.

The qualified equipment and assembly procedures should ensure that the screen connections (if installed correctly) will not experience overheating during the cable systems' expected lifetime. Single core and three core cables, and most types of cable screens such as wires, laminate, tapes, lead, corrugated metal, or a combination of these can be covered by the test. Screen wire cables using (only) connectors already tested and approved according IEC 61238-1-3, [7] are considered to be qualified.

The electrical tests specified in this recommendation aim to prove the suitability of screen connections for normal operating conditions and short-circuits. They do not necessarily apply to situations where the screen connection is subjected to lightning impulses, excessive mechanical vibration, shock or wet/corrosive conditions. In these instances, the tests in this recommendation may need to be supplemented by special tests which are not covered here.

When a screen connection design meets the requirements of this recommendation, it is expected that in service:

a) the resistance of the screen connection will remain stable over time.
b) the temperature of the screen connection will be of the same order or less than that of the cable screen, and below the maximum rated temperature for the cable materials.

# 2 Cable Screens and Metallic Laminate Design Types for the Distribution Network

This section gives an overview of examples of different designs of distribution network cables with focus on the type of ground screens, cable joints and different metallic screen connections.

## 2.1 Distribution Cable Types

### 2.1.1 Paper cables

Well over 100 years ago, impregnated paper was recognised as a suitable insulation medium for distribution voltages up to 10 kV, providing it was protected from moisture ingress. Before this, paper was only used as insulation material for telephone cables. Its use at distribution voltages required multiple paper layers to be applied to build up a sufficient thickness to withstand electrical breakdown.

To provide a compact cable, conductors were shaped and individually insulated to withstand the rated phase to phase voltage – i.e., half the required thickness on each core, and then covered with an additional 'belt' insulation layer to provide sufficient insulation thickness for each phase to withstand phase to earth voltage.

The cables were then sealed with a lead or aluminium sheath for moisture protection, and further mechanical protection added (steel tapes or wire armour). This is the classical 'belted' cable construction as depicted in Figure 2-1.

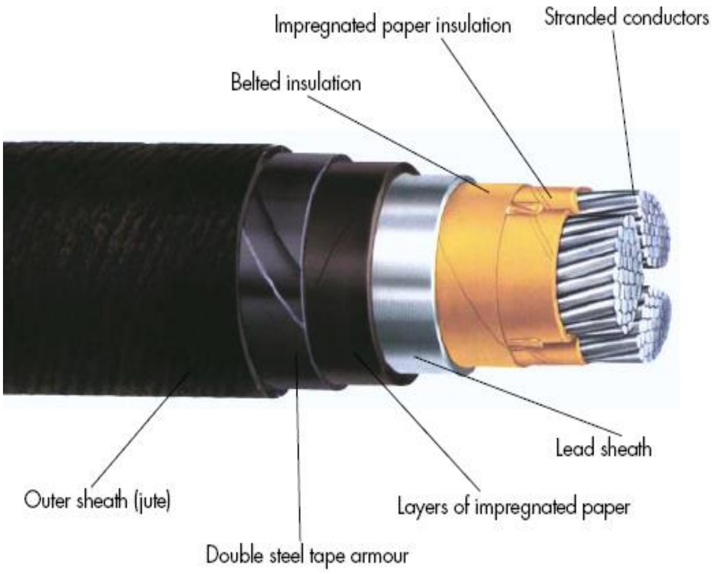



Figure 2-1: Paper insulated cable.

An improvement to this design was the invention of Martin Höchstädter in 1913 where a metallized paper screen over each core was introduced (US-Patent 1,199,789 and DRP 288 446). This transformed the non-radial field that existed within the insulation to a radial field, which created more even electrical stress distribution throughout the insulation. This in turn meant that the paper insulation could be used for voltages in excess of 20 kV with the same design of cable sheath as the belted cable.

### 2.1.2 Polymeric cables

The introduction of polymeric insulated medium voltage cables in the 1970s was the beginning of a tremendous diversification in cable constructions. Figure 2-2 shows just a few of more than 100 medium voltage cable designs that are possible. The screen of such modern cables can be helically applied copper wire or copper tape, extruded lead, or aluminium, laminated aluminium tape, aluminium wire, or even steel mesh. A combination of different screening and armouring solutions is also quite common, for example the combination of copper wires and laminated aluminium for screening of both medium and high voltage cables.

The medium voltage cable of the future may be 100% aluminium due to the cost and weight advantages it would provide. However, in the past, connection to aluminium screens has been shown to be somewhat unreliable. An effective connection method (or device) is needed to ensure the cable (and the public) are protected from harm in the event of a cable failure. Such a method or device must be proven to remain effective over long time.

Figure 2-2: Diversification in the cable design of polymeric cables.

## 2.2 Distribution Cable Accessories

For cables with copper wire screens, numerous cable accessories enable a direct screen connection by a type tested connector (Figure 2-3). But more and more accessories, especially those of the "all in one" design do not allow this possibility, even for cables with copper wire screen.

Figure 2-3: Direct screen connection by a compression connector.

These accessories, when used on cables with copper tape screen, lead sheath or aluminium laminate screen require a special screen connection device. In case of transition joints between paper insulated cables and polymeric cables, two different screen connection devices are often needed to make the screen connection. A number of different screen connection methods are depicted in the following section.

## 2.3 Metallic Screen Connection Designs

For all paper insulated cables the lead sheath has proven to be the best protection for the oil impregnated paper insulation against moisture. Traditionally, the screen connection in a joint or termination was implemented by the jointing tradesman soldering or lead wiping a copper braid onto the lead sheath. In more modern transition joints the soldering of a copper braid is often replaced by a constant force spring (roll spring), see Figure 2-4.

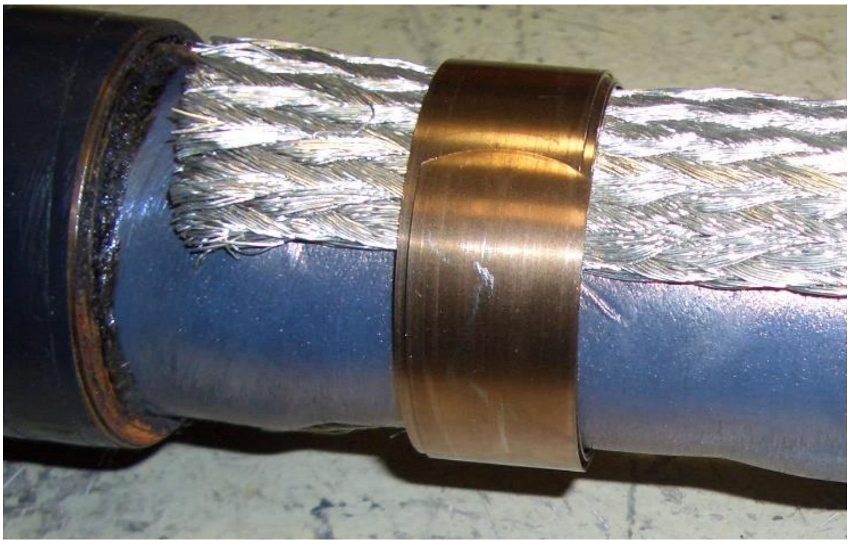


Figure 2-4: Screen connection by a copper braid and constant force spring.

To obtain cost reduction and lighter cable weight noted previously, the screen designs for medium voltage cables of the future will probably favour laminated aluminium screens. In case of high voltage cables, a combination of copper wire screen and laminated aluminium sheath is a cost optimal and installation friendly solution that is regularly used today. For these screen solutions an installation friendly and reliable screen connecting system is required.

The most critical screen connection for these cable designs is the connection to the laminated aluminium sheath.

Some of the commonly used connecting solutions are shown in Figure 2-5 to Figure 2-9.

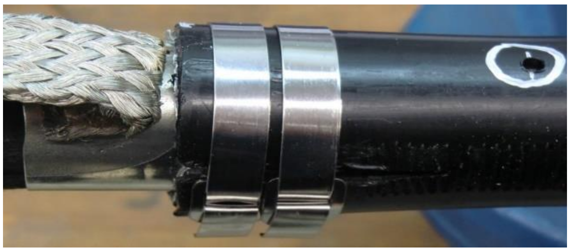


Figure 2-5: Screen connection by a screen plate and cable clamp ('Ligarex') (Main french networks solution solution).

Figure 2-6: Screen connection by a copper braid, "cheese grater" contact plate and cable clamp ('Ligarex').

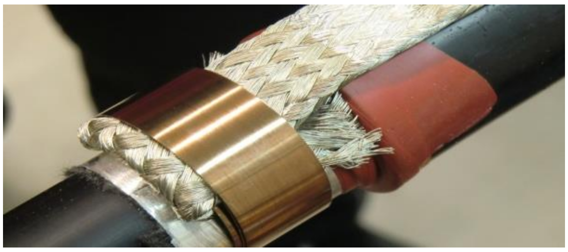


Figure 2-7: Screen connection by a copper braid and constant force spring.

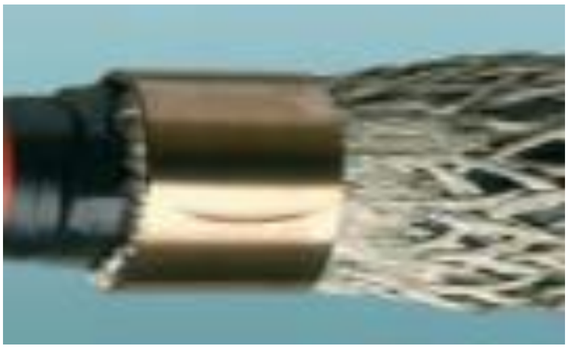


Figure 2-8: Screen connection by a copper mesh tube and constant force spring.

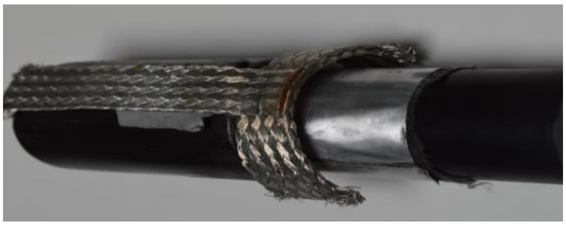


Figure 2-9: Screen connection by a copper braid for a combination with heat or cold shrink tubes.

# 3 Reported Service Failures Due to Thermal Overheating at Screen Connections – Cases

This section gives an overview of failures reported with root cause due to local overheating at the metallic cable screen connection. The failures reported are examples from different countries.

## 3.1 Case 1: Missing Laminate Grounding

A 24 kV cable with a shield made of copper wires and aluminium laminate tape was installed as a solidly bonded system with both ends of the copper wires connected directly to earth. However, the aluminium laminate was not bonded to the copper wires at these points, instead relying on the intermittent and random direct metallic connection to the copper wires throughout the length of the cable. The path of circulating current through these random, high resistance contacts caused local overheating at the contact points (and hence of the insulation) and resulted in many cable failures and significant repair costs.

After many costly repairs, a decision was taken to also bond the aluminium laminate to earth at both ends of the route utilising a soldering technique. This connection method proved to be unreliable and was later replaced using an abrasive plate technique.

The screen bonding was then changed to be grounded at one end only, thus eliminating any circulating currents, but allowing an induced standing voltage (proportional to load current and length of cable) to be present on the un-earthed end. This voltage was found to be less than 20 V which was acceptable for this installation.

Another example with the same type of cable was observed, this time a problem associated with cable joints overheating at the screen connections. Copper wires and copper mesh of the joint kit were not interconnected directly but were interlaced by two layers of roll-spring clamps. Roll-springs are made from stainless steel which has a significantly higher resistance than copper. In the proximity of the roll-springs, there was significant heating and discolouration of XLPE insulation. Further, due to the pressure exerted by the roll-springs and the elevated temperature, the copper screen was pressed into the insulation resulting in an uneven interface between layers.

Figure 3-1: Missing laminate grounding (66 kV 150 mm$^2$ Al TSLE).

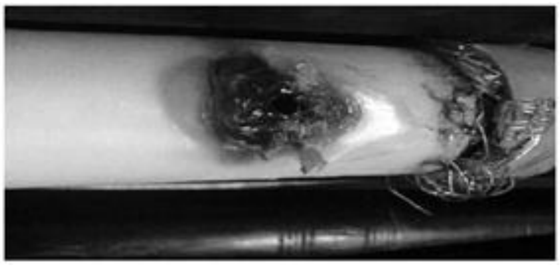


Figure 3-2: Missing laminate grounding (24 kV 1200mm$^2$ Al TSLF).

Figure 3-3: Missing laminate grounding (24 kV 400mm$^2$ Al TSLE), [11].

## 3.2 Case 2: Screen Interconnection and Wrong Installation of 630 mm$^2$ XLPE Cable

A fault was detected on a single core 630 mm$^2$ aluminium cable shortly after installation of new joints. The metallic screens of the cables were originally grounded only at one point (single-point bonding). Joints were installed on the cable line in such a manner that their screens were interconnected (as seen in Figure 3-4) which led to a creation of screen loops, thus allowing circulating current to flow. According to calculations, the screen current in such a configuration could reach 50 A, however, devices were dimensioned for only 20 A.

Wrapped resin joints (blue) were additionally installed between new joints and terminations and bonded to the earth. Several joints broke down shortly after commissioning. Resin was found between screen device ("cheese grater") and the cable screen during the investigation. Cable insulation faults were found near screen connections. Unfortunately, the resin contributes to insulate the screen connection, forcing more screen current to pass through semi-conductor layer of the cable, thus creating hot spots.

High screen current (50 A) together with the presence of resin contributed to the damage of the external semi-conductive layer of the cable and resulted in a fault in the cable insulation.

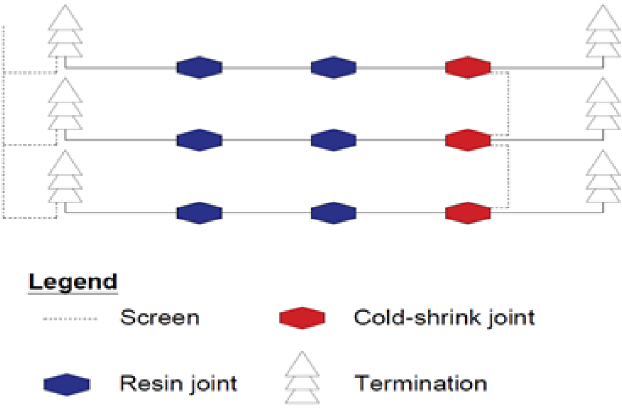



Figure 3-4: Scheme of cable and joints installation.

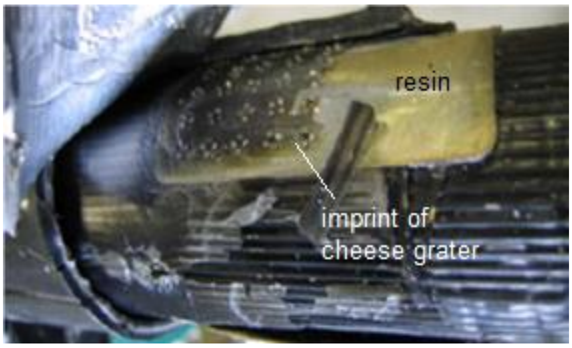



Figure 3-5: Presence of resin between "cheese grater" and Al cable screen.


Figure 3-6: Damage of external semi-conductive layer with a new grater to show the initial position.

Figure 3-7: Fault under "cheese grater".

## 3.3 Case 3: Wrong Dimensioning of 630 mm² XLPE Cable

A fault has occurred on a screen connection during the flow of a short-circuit. The cable had 630 $mm^2$ copper conductor cross-section with aluminium laminated screen of 1 mm thickness. A "cheese grater" system was used to provide the screen connection and was dimensioned for a short-circuit screen current of 2,5 kA/1 s. However, after the passage of the short-circuit current, the "cheese grater" was damaged as can be seen in Figure 3-8. The exact value of the short-circuit current is unknown but it must have been substantially higher than 2,5 kA.

Figure 3-8: Cable outer sheath and rest of screen device ("cheese grater").

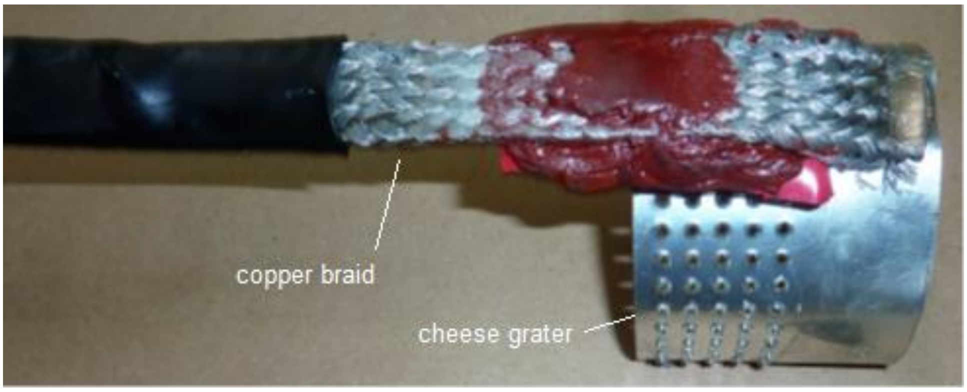


Figure 3-9: New "cheese grater" and sheath connection.

## 3.4 Case 4: Al Screen Fault of 630 mm² XLPE Cable

A fault on 20/22 kV cable occurred due to poor penetration of Al screen by the "cheese grater". Unfortunately, not much is known about this failure because there has been an ongoing investigation of the fault. Short-circuit current is unknown since the customer has not monitored it. The reason of the fault might be a wrong installation creating poor contacts and resulting in hot spots, thus the consecutive failure.

Figure 3-10: Damaged cable with ligarex.

Figure 3-11: "Cheese grater" and aluminium screen and laminate.

Figure 3-12: Comparison of a damaged "cheese grater" and a new grater.

Figure 3-13: Damaged cable with ligarex and aluminium screen.

## 3.5 Case 5: Al Screen Fault of 630 mm$^2$ XLPE Cable

Incorrectly installed roll-springs was a reason for a fault on a 38 kV and 630 mm$^2$ Al cable from a wind farm to shore. The cable was approximately 27 km long with cold-shrink joints applied.

Investigation revealed that the cable was loaded at 60 % of the maximum allowable ampacity when the fault occurred, and loading had never exceeded 70 % of the ampacity of the cable.

Figure 3-14 and Figure 3-15 show the faulty cable joint. Heat-shrink sleeve is not shrunk down over the joint but wrapped over for an extra mechanical protection. Incorrectly installed roll-spring generated a large amount of heat that melted glue on the heat-shrink sleeve that was wrapped around the joint.

Figure 3-14: Faulty 630 mm$^2$ Al cable.


Figure 3-15: Joint opened at roll spring location.

Figure 3-16 shows unrolled roll-spring where the sealing mastic melted into the roll-spring interlays and increased contact resistance. After further unwrapping of the roll-spring (Figure 3-17), it is clearly seen that the screen is completely mixed with the sealing mastic.

Figure 3-16: Unrolled roll spring.

Figure 3-17: Further unwrapping of roll spring.

## 3.6 Case 6: Al Screen Fault 1200 mm² XLPE Cable

The 24 kV 1x1200 mm² single core cables with Al conductor were installed in a hydropower plant with an annual production of about 2 TWh/year. Several cable groups connecting the generators to the grid were installed. Figure 3-16 shows an example of single core cables installed in trefoil configuration in three groups for one of the generators. The three cable groups were placed on cable ladders in a tunnel. The air gap was 140 mm between Group 2 and 1, and 170 mm between 1 and 3.

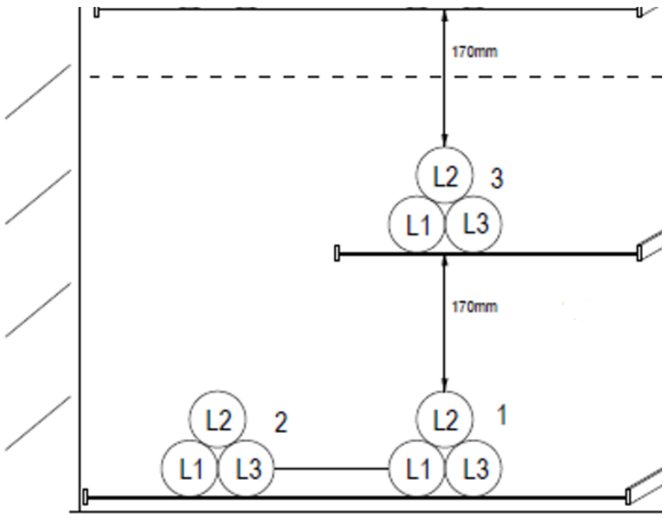



Figure 3-18: Cable layout for one of the generators organized in three groups (1-3). The numbers (L1-L3) indicate the different phases for the groups.

A semi-conductive swelling tape was helically applied to the cable core, and copper wires were then positioned on these tapes (50 mm²). Then a semi-conductive tape and an insulating swelling tape (interlocked) were helically applied on to the copper wires. Within the polymeric outer sheath, a water-tight aluminium laminate with a thickness of 200 µm was applied (38 mm²). The single core cables were installed in trefoil configuration. The longest cable section was 450 meters.

After one year in service a termination failure occurred, but no further examinations were performed as an installation failure was expected. The next year a new cable failure occurred, and indications of overheating was detected in other cable sections as deformations of the outer sheath at cable clamps. Then it was suggested that missing connections between the Al laminate and the copper screen wires, which at that time was the frequent practice for cable installation projects, were the root cause to the observed local overheating.

The Al laminate and copper screens were connected and grounded in both cable ends. For a symmetric load of 2700 A in each phase, i.e. about 900 A in each conductor, it is calculated that the currents in the copper screens are high in magnitude, in the range of 120 – 130 A. The induced currents in the Al laminate are in the range of 60 – 64 A. The total induced current to the ground (or bypassing cable joints) is in the range of 180 – 194 A. If the laminate and screen wires are not properly connected at the terminations, the induced current in the laminate may be transferred through an accidental connection to some few copper wires causing high local temperature rise. See results for all three cables for Phase 1 in Table 3-1.

Table 3-1 Results from current calculation for Phase L1.

| Core No. | Re () [A] | Im () [A] | Abs () [A] | % of conductor current |
|---|---|---|---|---|
| 1 – conductor | 871 | 6.95 | 871 | |
| 2 – conductor | 899 | -53.9 | 901 | |
| 3 – conductor | 931 | 47.0 | 932 | |
| 1 – Cu screen | -31.1 | -127.5 | 131.2 | 15.1 |
| 2 – Cu screen | -21.9 | -129.0 | 130.8 | 14.5 |
| 3 – Cu screen | -31.0 | -117.5 | 121.5 | 13.0 |
| 1 – Al sheet | -14.2 | -61.9 | 63.5 | 7.3 |
| 2 – Al sheet | -10.4 | -62.7 | 63.6 | 7.1 |
| 3 – Al sheet | -13.9 | -57.7 | 59.4 | 6.4 |

Based on these calculations, the Al laminate and the copper screen were disconnected from ground in one end. At the disconnected side, the Al laminate and the ground screen wires were not connected. For a symmetric load of 2700 A in each phase, the induced voltage in the copper screens were less than 25 V for the 450 m long cable section. The induced voltage was higher in the Al laminate than in the copper screen, dependent on the spacing between the screens. In case of a spacing of 2.5 mm the induced voltage will be about 7% higher in magnitude, but decreased to 1-2 % in case of a spacing of 1.0 mm.

When the Al laminate and the Cu screen wires were connected also at the open-end side (still disconnected from ground), the probability for current loops at random contact spots along the cable route was reduced. The magnitude of the induced currents depends on the spacing between the screens, but less than 4 A for trefoil configuration. This current will increase with increased distance between each core at the bus bar connection (e.g., from trefoil to flat formation). This solution was finally used for this installation.

# 4 Test Recommendations for Screen Power Cable Connections

In this Section, laboratory test recommendations for cable screen connections are presented. The recommendation has its basis in the electrical part of the IEC 61238-1-3 standard, [7], i.e., it presumes that the ageing of electrical contacts is caused by two processes. First the contact force can become smaller by the creeping of the materials in the connection. If the contact force is smaller than a minimal contact force, then the contact resistance will be significantly higher. The second process concerns chemical reactions on constriction areas.

However, there are clear differences between this recommendation and the IEC 61238-1-3 standard, e.g. regarding the test set-up: The use of two current circuits, the use of insulated conductors, the use of inherent equalizers, the number of short-circuits and temperature cycles, and in the definition of the acceptance requirements.

The recommendations shall be applied to metallic cable screen connection devices not covered by IEC 61238-1-3.

The Section is divided in five parts. The first part (4.2) describes how to determine the test screen current used in the heat cycles and short-circuit test. In the second, (4.3), the test setup is defined. Next, the resistance and temperature measurements are described (4.4-4.5). Then, the test programme (heat cycles and short-circuits) is presented (4.6-4.7). Finally, assessment of results, test report and evaluations of changes/modifications to devices are given (4.8-4.10).

## 4.1 Flowchart Diagram for Testing

A flowchart diagram for testing of screen connection devices is given in Figure 4-1.

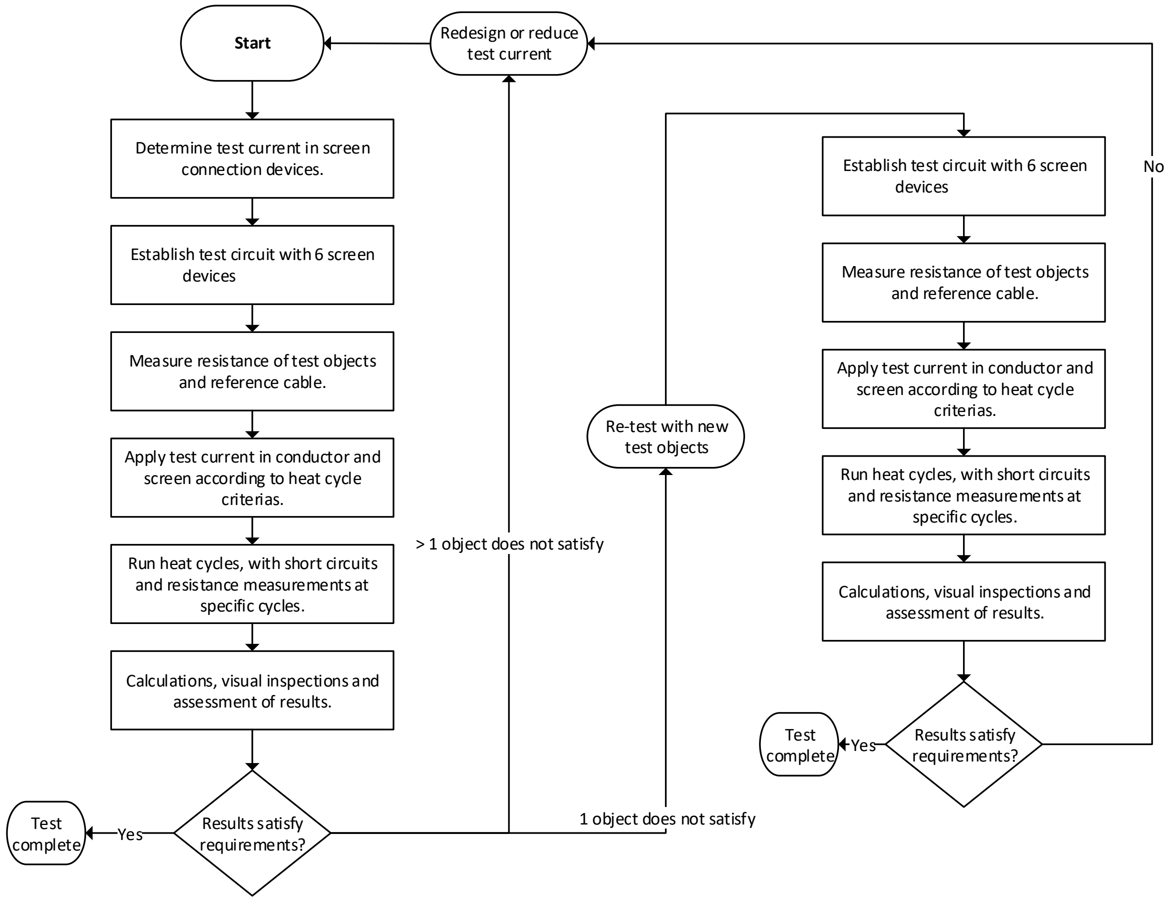



Figure 4-1: Flowchart for implementation of screen connection test.

## 4.2 Test Screen Currents

The screen current ($I_{NS}$) applied during the heat cycles shall be at least 20% higher than the maximum allowed screen current in the screen connection device during operation ($I_N$), ($I_{NS} \geq 1.2 \cdot I_N$). The current shall be alternating at power frequency (50 or 60 Hz). If the test is performed for a specific application, $I_N$ can be determined prior to the test through simulations and/or trials.

Changes in the loop resistance will affect the test current. The screen current level shall be kept stable within a limit of $I_{NS}$ [0,+10%] during the test.

A set of recommended test classes for screen connection devices are shown in Table 1. Each test class corresponds to a maximum operating current in the screen connection device. A screen connection device with test class 25 can in service be exposed to currents less than or equal to 25 A. For test class 25, the minimum screen test current is 30 A.

Table 4-1. Recommendation for Test Classes.

| Test Class | Maximum Operating Current, $I_N$ [A] | Minimum Screen Test Current, $I_{NS}$ [A] |
|---|---|---|
| Class 25 | ≤ 25 | 30 |
| Class 50 | ≤ 50 | 60 |
| Class 100 | ≤ 100 | 120 |
| Class 150 | ≤ 150 | 180 |
| Class 200 | ≤ 200 | 240 |
| Class 250 | ≤ 250 | 300 |
| Class 300 | ≤ 300 | 360 |
| Class $I_N$ | ≤ $I_N$ | ≤1.2· $I_N$ |

The screen current applied during short-circuit shall be equal to or higher than the maximum short-circuit current the screen connection device will be subjected to in service. It can be chosen in accordance to the standard of which the cable screen itself has been tested, for example according to CENELEC HD 620, [9], IEC 60986 [6] ($U_m$=7,2-36 kV) or IEC 61443[5] ($U_m$>36 kV). Alternatively, it can be chosen based on considerations of the use of the cable or national standards for maximum allowed short-circuit currents.

## 4.3 Test Setup

The screen connection devices shall be installed as specified in their respective assembly procedures. The assembly procedure used shall precisely indicate all assembly steps and tools, materials, tightening torques etc. Note that only the actual screen connection device needs to be installed in the test loop and not the complete joint or termination body. If the screen connection device is an integrated part of the joint or termination body these devices need to be included.

The test loop shall be installed in a location with stagnant air condition. The ambient air temperature in the test location shall be between 15°C and 30°C. The test loop may be of any shape, provided that it is arranged in such a way that there is no adverse effect from the floor, walls, ceiling or neighbouring conductors.

Retightening of bolts or screws (if any) of the tested screen connection devices or any other part influencing the screen connection contact resistances during the test is not permitted.

### 4.3.1 Test Objects

The test objects are defined between two voltage measurement points. The suitable measurement points will depend on how the metallic screen(s) and screen connection device(s) are constructed.

One of the three alternatives below shall be used. The voltage measurement points and equalizer points are further described in Sections 4.3.2 and 4.3.3, respectively. The alternatives 1-3 are illustrated in Figure 4-2 for metallic screen(s) connected by one screen connection device. If two or more devices are connected, see Figure 4-3.

1. Test object alternative 1: Between the midpoint of two adjacent cables. This alternative can be used if the screen at the midpoint of the cables has an equalized contact surface, or if this can be made. The contact surface must be made accessible, such as by removing cable jacket.
2. Test object alternative 2: At the midpoint of two screen connection device links. This alternative can be used if the screen connection device link has an equalized contact surface, or if this can be made.
3. Test object alternative 3: Between the middle of two cable screen device links and midpoint of the cable. The number cables in the circuit may be reduced to ½ compared to the other two alternatives, see Section 4.3.4. This alternative can only be used for cable screens consisting of one metallic element, such as aluminium laminate, and where the screen connection device link has an equalized contact surface.

The screen connection devices shall be installed with a distance of 1 m (d) to limit thermal influence from adjacent screen connections. For large conductor cross sections, the distance may need to be increased. The distance between two test objects (d') must represent a real distance as if it was across a cable joint. Cable conductor links/joints are optional as some screen connection devices can be installed without cutting the cable.

At least one reference cable screen ($\ell_{RS}$) shall be installed in the test loop, $\ell_{RS}$ = 2 x d.

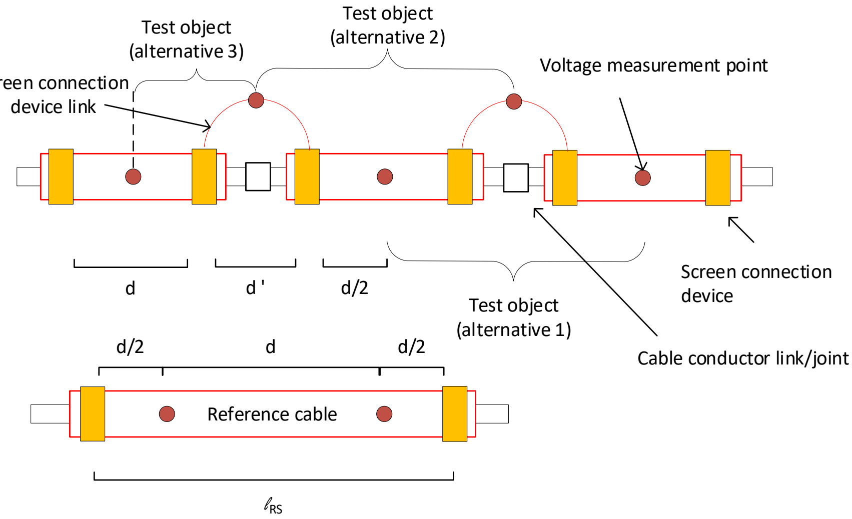



Figure 4-2: Lengths and measurement points of (upper) test cable with one screen connection device (lower) reference cable.

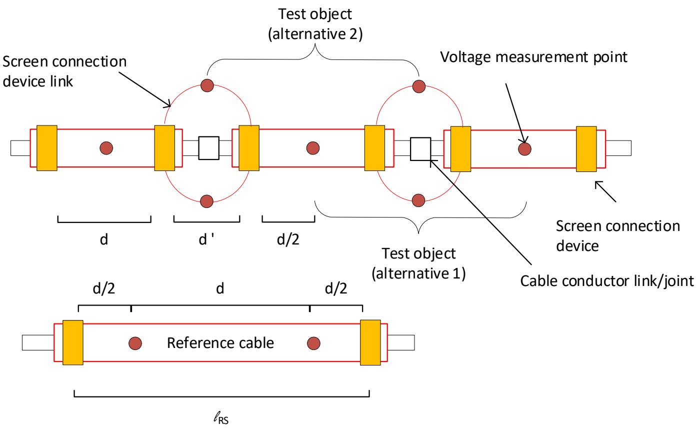



Figure 4-3: Lengths and measurement points of (upper) test cable with two or more screen connection device and (lower) reference cable.

### 4.3.2 Voltage Measurement Point

The voltage measurement points for the three alternative test objects defined in the previous section is detailed below. The measurements themselves are described in Section 4.4. If the metallic screen(s) are connected by one metallic connection device, the measurement points will be as seen Figure 4-4 a). If the metallic screen(s) are connected by two or more individual connection devices, see Figure 4-4 b).

At the voltage measurement points, the current must flow in a well-defined solid part like in an equalizer. For screen connection devices where there is no inherent voltage measurement point, such points need to be made. Further description of equalizers is given in Section 4.3.3.

1. Test object alternative 1 ($V_1$): The voltage shall be measured between the screen at the midpoints of the cable.
2. Test object alternative 2 ($V_2$ and $U_2$): The voltage shall be measured using the voltage measurement point on a screen connection device link, to the same measurement point on the following screen connection device link. For cables with two or more screen connection devices, i.e. with separate current paths, voltage measurement points shall be identified in all current paths. This is indicated as $V_2$ and $U_2$ in Figure 4-4 b).
3. Test object alternative 3 ($V_3$): The voltage shall be measured between the voltage measurement point on the centre of a screen connection device link to a point at the metallic screen at the cable, as shown in Figure 4-4 a).

Only one of the above test object alternatives shall be used, i.e. either alternative 1, 2 or 3.


(a) Voltage measurement connection points for a cable with one screen connection device.

(b) Voltage measurement connection points for a cable with two or more screen connection devices.

Figure 4-4: Voltage measurement alternatives $V_1$, $V_2/U_2$ and $V_3$ for test cable with (a) one or (b) two or more screen connection device(s).

### 4.3.3 Equalization points

Equalization points (or equalizers) shall be used when the voltage measurement point consists of two or more metallic elements, such as braids, mesh or multiple copper wires. When the voltage measurement point consists of one metallic element, such as aluminium laminate or cable lug, there is no need to make equalization points. The equalizers secure that the current path will be determined by the test objects and not how the feeder is connected. The equalizer points shall connect all metallic elements without introducing voltage differences between the different metallic elements in the equalizer points. The equalizer must be electrically and mechanically unchanged through the heat cycles and the short-circuit. For all practical purposes this means that the equalizer should be welded or soldered.

### 4.3.4 Test Circuits

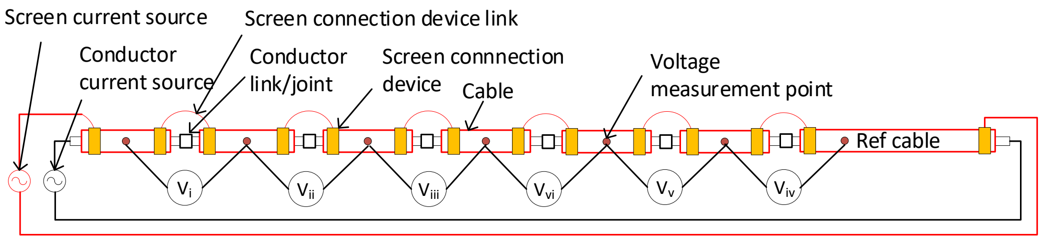
The test circuit shall consist of six test objects. These are indicated:

1. Test object alternative 1: Figure 4-5 a)-d).
2. Test object alternative 2: Figure 4-6 a)-d).
3. Test object alternative 3: Figure 4-7 a)-b).

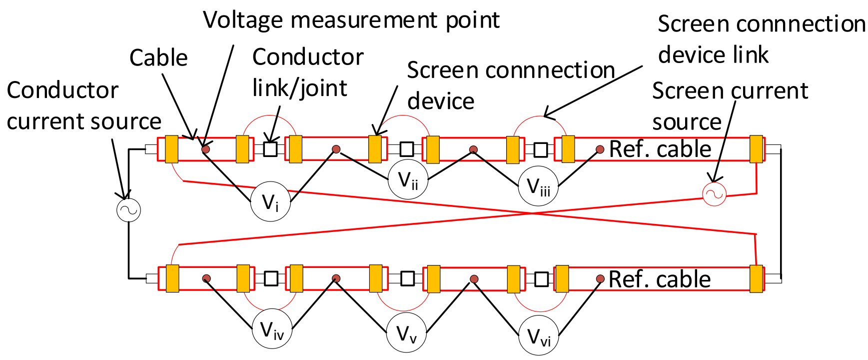
Depending on the test object alternative (1, 2 or 3 defined in Section 4.3.1), there are some differences in test circuit layout. Only <u>one</u> of the below test circuits shall be used for the chosen test object alternative. The appropriate will depend on design of screen(s) and screen connection devices(s). c) and d) are not applicable for test object alternative 3.

a) Single screen connection device. The resulting current through the screen is the combination of applied current by the screen current source and induced current by the magnetic field generated by the current in the cable conductor.
b) Single screen connection device – cancellation of induced screen currents. The resulting current through the screen is the applied current by the screen current source only. There will be no net induced current by the magnetic field generated by the current in the cable conductor.
c) Similar as a) but with two or more screen connection devices. Equalizers shall allow the screen current to distribute between the different screen conductors. One cable length shall be positioned between the equalizers and the test object to reduce end effects. Currents can in many cases be transferred between the different screen conductors in the cables.
d) Similar as b), but with two or more screen connection devices. Equalizers shall allow the screen current to distribute between the different screen conductors. One cable length shall be positioned between the equalizers and the test object to reduce end effects. Currents can in many cases be transferred between the different screen conductors in the cables.

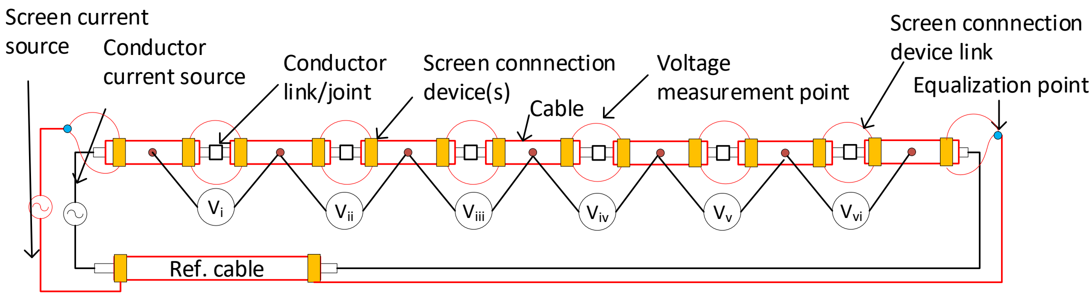
If the metallic screens and screen connection devices are constructed in such a way that the conductor links/joints are not needed for the test circuits, the conductor links/joints may be omitted. This will keep the insulation system of the cable intact.



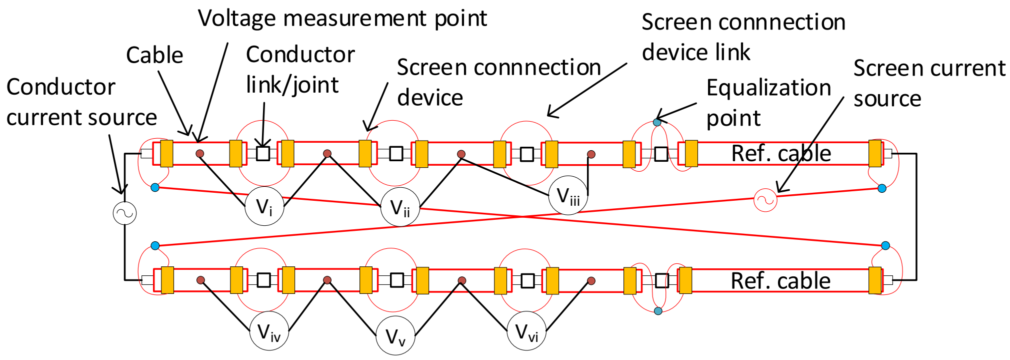

a) Single screen connection device.




b) Single screen connection device – cancellation of induced screen currents. One of the reference cables can be omitted.

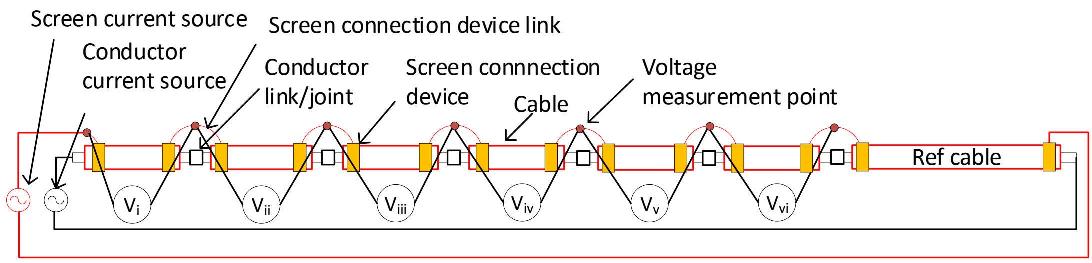



c) Two or more screen connection devices. Two devices are indicated in this sketch.

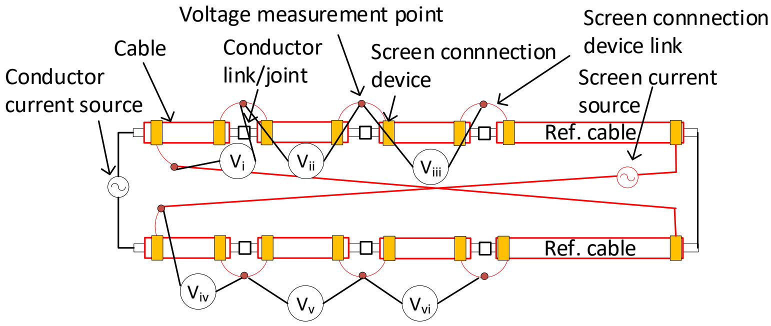



d) Two or more screen connection devices – cancellation of induced screen currents. Two devices are indicated in this sketch. One of the reference cables can be omitted.

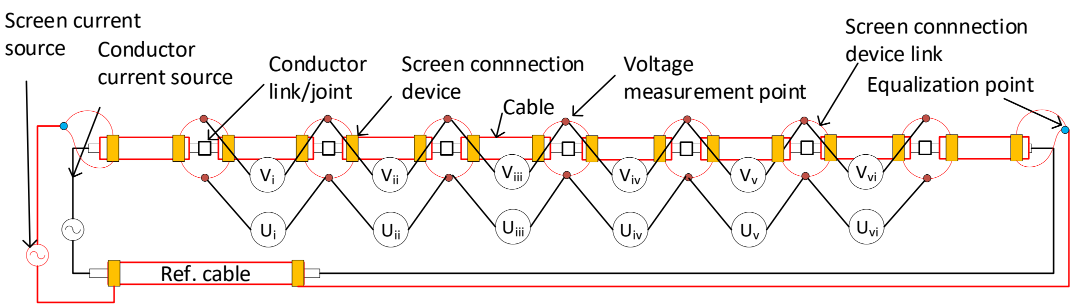
Figure 4-5: Test circuits for test object alternative 1. Voltages over the test objects to be measured as descried in Section 4.4.



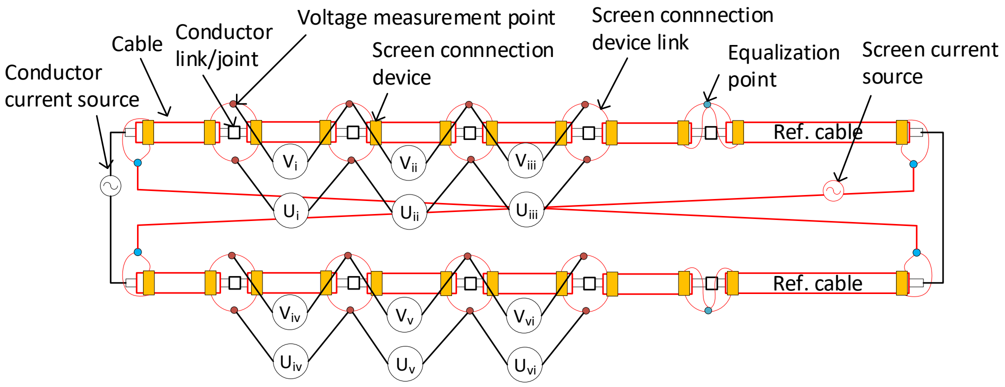

a) Single screen connection device.




b) Single screen connection device – cancellation of induced screen currents. One of the reference cables can be omitted.

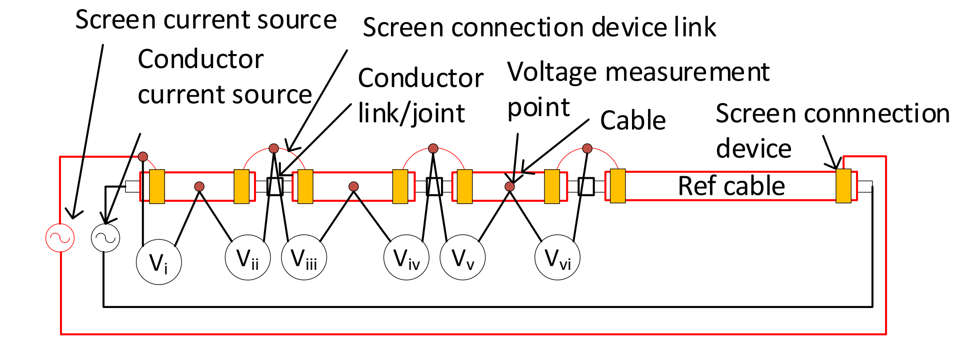



c) Two or more screen connection devices. Two devices are indicated in this sketch.

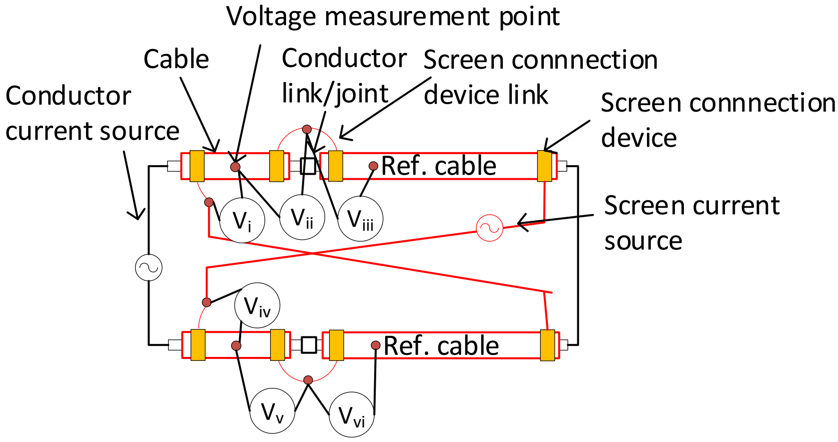



d) Two or more screen connection devices – cancellation of induced screen currents. Two devices are indicated in this sketch. One of the reference cables can be omitted.

Figure 4-6: Test circuits for test object alternative 2. Voltages over the test objects to be measured as descried in Section 4.4.




a) Single screen connection device.




b) Single screen connection device – cancellation of induced screen currents. One of the reference cables can be omitted.

Figure 4-7: Test circuits for test object alternative 3. Voltages over the test objects to be measured as descried in Section 4.4.

## 4.4 Resistance Measurements

### 4.4.1 Instrument Accuracy

Measurements of electrical resistances between the voltage measurement points shall be made at ambient temperature under steady temperature conditions in the test loop and test location. The ambient temperature shall be between 15 and 30°C.

The temperature of the screen connection devices and reference screen shall be recorded when resistance measurements are made. For direct comparison, the resistance values shall be corrected to 20°C. The accuracy of the resistance measurements shall be according to the following, similar as IEC 61238-1.

Indirect resistance readings:
– Voltage measurements shall have an accuracy within ±0.5 % or ±10 µV, whichever is the greater.
– Current measurements shall have an accuracy within ±0.5 % or ±0.1 A, whichever is the greater.

Direct resistance readings:
– Resistance measurements shall have an accuracy within ±1 % or ±0.5 µΩ, whichever is the greater when the instrument is calibrated against a certified standard resistance.

The measurements shall be performed using the 4-probe method by passing a direct current (DC) of less than 15% (typically 10%) of the AC screen test current through the screens and measure the potential difference between specific voltage measurement points. The ratio between the potential difference and direct current is the resistance between those points. To improve the accuracy of the resistance measurement, the same magnitude of direct current shall be used throughout the test programme.

### 4.4.2 Measurement Intervals

The resistances shall at least be measured after the following number of cycles: 0 (before first heat cycle), 50, 100, 150 (before and after short-circuits), 200, 250 300, 350, 400, 450 and 500. A tolerance of +/- 5 cycles is accepted.

### 4.4.3 Resistance of The Reference Cable

If the screen consists of one single metallic element, such as an aluminium laminate, the resistance of the reference cable screen shall be measured between two voltage measurement points on the reference cable positioned as shown in Figure 4-2. The measured value is divided by the distance between the voltage measurement points to obtain the screen resistance per meter.

If the screen consists of two or more metallic elements, the resistance of the different current paths shall be measured individually (without influence from the other screen(s)) on a 1 m sample and the total resistance shall be calculated. The screens may be dissected to perform the measurements.

## 4.5 Temperature Measurements

Temperature measurements shall be made continuously throughout the test. Temperatures of all screen connections, reference cable conductor(s), reference cable screen(s) and ambient shall be measured. The temperature measurements of the screen connections shall be made close to the contact interface yielding the highest temperature during the first heat cycle. If the screen connection device consists of multiple current paths with independent contacts, the temperature shall be measured at all such paths. This can of example be one temperature measurement for the aluminium laminate connection and one for the copper screen connection for cables where they are connected with independent devices. The temperature measurements of the reference cable conductor and the reference cable screen shall be made at the middle of the reference cable. The ambient temperature shall be measured approximately 2 m from any current carrying part of the set-up.

The recommended method of temperature measurement is to use thermocouples. Temperature readings shall have an accuracy within ±2°C.

## 4.6 Heat Cycle Test Programme

A current $I_{NS}$, as defined in Section 4.2, is applied to the screen and $I_{NC}$ to the conductor. The purpose of $I_{NC}$ is to add heat to the cable such that thermal equilibrium is reached at a higher temperature of the screen than $I_{NS}$ would allow by itself. To determine $I_{NC}$, the current level is set such that thermal equilibrium is obtained when $\theta_{RC}$ is within 5°C above the maximum design temperature of the strictest cable element (typical XLPE = 90°C).

The heating duration is then set as the time required for thermal equilibrium to be reached. Thermal equilibrium is reached when none of the measured temperatures varies more than 2°C over a 10 minute period. See Figure 4-8.

At temperature equilibrium, $I_{NS}$ and $I_{NC}$ shall be turned off. When all measured temperatures have cooled to temperatures of 35°C or less, the power shall be turned on. The heating time (*t1)* should be used throughout the test, whereas the cooling time (*t2*) should be adjusted (if necessary) to maintain the below 35°C requirement before the start of the next heat cycle. The durations of *t1* and *t2* shall be recorded.

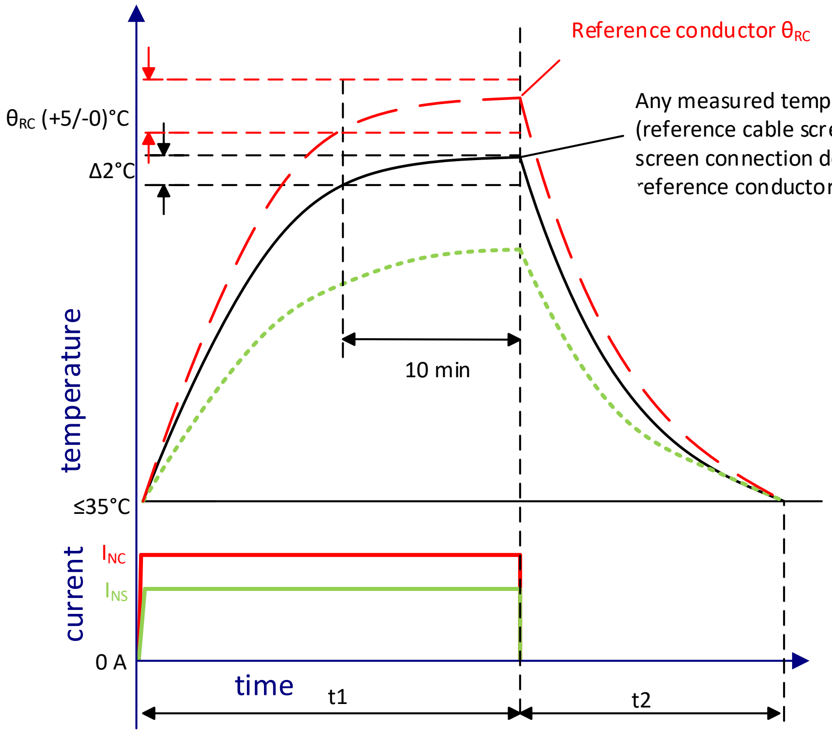



Figure 4-8: Schematic diagram of one heat cycle (t1+t2), temperatures and currents.

If accelerated cooling is used, it shall act on the entire of the loop. The temperature of the cooling air shall be within ambient temperature limits of 15-30°C.

## 4.7 Short-Circuit Test Programme

Two short-circuits shall be applied after the 150th heat cycle. The short-circuit shall be applied to the cable screen only. Screen connection resistance measurements shall be made before and after the two short-circuits (not between).

In the test report, the short-circuits shall be defined either by:

- Maximum temperature, time and approximate current,

or

- Actual current and time and approximate maximum temperature.

Before each short-circuit, the test loop shall have a temperature between 15 and 35°C.

## 4.8 Assessment of Results and Acceptance Criteria

All six test objects shall satisfy the requirements outlined in this section. If one test object does not satisfy one or more of the requirements, a re-test may be carried out with six new test objects. In this event, all test objects shall satisfy the requirements. If more than one test object does not satisfy one or more of the requirements, no further retest is permitted, and the type of screen connection shall be deemed as not conforming to this test procedure at the tested current magnitude.

### 4.8.1 Visual Inspection

The test objects shall be visually examined prior to the first and after the final (500$^{th}$) heat cycle, in addition to prior to and after the short-circuit test. Any findings shall be documented by photos. The tests shall leave no visible deterioration or damages on the cable surfaces (incl. semiconductor) in locations close to the screen connections.

For short-circuit tests, any movements, displacement or change to the screen connections shall be documented.

After the final heat cycle, the test objects shall be dissected.

### 4.8.2 Screen Connection Device Temperature

During heat cycling, the temperature of the screen connection devices shall be lower than the temperature of the screen, as measured on the reference cable.

### 4.8.3 Contact Resistance

The contact resistance requirements shall be based on the four parameters below:

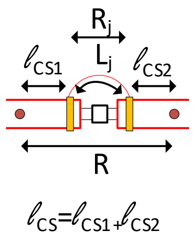
| | |
|---|---|
| Initial scatter, δ, should be maximum | Note 1 |
| Resistance factor change, $Y_A$, should be maximum | Note 1 |
| Resistance factor change, $Y_B$, should be maximum | Note 1 |
| Resistance factor ratio, *λ*, should be maximum | Note 1 |

Note 1: Additional investigations are needed to specify suitable values for screen connections. Experience from contact testing in general, not specific from screen connection devices, suggest the following values as foundation for further testing: $\delta$=0.3, $Y_A$=0.1, $Y_B$=0.1 and $\lambda$=2.0. These values have <u>not</u> been tried on experimental results and the quality and suitability of these indicated levels have thus not been verified.

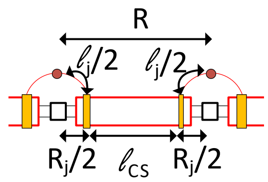
The calculation methods for the requirement parameters are given in Sections 4.8.3.1 to 4.8.3.4.

#### 4.8.3.1 Contact Resistance Factor

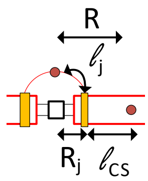
An individual connector resistance factor k enables a common method of connector assessment to be made over the range of conductor cross-sectional areas and screen connections applicable to this test recommendation. See terminology in Figure 4-9 for the different test object alternatives 1-3 and reference cable.



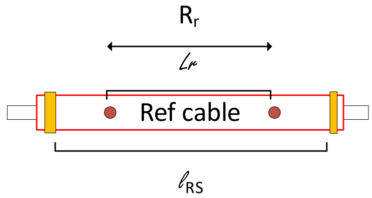

a) Test object alternative 1.




b) Test object alternative 2.




c) Test object alternative 3.




d) Reference cable.

Figure 4-9: Parameters for contact resistance factor

The resistance, referred to 20°C, between voltage measurement points is as follows:

$$R = \frac{U}{I} \times \frac{1}{1 + \alpha(\theta_{XS} - 20)}$$

where the temperature coefficient of resistance α, for the purposes of this test recommendation, is regarded as equal for copper and aluminium:

$$\alpha = 0.004\ \mathrm{K}^{-1}$$

The screen resistance of the reference conductor, referred to 20°C, is when measured directly on the reference cable:

$$R_r = \frac{U_r}{I_r} \cdot \frac{1}{1 + \alpha(\theta_{Rr} - 20)}$$

or, alternatively, when measured on individual current paths:

$$R_r = R_{r\theta} \cdot \frac{1}{1 + \alpha(\theta_r - 20)}$$

where $R_{r\Theta}$ is the resistance determined at $\Theta_r$.

The connector resistance $R_j$ is then:

$$R_j = R - R_r \cdot \frac{l_{cs}}{l_r}$$

where $l_{cs}$ is the length of the conductor screen being a part of the current path between voltage measurement points (typically equal to *d*, but the length needs to be measured for the individual test objects).

The connector resistance factor *k* is:

$$k = \frac{R_j}{R_r} \cdot \frac{l_r}{l_j}$$

where $l_j$ is the length of the screen connection devices.

### 4.8.3.2 Initial scatter *δ*

The initial scatter gives information as to how the design of a contact system will behave on a certain conductor immediately after installation, before any ageing effect starts. The six tested samples are considered to be enough to estimate the identification of a connector "family". If the resistance factors for the tested connector type are almost equal, it may be assumed that one will get the same result when using the described design and assembling method on the same related type of conductor. For this calculation the *k* factors at cycle 0 shall be used.

The scatter between the six values of *k* (one value for each of the six screen connection devices) at cycle zero is calculated as follows:

Calculate the mean value:

$$\overline{K_0} = \frac{1}{6}\sum_{1}^{6} k_0$$

then the standard deviation:

$$s_0 = \sqrt{\frac{1}{5}\sum_{1}^{6}(k_0 - \overline{K_0})^2}$$

and finally, the scatter:

$$\delta = \frac{1}{\sqrt{6}}\frac{s_0}{\overline{K_0}}t_s$$

where
$t_s$ is the Student coefficient;
$t_s = t_{5;0.995}$ = 4.032 for 99% two-sided confidence level and five degrees of freedom;
hence:

$$\delta = 1.65\frac{s_0}{\overline{K_0}}$$

### 4.8.3.3 Resistance factor changes $Y_A$ and $Y_B$

Generally, the ageing behaviour of an electrical contact caused by chemical and physical changes at the constriction areas can be divided into different phases: during formation, stable constriction areas are developed; in the second phase of ageing, relative stability, the connector resistance increases only very little. This is the phase in which the heat cycle test occurs. In the third phase, accelerated ageing, the velocity of chemical processes increases due to the higher temperature. During accelerated ageing, the contact resistance increases considerably. This phase should not be reached during the test.

Since the test contains short-circuits at 150 heat cycles, the formation phase occurs twice, first at the installation, secondly at the short-circuits. Therefore, the relative stability is assessed twice: between 50 and 150 cycles, and between 200 and 500 cycles.

The resistance factor changes $Y_A$ and $Y_B$ (for each connector at each measurement except 0 and 150 after short-circuit) are given by:

$$Y_A = \left| \frac{k - \overline{k_{50-150}}}{\overline{k_{50-150}}} \right|$$

$$Y_B = \left| \frac{k - \overline{k_{200-500}}}{\overline{k_{200-500}}} \right|$$

where $Y_A$ is determined over the five measurements between 50 and 150 (prior to short-circuits) heat cycles, and $Y_B$ is determined over the five measurements between 200 and 500 heat cycles.

$$\overline{k_{50-150}} = \frac{k_{50} + k_{100} + k_{150}}{3}$$

$$\overline{k_{200-500}} = \frac{k_{200} + k_{250} + k_{300} + k_{350} + k_{400} + k_{450} + k_{500}}{7}$$

### 4.8.3.4 Resistance factor ratio $\lambda$

The resistance factor ratio is a measure of the maximum change in resistance during the test compared to the initial value. The resistance factor $\lambda$ for each individual measurement is determined by:

$$\lambda = \frac{k}{k_0}$$

where:
$k$ is the connector resistance factor for each connector found at any stage of the measurement series and,
$k_0$ is the connector resistance factor of the same connector measured at cycle zero.

## 4.9 Test Report

The test report shall as a minimum include the following information:

- Cable and cable screen design (or similar as IEC 60502-4 Appendix A, [2])
    - cable standard
    - rated voltage $U_0/U(U_m)$
    - construction (single, three-core, individually screened)
    - conductor (material, design and cross section)
    - insulation material
    - metallic screen (material, design and cross section)
    - oversheath
    - water blocking
    - actual diameters (conductor, insulation, insulation screen, metallic screen, oversheath)
    - datasheet with drawing and dimensions
    - manufacturer
- Screen connection design and tooling
    - material(s)
    - assembly method
    - tooling, dies and necessary setting
    - bolts, nuts, washers, torque, etc.;
    - preparation of contact surfaces, if applicable
    - type, reference number and any other identification of the screen connection
    - datasheet with drawing and dimensions
    - manufacturer
- Installation of test loop, incl. potential connection method.
- Conductor and screen currents at equilibrium temperatures
- Data on short-circuits
- Temperature measurements
- Electrical test results
- Visual test results

It is advisable to show a graph of the screen connections resistance and screen connection device temperatures as a function of temperature cycle number.

## 4.10 Evaluation of Changes and Modifications in a Prequalified System

In Table 4-2 an evaluation of the degree of allowed changes and modifications in a qualified system is presented. A premise is that the material is a relevant part of the screen connection system.

Table 4-2. Changes and modification in a qualified system

| ***Component*** | ***Type of modification*** | ***Comment*** |
|---|---|---|
| ***Cable*** | | |
| Bedding (layer over extruded semicon. screen) | Change of manufacturing process, material or thickness | No re-test required |
| | | |
| Screen wires | Change of manufacturing process | No re-test required |
| | Change of material or cross section outside range of approval (largest/smallest) | Re-test required |
| | | |
| Screen laminate | Change of manufacturing process | No re-test required |
| | Change of material or cross section outside range of approval (largest/smallest) | Re-test required |
| | Change of coating/glue inside laminate | Re-test required |
| | | |
| Screen tapes | Change of manufacturing process | No re-test required |
| | Change of material or cross section outside range of approval (largest/smallest) | Re-test required |
| | | |
| Outer sheath | Change of manufacturing process | No re-test required |
| | Change of materials | Re-test required |
| | Change in bonding material and/or process to metal screen | Re-test required |
| | | |
| ***Screen Connection Device/System*** | | |
| Joint screen or termination earthing conductor | Change of material or cross section outside range of approval (largest/smallest) | Re-test required |
| Screen connection device | Change in material, size, shape, cross section or number of spikes | Re-test required |
| Device (if any) for applying radial force to screen connection device | Change in design, material, size, shape | Re-test required |

## 5 References

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