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IMPROVEMENTS IN SUPERABSORBENT WATER BLOCKING MATERIALS FOR NEW POWER CABLE APPLICATIONS

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ABSTRACT

Cables that are not longitudinally water blocked are vulnerable to water ingress over long lengths of hundreds of meters or more. In these events, electric utilities and/or cable producers may suffer high cable replacement costs or delays caused by long cable lead times or right-of-way problems. Conversely, properly water blocked cables limit water ingress to a distance of typically less than 1 meter.

Recently, cable and water blocking material producers have witnessed and reacted to a clear industry trend towards complete longitudinal water blocking of power cables, including the conductor, rather than the traditional requirement for "screen only" water blocking. To address these new challenges, new water blocking materials were developed by Geca Tapes for use under the strenuous conditions of CV extrusion and decades of service at conductor operating temperatures. The new materials included a thin water blocking tape for use in power conductors, a new high-capacity water blocking yarn designed for use in conductors and two new water blocking filler yarns designed for use in the interstitial areas between conductors in LV and MV multicore cables

In addition, methods were developed to analyze power cable geometry and produce an estimated bill of materials for water blocking. This information proved useful to cables makers for verification trials of new water blocked cable designs.

KEYWORDS

Longitudinal water blocking, superabsorbent polymer, water blocking yarn, water blocking filler, water blocking tape

INTRODUCTION

It is well accepted in the power industry that longitudinal water ingress can cause cable failures, a reduction in cable network reliability, an increase in maintenance costs and/or a reduction in cable lifetime [1][2][3]. Reported problems encountered by power utilities due to water ingress into cables include:

- High cable repair and replacement costs that result when water catastrophically invades a long, rather than limited, distance into the cable
- Corrosion to metallic cable components due to the presence of moisture
- Insulation degradation, water trees [4]

Historically, a common manifestation of water ingress into cables was the formation of water trees in XLPE insulation. The problem was particularly serious in early versions of XLPE but recent improvements in insulation technology have greatly reduced the occurrence of water trees. Nonetheless, improved XLPE may not be economically or technically viable for all types of conductor insulation and other concerns over water ingress remain.

Some electric utilities have described in confidence to Geca Tapes personnel that water ingress into cables over long lengths has caused serious problems and costly repairs. It was further explained that failures of the water seals in power cable joints are on the increase and as a result, utilities have experienced a corresponding surge in cable problems and an increased frequency and severity of water damage. One postulated root cause of the increased power cable joint problems is the general reduction of in-house cable installation, splicing and commissioning skills due to privatization/deregulation and a concurrent trend toward subcontracting cable works via lowest-price tendering.

To address these issues in a power industry international document, the IEEE is now working on a major upgrade to IEEE-1142. Plans call for the document to be renamed "*Guide for the Selection, Testing, Application and Installation of Cables Having Radial Moisture Barriers and/or Longitudinal Water Blocking*".

ROOT CAUSES AND AN IMPORTANT CAVEAT

The real world conditions under which cables are transported, stored, installed and operated provide opportunity for longitudinal water ingress including:

- Storage, especially if the cable end is left uncapped
- Damage during transport, trans-shipping, drum handling, forklifts, etc
- Cable installation - pulling, laying in trenches, backfilling, laminar flow blowing, newly-developed water flowing techniques
- Cable systems catastrophically exposed to water – flooded tunnels, dam & levee breaches, rising seawater levels due to global warming, etc.
- A joint is improperly assembled or a joint seal fails
- Civil works damage, accidents, theft, pests, weather

Historically, these dangers have been addressed on a limited basis by longitudinal water blocking <u>of the screen</u> in MV and HV cables. More recently, many electric utilities began to specify longitudinal water blocking of other parts of the cable structure including ①circular conductors, ②segmented conductors, ③the interstitial areas in multicore MV cables, ④steel wire armoring and ⑤steel tape armoring. It is these new, non-traditional water blocking requirements that drive the need to verify performance of existing materials under more strenuous conditions or to develop new materials as needed.

Of particular note are the higher operating temperatures in the conductor when compared to the screen, therefore water blocking materials used successfully in the screen in the past may or may not be fit for conductor water blocking. Another key fact is that, unlike water blocking materials used in the screen, water blocking materials used in the conductor are subject to significant thermal stress during CV extrusion.

MATERIAL DEVELOPMENT

The development project described below and shown in flowchart form in Figure 1 addressed this need and included extensive testing of superabsorbers, water blocking tapes and water blocking yarns under a broad range of thermal and chemical conditions. Careful attention was paid to the economics of water blocking materials, particularly for those designed for use in the interstitial area in multicore MV cables.

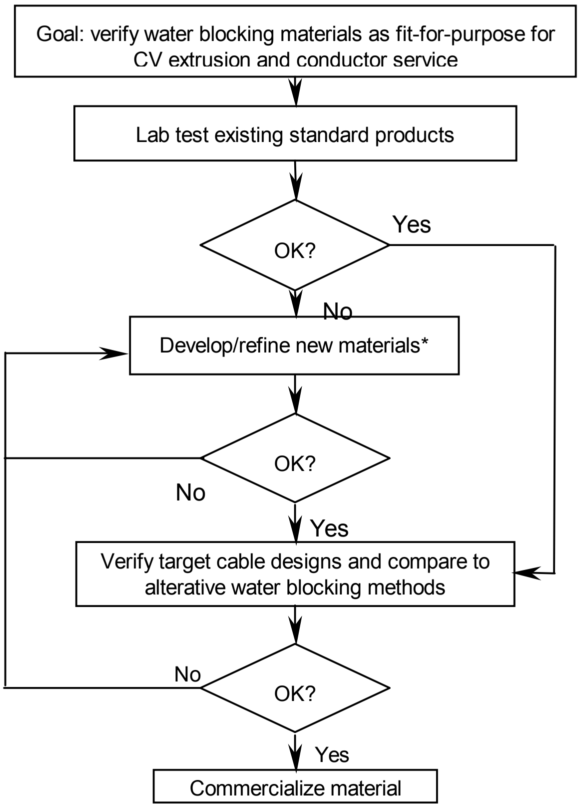

Figure 2: Development Flowchart

*Methods available to develop and refine new materials included:

- Modify superabsorbent powder (tape)
- Modify superabsorbent fiber (yarn)
- Modify/develop superabsorbent coatings (tape or yarn)
- Develop mixtures of superabsorbent powders (tape)
- Modify woven substrates (tape) and other raw materials

The input of cable makers was vital to the success of the project and a number of cable makers were polled for their requirements. Cable producers pointed out that the most difficult thermal conditions occur in conductors, and therefore conductor operating temperature profiles were used during the study. Specific material properties identified by cable producers early in the development cycle are listed in Table 1.

Material	Usage
Thin non-conductive water blocking tape	Middle/penultimate layers in circular conductors and segments
Small water blocking yarn about 1.5 mm diameter	Circular conductors and conductor segments
High capacity water blocking yarn about 2 mm diameter	Circular conductors and conductor segments with significant free space, avoiding wire breakage during compacting
Filler yarns about 2.5 and 4.5 mm diameter	Interstitial area in multicore MV cable

Table 1: Water blocking materials for conductors

Note that water blocking tapes for peripheral wrapping of conductors and water blocking tapes for segment separation were included in the development program but are not covered in this paper.

Superabsorber Testing & Selection

Superabsorbers selection is critical to assure proper water blocking characteristics of a yarn or tape and caution is necessary because many superabsorbers are custom designed for non-cable applications including personal hygiene, food packaging and agriculture. Table 2 lists a number of types of basic superabsorbent materials and key properties of each.

Material	Description
Carboxyl Methyl Cellulose (CMC)	Non-polymeric, subject to fungus and bacteriological attack, unacceptable thermal stability at cable operation temperatures
Acrylamides	Polymeric, slow swelling, low capacity, suitable for hygiene applications but not suitable for cables
Polyacrylics	Long chain cross-linked polymer. Excellent thermal stability, high gel strength, well suited for power conductor water blocking.

Table 2: Types and properties of superabsorbers

Experimental results indicate that many superabsorbers do not have the absorption speed, absorption capacity, thermal stability and other key properties needed for use in cables, so candidate superabsorbers were subjected to careful scrutiny. The absorption and thermal stability issues with candidate acrylamides and the biological concerns with CMC precluded their use cable tapes & yarns. Likewise, superabsorbers designed for single use were found to be highly unsuitable for use in cables. Conversely, certain superabsorbent polyacrylics were found to be well suited for use in cable conductors because of their excellent thermal properties and gel strength. They are hydrophilic cross-linked polymers that can absorb water but do not dissolve because of their polymeric structure. When these polymers are dry, the polymeric chain is coiled and lined with carboxyl groups (-COOH). When wetted, the carboxyl groups change to negatively charged carboxylates (COO^-). The carboxylates force the polyacrylate chains to “uncoil”, resulting in a rapidly formed gel.

The chemical composition, manufacturing method (bead polymerization versus belt polymerization) and cross-linking of superabsorbers were found to be key determinants of performance under the thermal duress associated with CV extrusion and long term service at conductor operating temperatures.

Artificial Ageing of Superabsorbers

As part of the superabsorber selection and qualification process, different superabsorbent powders, powder mixtures and powder/copper mixtures were heat-aged at 90◦C for a period of 18 months. Each month, random samples were extracted, assembled into a tape and tested for swelling height in mm. During that time, the superabsorber exhibited no measurable degradation in water absorption over time as shown in Figure 2.

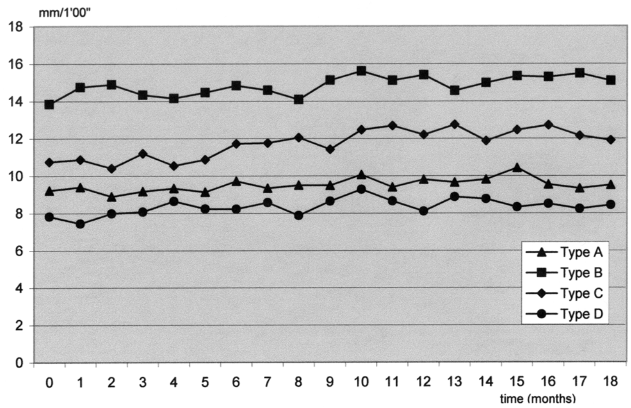

Figure 2: Heat ageing, superabsorbent powder (90°C)

For candidate superabsorbent fibers used in yarns, the heat ageing was done at 90◦C for 12 months (as of April 2007). At different points in time, material was randomly extracted and subject to water absorption testing. The results and curve fit are shown in Figure 3.

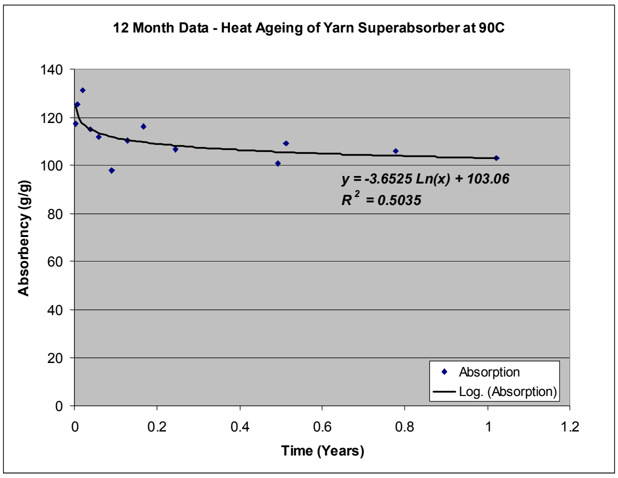

Figure 3: Heat ageing, superabsorbent fiber (90°C)

An equation, based on a logarithmic curve fit relating absorption against time at 90◦C is shown in Equation 1.

$$y = -3.6525\ln(x) + 103.08 \qquad [1]$$

The equation was used to produce the following projection that shows that the superabsorbent fiber maintains nearly 80% of it's absorption after 30 years.

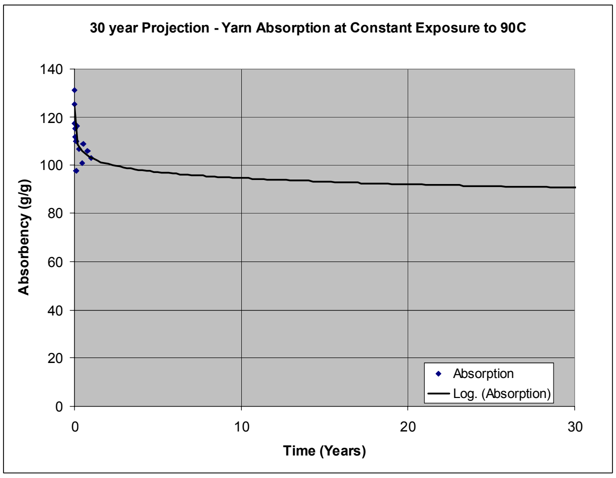

Figure 4: Predicted performance of superabsorbent fiber (90°C)

Gel Strength of Heat-Aged Superabsorbers

Water absorption by itself is not a complete indicator of the ability to water block free space in cables and, therefore, gel strength of superabsorbers under different conditions was carefully studied. Following are some materials combinations that were subject to long-term heat ageing at 90◦C.

- Superabsorbent powder
- Superabsorbent fiber
- Mixtures of superabsorbent powder
- Superabsorbent powder and fiber in contact with copper
- Superabsorbent powder and fiber mixed with copper corrosion inhibitor

The effect of heat ageing of the dry superabsorber at 90◦C on gel stability was then measured for candidate superabsorbers. Table 3 shows results as an average of random samples.

Type	Gel strength, control cP	Gel Strenth, post-ageing, cP
A	11800	11600
B	12100	12600
C	14775	13350
D	13750	14500
E	10925	7875
F	14875	9325

Table 3: Gel strength, heat aged superabsorber (90°C)

Based on the test results, superabsorbers with substandard performance were eliminated from consideration, Type E and F for example, while more promising superabsorbers were subject to further testing.

Thin Water Blocking Tape for Conductor

Water blocking tapes are an excellent and practial medium for longitudinal water blocking of most types of power cables. Figure 5 shows the formation of water blocking gel that occurs when such tape comes into contact with water.

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Figure 5: Water blocking tape, dry and wet

Experience indicates that the ideal water blocking tape for use in power conductors is a single-web non-conductive tape. They are generally thinner and more cost-effective than dual web water blocking tapes. Table 4 lists the targeted properties for tapes tailored for use in power conductors, all of which were realized.

PROPERTY	RATIONALE
Less than 0.15 mm thick	Minimize conductor diameter, enhance breakdown of tape after compacting
Fast, swelling, good volume	Minimize water ingress
High gel strength	Prevent water migration and gel creep
Repeatable water blocking	Allow for wet-dry cycles that might occur while the cable is in service.
Thermally stable	Withstand the thermal conditions during cable processing and service
Corrosion inhibitor	Minimize the rate of corrosion of conductor wires
Good tensile strength	Allow easy cable manufacturing

Table 4: Target properties of water blocking tapes

The binder used to produce the non-woven substrate was chosen to give a balance between tape elongation and the ability of the web to break apart during the wire compacting process. Without this breakage, an unwanted increase in resistance can result. Figure 6 shows how a well-made water blocking tape breaks apart due to wire compacting.

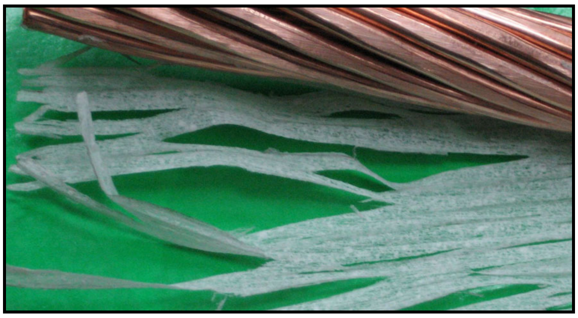

Figure 6: Water blocking tape after removal of wires

Once the properties of the superabsorber and the unaged tape were considered satisfactory, samples of finished production tapes were heat aged for 12 months. Water blocking performance of heat-aged tapes (i.e. gel volume) was measured with the "cup & ram" method that gives a plot of time versus swelling height. Following are swelling plots of the tape both before and after heat ageing.

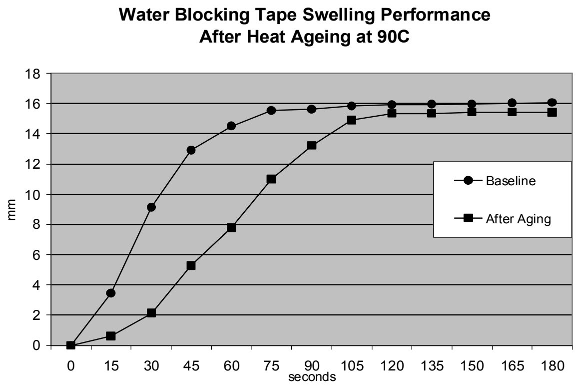

Figure 7: Tape Swelling Performance After Heat Ageing for 12 Months at 90°C.

It was noted that although there was a measurable decrease in the swelling speed of the post-aged tapes, the swelling height reached the control value after about 2 minutes.

Type 1 Yarn: Small Water Blocking Yarn for Conductor

The use of small diameter wires and formidable compacting methods used in conductor manufacturing result in limited free space in the cable structure and drive the need for a relatively low profile water, cost-effective blocking yarn. The design targets for the small water blocking yarn for use in conductors included:

- Fast swelling
- High swelling capacity relative to yarn size
- Diameter of less than 1.5 mm to prevent distortion of the geometry of small conductors
- Easily compressible to prevent distortion of the conductor geometry.

For this application, an existing 1.3 mm diameter yarn produced by Geca Tapes was found to perform well both in lab tests and in longitudinal water penetration testing of finished cables to IEC standards [6][7][8].

Type 1 yarn is now widely used in the production of water blocked circular and segmented conductors including sizes ranging from 50 mm^2 to 2500 mm^2. It is a spun yarn made with a combination of superabsorbent staple fiber, polyester staple fiber, one or more continuous strength filaments in the center of the spun yarn and a helically applied continuous strength filament around the yarn periphery.

Heat ageing of the finished yarn for 12 months revealed absorption performance identical to that of the superabsorber itself.

Type 2 Yarn: High Capacity Water Blocking Yarn for Conductor

Some power conductors contain a large amount of free space – compressed conductors with large diameter wires, for example. This drives the need for a high swelling capacity yarn. The design targets for this product include:

- Fast, high capacity swelling relative to yarn size
- Diameter of less than 2.0 mm to prevent distortion of the conductor geometry or wire breakage during compacting

- Easily compressible to prevent distortion of the conductor geometry.

For this application, a new yarn was developed that performed well both in lab and cable tests. The yarn has the same raw materials and fundamental construction as Type 1 yarn with a higher percentage of superabsorbent fiber to provide formation of a large amount of water blocking gel upon contact with water.

Heat ageing of the finished yarn for 12 months revealed absorption performance identical to that of the superabsorber itself.

Type 3 and Type 4 Yarns: Water Blocking Filler Yarns for Multicore MV Power Cables

Multicore power cables present a unique techno-economic challenge. Because of the large amount of free space in multicore LV and MV power cables, a large amount of superabsorber is needed to pass indicated water blocking requirements. Following were the chosen target requirements:

- Fast, high capacity swelling relative to yarn size
- Diameter of 2.5 mm for LV and smaller sized MV cables.
- Diameter of 4.5 mm for larger sized multicore MV cables.
- Easily compressible to prevent distortion of the core

However, the bill of materials needed for water blocking must remain economically viable. To this end, two new yarns were developed, both based on the use of superabsorbent fiber and both performed well both in lab and cable tests. One was optimized for absorption (Type 3) and the other for tensile strength (Type 4). Key properties of these materials are as follows:

Property	Type 3	Type 4	Units
Diameter	4.5	2.5	Mm
Absorption Speed	45	23	ml/g/1'00"
Absorption Capacity	50	30	ml/g
Tensile Strength	80	170	N

Heat ageing of the two finished yarns for 12 months revealed absorption performance identical to that of the superabsorber itself.

WATER BLOCKING CONDUCTORS

While designing cables, it is important to use the (de-rated) tape/yarn absorption properties predicted at the end of the cable service life. This will assure that the cable is water blocked not only when new, but after decades of service. To this end, insight on the long-term performance of water blocking materials and computerized methods were developed to allow analysis of different conductor designs to generate an estimated bill of materials for necessary cable verification trials.

Step 1: Assess Conductor Free Space

The boundaries of the continuous areas of free space in the conductor were determined and the amount of free space was calculated. Each layer of free space is given separate consideration as shown in Figure 8.

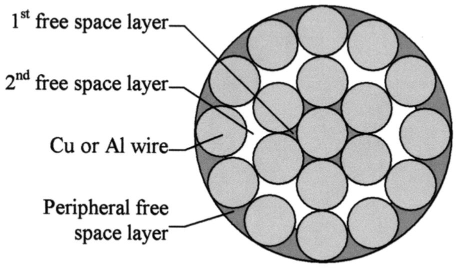

Figure 8: Conductor free space

Step 2: Match Materials to Free Space

Studies showed that successful conductor water blocking is highly dependent on the ratio between the amount of gel produced by the water blocking materials (de-rated for ageing effects) and the amount of free space in the conductor. The free space must be properly overfilled to provide acceptable water blocking performance.

Step 3: Conductor Manufacturing

Conductors were stranded with the selected number and type of water blocking materials and then subjected to the temperature and pressure of typical triple extrusion conditions. During stranding the tapes were applied helically or longitudinally using available serving equipment. Yarns were applied helically whenever possible.

Step 4: Conductor Water Ingress Test

The conductors were then subject to testing to IEC 60502-2 [6] for a medium voltage design, IEC 60840 [7] for a high voltage design and IEC 62067 [8] for an extra high voltage conductor. These tests are widely used in the cable industry and are often referenced by the electric utility or other cable end users to specify the required level of cable performance to the cable manufacturer. The IEC standards give specific requirements for the test gauge length and the conductor heating cycles. Figure 9 shows the fixture used.

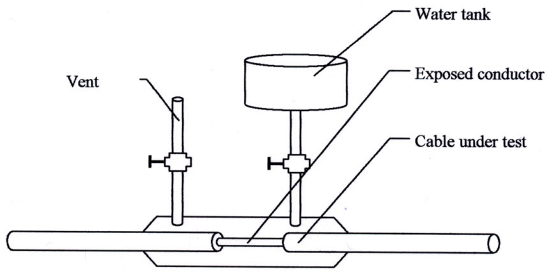

Figure 9: Water penetration test fixture

The results were excellent for all cable designs with water ingress well within the stated pass-fail criteria.

CABLE VERIFICATION TESTS

The final step was to prove that the materials and methods work well with completed cables that are longitudinally water blocked in all potential water paths (conductor, screen, steel wire armor, metal tape armor, inter-conductor spaces in multicore cables, etc). A number of cable producers, based on guidance from Geca Tapes, subsequently developed extensive families of fully water blocked cable designs that met the end-user water blocking requirements. Figure 10 and

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Table 5 give an example of one successfully qualified medium voltage cable design.

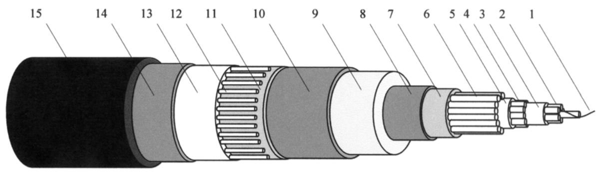

Figure 10: Fully water blocked MV cable

It.	Description
1	**Water blocking yarns**
2	1+6 wire layer
3	**Non-conductive water blocking tape**
4	+12 wire layer
5	**Non-conductive water blocking tape**
6	+18 wire layer
7	**Semi-conductive water blocking peripheral tape**
8	Extruded conductor screen
9	XLPE insulation
10	Extruded insulation screen
11	**Semi-conductive water blocking bedding tape**
12	Screen wires
13	**Non-conductive water blocking tape**
14	Polymer coated aluminum tape radial moisture barrier
15	Outer sheath

Table 5: Components of fully water blocked MV cable

CONCLUSIONS

Extensive study of raw material properties, finished water blocking tapes & yarns and iterative cable manufacturing trials led to the successful development of materials and cable design methods needed for predictable, long-term water blocking of power cables. Important insight was gained about the key material properties and the cable design strategies needed for longitudinal water blocking. As a result, it is now possible for Geca Tapes to analyze any power cable structure, including conductors, compare them to the stated water blocking requirements and compile a bill of materials for cabling verification trials & testing.

The benefits of these methods extend to the end users of power cable who now have the option to optimize cable lifetime by specifying full longitudinal water blocking of LV, MV and HV cables.

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