The invention relates to an electric power cable (1) comprising a metal conductor (2) and an electric insulation system (12) radially surrounding the conductor (2) and to a process for the production of the cable. The insulation system (12) comprises a first semi-conducting layer (4) comprising a polyethylene-based base polymer, wherein the first semi-conducting layer (4) surrounds the conductor (2).

Further, the insulation system comprises an insulation layer (6) comprising a polyethylene-based base polymer, wherein the insulation layer (6) is in contact with and surrounds the first semi-conducting layer (4) radially outwards, and a second semi-conducting layer (8) comprising a polyethylene-based base polymer, wherein the second semi-conducting layer (8) is in contact with and surrounds the insulation layer (6) radially outwards. The base polymer in the first semi-conducting layer (4) is non-cross-linked, and the base polymer in the insulation layer (6) is cross-linked, whereby a uniform electric field distribution in the insulation system (12) is obtained.
ELECTRIC POWER CABLE AND PROCESS FOR THE PRODUCTION OF ELECTRIC POWER CABLE

TECHNICAL FIELD

The present invention relates to an electric power cable and to a process for the production of an electric power cable as defined in the appended claims.

BACKGROUND ART

Electric power cables are used to transmit electric power at a medium or high voltage. The cables comprise normally a conductor and radially surrounding polymeric insulation system comprising at least two semi-conducting layers and one insulation layer comprising polymeric material. Electric power cables may be buried into the ground whereby they are called land cables. The electric power cables may also be buried into a sea bed or they may freely extend between two fixing points in sea water and cables of this type are called submarine, sea water or underwater power cables. Areas, where energy is on the one hand needed and on the other hand produced, may be located at a long distance from each other which increases a need for safe power transfer.

In order to meet the demands for safe power transfer, the insulation systems need to be of high quality to ensure correct electrical and mechanical behaviour during the transmission of electric power. To electrically insulate the conductor, an insulation system including semi-conducting and insulating polymeric layers is arranged to surround the conductor. Unless the power cables are appropriately insulated, significant leakage currents will flow in the radial direction of the cables, from the conductor to the surrounding grounded screen. Such leakage currents give rise to significant power losses, as well as to heating of the electrical insulation. The heating of the insulation can further increase the leakage current due to the reduction of the resistance with the increasing temperature. To avoid power losses and possible thermal runaway, the leakage current should therefore be kept as small and stable as possible.

The polymeric materials are extruded to provide the semi-conducting and insulating layers to surround the conductor. In the semi-conducting layers, a conductive filler or additive is used to render the layers semi-conductive, and in the insulation layer no conductive filler or only a
small amount that does not render the insulation layer conductive is used. The polymeric material is also cross-linked to render the polymer sufficient mechanical strength. After extrusion and cross-linking, the cables are usually heat-treated which helps to remove a portion of the cross-linking by-products from the cable insulation system. Most of the by-products in the outer semi-conducting layer are usually degassed already in the extrusion line or during the heat treatment.

There have been many attempts to improve electrical properties of insulation systems. For example, there have been attempts to reduce the conductivity of the insulation material, while the insulation material has good mechanical properties. For example, WO2014000820 describes an insulation material having a reduced conductivity or no conductivity at all while good mechanical properties are maintained. The object is attained by a polyethylene-based polymer comprising a specific amount of 0.1 to 2.0 wt.% of a cross-linking agent and 0.01 to 0.5 wt.% nucleating agent, based on the weight of the polymer and wherein the nucleating agent comprises 40-80 wt.% calcium cyclo-dicarboxylate and 20-60 wt.% zinc stearate, based on the weight of the nucleating agent. Despite the attempts to reduce conductivity of the insulation material, there is still the need for improvement of the polymeric insulation systems. For example it is desirable to obtain as uniform electric field in the cable as possible. It is also desirable to obtain a cable with better electric field distribution with improved mechanical properties and thus to provide a cable with a more robust insulation system.

SUMMARY OF THE INVENTION

The inventors of the present invention have realized that in the prior art cables there is a problem of obtaining a uniform electric field in the cable. The inventors have detected that even if the insulation material has low conductivity or no conductivity at all, the by-products originating from cross-linking reaction in the inner semi-conducting layer can diffuse to the innermost parts of the insulation layer adjacent to the inner semi-conducting layer. The diffusion can occur when the cable insulation system is heat-treated to remove a portion of the cross-linking by-products from the cable insulation system. Thus, since the chemicals can leave the insulation system only through the outer semi-conducting layer of the cable, this leads to a non-uniform distribution of by-products in the system. Thus, the inner parts will have a higher by-product content than the outer parts, and thus higher conductivity.
Therefore, there is a risk for locally high electric field which will increase the risk for breakdown and be detrimental for the insulation system.

Therefore, it is an object of the present invention to provide as uniform electric field distribution in the power cable as possible while good mechanical properties can be maintained or even improved. Especially, it is an object to provide a cable with more uniform electric field distribution both at high temperatures and also during thermal dynamics, i.e. temperature cycles. Furthermore, it is an object to provide a cable with a more robust insulation system.

Also, by providing a more uniform electric field distribution, it will be possible to increase the cable voltage level, average electric field and also higher conductor temperatures.

It is also an object of the present invention to provide a transmission power cable with an electrical insulation system having improved insulation properties and which is suitable for high voltage or medium voltage power cable applications.

It is a further object of the invention to provide an insulation layer that does not require modification of the base polymer per se.

It is a still further object of the invention to provide an improved and modified insulation material which is simple and cost-efficient.

A still further object of the present invention is to provide reliable transfer of electrical power.

It is also an object of the present invention to provide a power cable, and especially an HVDC or MVDC cable having improved electrical properties.

The above-mentioned objects are achieved by an electric power cable comprising a metal conductor and an electric insulation system radially surrounding the conductor, which insulation system comprises:

- a first semi-conducting layer comprising a polyethylene-based base polymer, wherein the first semi-conducting layer surrounds the conductor;
- an insulation layer comprising a polyethylene-based base polymer, wherein the insulation layer is in contact with and surrounds the first semi-conducting layer radially outwards; and
- a second semi-conducting layer comprising a polyethylene-based base polymer, wherein the second semi-conducting layer is in contact with and surrounds the insulation layer radially outwards.

The polyethylene-based base polymer in the first semi-conducting layer is non-cross-linked and the base polymer in the insulation layer is cross-linked. In this way, it can be assured that the insulation system and especially the insulation layer in the insulation system will contain a reduced amount of cross-linking by-products after the curing/vulcanizing procedure during which cross-linking occurs. The by-products can negatively affect the electrical properties of the insulation layer and/or system. At the same time, since the insulation layer is cross-linked, the mechanical properties of the cable are affected minimally, whereby sufficient mechanical strength for the cable can be provided. No cross-linking material, such as peroxide etc., is added to the first semiconducting layer and thus the amount of by-products created during vulcanization or curing procedure affecting negatively the insulation layer can be minimized. By cross-linking the base polymer in at least the insulation layer, the insulation system is rendered more resistant against softening and loss of shape at higher temperatures, such as above 70°C. The base polymer used in the layers of the insulation system is polyethylene-based. Thus, the insulation system is more flexible compared to other polyolefin-based polymers, such as polypropylene which is stiff, which facilitates the handling of the cables.

The base polymer in the first semi-conducting layer is not cross-linked and contains no added cross-linking agent. However, some of the cross-linking agent added to the base polymer in the insulation layer may diffuse to the first semi-conducting layer before curing procedure in which the cross-linking occurs. However, the content of the cross-linking agent will be less than 0.5 wt. %, based on the weight of the first semi-conducting layer. The diffused cross-linking agent will stay close to the outer surface region of the first semi-conducting layer and thus, when the cable including the insulation system is cured, some cross-linking may occur at the interface between the first semi-conducting layer and the insulation layer. This causes a bonding between the semi-conducting layer and the insulation layer, which further improves the mechanical properties of the cable. According to another embodiment, the base polymer in the first semi-conducting layer is free of a cross-linking agent. In this way the amount of cross-linking by-products can be minimized.
The base polymer in the insulation layer can be cross-linked with dicumyl peroxide cross-linking agent, which is a peroxide-based compound. This provides for very good mechanical and electrical properties for the insulation layer.

According to one embodiment, the base polymer in the second semi-conducting layer is also cross-linked. This further improves the mechanical properties of the cable. The base polymer in the second semi-conducting layer may be cross-linked with the same kind of cross-linking agent as the insulation layer, for example with a peroxide-based cross-linking agent, such as the above-mentioned dicumyl peroxide cross-linking agent. By using same kind of cross-linking agents the production process can be simplified.

According to another embodiment, the base polymer in the second semi-conducting layer can be cross-linked with a cross-linking agent that is different from the cross-linking agent used to cross-link the insulation layer and can be for example another kind of peroxide-based cross-linking agent. For example, the cross-linking agent can be a bisperoxide-compound, such as bis(tert-butyldioxyisopropyl)benzene. By using different cross-linking agents, different properties may be provided to the insulation layer and the semi-conducting layer, respectively.

The polyethylene-based base polymer may be a low density polyethylene (LDPE), ultra-low density polyethylene, linear low density polyethylene, high density polyethylene (HDPE), ultra-high density polyethylene, or a mixture thereof. The polymeric material renders the insulation system relatively thermally stable and flexible while an effective insulation property is obtained. Preferably, the polyethylene polymer is a low density polyethylene (LDPE).

The first and the second semi-conducting layers comprise conductive particles in an amount of from 10 to 40 % by weight, based on the total weight of the first and/or the second semi-conducting layer, respectively. In this way sufficient amount of conductive particles can be provided to render the layer semi-conducting properties. The conductive particles may be of any suitable kind and preferably comprise carbon black, which is a stable product that tolerates high temperatures.

The cable is suitably a power transmission cable having a rated voltage of 50 kV or higher. The cable is preferably a high voltage direct current (HVDC) cable.
The objects above are also attained by a process for the production of an electric power cable comprising the steps of:

i) providing a conductor;

ii) extruding a first semi-conducting layer comprising a polyethylene-based base polymer to surround the conductor radially outwards, wherein no cross-linking agent is added to the base polymer in the first semi-conducting layer;

iii) extruding an insulation layer comprising a polyethylene-based base polymer and a cross-linking agent, to be in contact with the first semi-conducting layer and to surround the first semi-conducting layer radially outwards;

iv) extruding a second semi-conducting layer comprising a polyethylene-based base polymer and optionally a cross-linking agent, to be in contact with the insulation layer and to surround the insulation layer radially outwards;

v) subjecting the cable to a curing procedure.

The extrusion steps ii)-iv) may be performed simultaneously or in sequence. The curing is performed at elevated temperature and can be performed at a temperature of from 150-350°C.

In the step iii), the base polymer in the insulation layer can be cross-linked by using dicumyl peroxide as a cross-linking agent. This provides for very good mechanical and electrical properties for the insulation layer.

In the step iv) the second semi-conducting layer can comprise a cross-linking agent to improve the mechanical properties of the cable. According to one embodiment, the base polymer in the second semi-conducting layer is cross-linked by using the same kind of cross-linking agent as used for the insulation layer. For example, the base polymer in the second semi-conducting layer can be cross-linked by using dicumyl peroxide as a cross-linking agent. Therefore, a simple production process may be provided.

According to another embodiment, the base polymer in the second semi-conducting layer is cross-linked by using a cross-linking agent that is different from the cross-linking agent used to cross-link the insulation layer. For example, the cross-linking agent may be another kind of peroxide-based compound than dicumyl peroxide. For example, the cross-linking agent can be
a bisperoxide such as bis(tert-butyldioxyisopropyl)benzene. Thus, further improved mechanical properties for the semi-conducting layer may be provided, and the mechanical and electrical properties for each layer can be modified in accordance with specific needs for the layers.

The process may further comprise a step of:

vi) heat treating and degassing the cable to remove cross-linking by-products.

In this way, the amount of cross-linking by-products negatively affecting the cable can be minimized.

Further aspects, features and advantages of the present invention are described more in detail in the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

Examples according to the present invention will be described below with reference to the accompanied drawings in which:

Fig. 1 is a side view of a single phase electric power cable according to the present invention;

Fig. 2 is a cross-section of a single phase electric power cable according to the present invention;

Fig. 3 is a flow chart showing the steps of a process for the production of the electric power cable according to the present invention.

Fig. 4 shows results from a test showing accumulation of cross-linking by-products with respect to the radial position.

Fig. 5 shows a temperature curve used during measurements shown in Example 2 and Fig. 6.

Fig. 6 shows conductivity of samples obtained during a temperature-treatment shown in Fig. 5.
DETAILED DESCRIPTION

Electric power cables, also called electric transmission power cables, are aimed for transmitting electric power. The demands with regard to electric and mechanical properties are increasing due to increased demand for electricity and long distances electricity needs to be transmitted.

The electric power cable is preferably of a type single phase electric power cable. For example, the cable may be high voltage direct current (HVDC) cable, extra high voltage cable (EHV), medium-voltage cable or low-voltage cable.

The electric transmission power cables comprise a conductor, which is usually mainly constituted by a metal such as copper or aluminum. The conductor is surrounded by an electric insulation system which comprises a first semi-conducting layer, insulation layer and a second semi-conducting layer. An insulation layer is located between the semi-conducting layers. Single phase cables comprise one conductor.

Normally, the conductor has a generally circular cross section, even though alternative shapes might be conceived. The radially surrounding electric insulation system with insulation and semi-conducting layers usually has a cross-section with an outer peripheral shape corresponding to the outer peripheral shape of the conductor, normally a generally circular outer periphery, and the insulation system surrounds the conductor radially and concentrically. In this way uniform insulation in the cable can be obtained and electrical properties of the cable can be improved.

The cables may be underwater power cables or the cables may be land cables. The cable is preferably a power transmission cable having a rated voltage of 50 kV or higher, and is thus suitable for use as a high voltage transmission power cable. Preferably, the cable is a high voltage direct current (HVDC) cable.

According to the present disclosure, the conductor is surrounded by an electric insulation system which comprises a first semi-conducting layer, insulation layer and a second semi-conducting layer.
In the insulation system, the insulation layer or layers should have insulation properties and essentially no conductivity or very low conductivity. The semi-conducting layer or layers can be rendered semi-conducting by using for example fillers having conducting properties.

By insulation layer is meant a layer of a material that resists electricity. The conductivity of the insulation material may be for example of from about 1*10^-8 to about 1*10^-20 S/m at 20 °C, typically from 1*10^-8 to 1*10^-18, depending of the magnitude of the electric field.

By semi-conducting layer is meant a layer of a material that has an electrical conductivity that is lower than that of a conductor but that is not an insulator. The conductivity of the semi-conducting material may be typically of larger than 10^-5 S/m at 20 °C, such as up to about 10 or 10^2 S/m. Typically, the conductivity is less than 10^3 S/m at 20 °C.

By conductivity is meant the property of transmitting electricity. The conductivity of a conducting material is more than about 10^3 S/m at 20 °C. For example, carbon black has a conductivity of about 1000 S/m. Basically there is no upper limit, but in practical solutions the upper limit is about 10^8 S/m at 20 °C.

Fig. 1 is a partially cut side view of an electric cable 1 according to the present invention, and Fig. 2 shows a radial cross section thereof. The cable 1 comprises a conductor 2, a first semi-conducting layer 4 radially innermost and closest to the conductor 2, insulation layer 6 radially surrounding and in contact with the first semi-conducting layer 4 and a second semi-conducting layer 8 radially outermost from the conductor and in contact with the insulation layer. The first semi-conducting layer 4, the insulation layer 6 and the second semi-conducting layer 8 together form an insulation system 12 (shown only in Fig. 1) for the transmission power cable 1. There may be more than one insulation layer and there may be more than one semi-conducting layer in the insulation system, such as 1-4 insulation layers and 1-4 semi-conducting layers. The transmission power cable 1 in Fig. 1 and 2 is surrounded by an outer sheath 10.

According to one embodiment, the insulation system can be directly attached to and arranged to be in contact with the conductor. In this way effective insulation can be provided. The conductor may be also indirectly surrounded by the polymeric insulation system, i.e. the
electric power cable may comprise at least one material layer between the conductor and the insulation system. In this way it is possible to e.g. customize cables.

The conductor and the insulation system can be surrounded by further material or layers of material. Further materials and layers may have different tasks such as that of holding the different cable parts together, giving the cable mechanical strength and protecting the cable against physical as well as chemical attacks, e.g. corrosion. Such materials and layers are commonly known to the person skilled in the art. For example, such further materials may include armouring, for example steel wires, or sheath-like barriers to provide a water barrier for the cables.

In the insulation system, the polymeric material or the base polymer of the semi-conducting layers and the insulation layers comprises or consists of a polyethylene-based polymer and can be selected from low density polyethylene, ultra-low density polyethylene, linear low density polyethylene, high density polyethylene and ultra-high density polyethylene or mixtures thereof. Preferably, the polyethylene polymer is low density polyethylene. The polymeric material renders the insulation system relatively thermally stable while an effective insulation property is obtained. Also, polyethylene is a material that is softer and more flexible than other olefin-based polymers, such as polypropylene. The base polymer in all layers of the insulation system is preferably the same so that the production process can be easily controlled. In this way, only different fillers and additives need to be added, and the base polymer per se needs not to be modified.

Different additives and fillers can be added to the base polymer to render the polymeric material desired properties. Additives may be for example stabilizers such as antioxidants, nucleating agents, inorganic fillers, cross-linkers, cross-linking boosters such as 2,4,6-triallyl cyanurate, scorch retard agents and flame retardants. Stabilizers, particularly antioxidants prevent negative effects of oxidation.

At least the first semi-conducting layer, which is located closest to the conductor and surrounds the conductor, is non-cross-linked. However, during the manufacture of the cable, it is possible that minor amount of a cross-linking agent will diffuse from the surrounding insulation layer to the first semi-conducting layer. The cross-linking agent may mainly diffuse to the surface of the semi-conducting layer. Thus, when the cable is cured the diffused cross-
linking agent can react and some cross-linking may occur at the interface between the surface of the first semi-conducting layer and the insulation layer. This may lead to bonding between the first semi-conducting layer and the insulation layer which further strengthens the mechanical properties of the cable. The diffusion of the cross-linking agent from the insulation layer occurs naturally. By non-cross-linked is thus meant in this application that no cross-linking agent is actively added to the base polymer of the first semi-conducting layer.

The first semi-conducting layer is thus essentially free of a cross-linking agent. This means that it contains less than 0.5 wt. % of a cross-linking agent. As explained above, small amounts of a cross-linking agent may naturally diffuse from the neighboring insulation layer which comprises an added cross-linking agent to the first insulation layer. The first semi-conducting layer has thermoplastic properties and contains no cross-linking by-products that diffuse into the neighboring insulation layer. Cross-linking by-products are a group of chemicals which are formed during cross-linking of polymers, for example polyethylene, due to chemical reactions of radicals forming from cross-linking agents, such as peroxide and the polymer.

By assuring that at least the first semi-conducting layer is non-cross-linked the insulation system will contain a reduced amount of cross-linking by-products that can negatively affect the electrical properties of the insulation system, especially compared to insulation systems in which all layers are cross-linked. Also, since the innermost layer is non-cross-linked, the mechanical properties of the cables are affected minimally. By cross-linking the base polymer in the insulation layer it is rendered more resistant against softening and loss of shape at higher temperatures, such as above 70°C, especially in case the polymer matrix is a low density polyethylene (LDPE).

The insulation layer and optionally the second semi-conducting layers are cross-linked. According to one embodiment the second semi-conducting layer is non-cross-linked and is thus essentially free of a cross-linking agent. According to an alternative embodiment, the second semi-conducting layer is cross-linked. Cross-linking ensures that sufficient mechanical strength for the cable is provided.

The cross-linking agent for the base polymer in the insulation layer and optionally in the second semi-conducting layer may be any cross-linking agent suitable for use in connection with a polyethylene polymer or copolymer thereof, such as a peroxide-based, silane-based
cross-linking agent or azo-compounds. The cross-linking may also be performed by radiation. Preferably, the cross-linking agent is peroxide-based, such as for example dicumyl peroxide (DCP) or a highly active bisperoxide, bis(tert-butylidioxyisopropyl)-benzene. The cross-linking agent in the insulation layer and in the second semi-conducting layer may be different from each other. In this way the cross-linking agent can be adjusted to the specific needs of the respective materials in the layers. For example, the insulation layer may be cross-linked with DCP and the semi-conducting layer with another type of peroxide-based compound, such as a highly active bisperoxide, bis(tert-butylidioxyisopropyl)-benzene.

The amount of the cross-linking agent can be from 0.1-2.0 % by weight, based on the weight of the base polymer, to ensure sufficient cross-linking.

The semi-conducting layer or layers may comprise conductive particles that render the semi-conducting layer the desired conductivity. The conductive particles may be of any kind, such as metallic conductive filler particles or carbon black. The content of the particles may vary e.g. between 10 to 40 % by weight, based on the total weight of the semi-conducting layer. Carbon black is often used due to its stability also at high temperatures.

The process for the production of the present electric power cable is schematically illustrated in the flow chart of Fig. 3. The process comprises the following steps:

i) providing a conductor 2;
ii) extruding a first semi-conducting layer 4 comprising a polyethylene-based base polymer to surround the conductor 2 radially outwards, wherein no cross-linking agent is added to the base polymer in the first semi-conducting layer 4;
iii) extruding an insulation layer 6 comprising a polyethylene-based base polymer and a cross-linking agent to be in contact with the first semi-conducting layer 4 and to surround the first semi-conducting layer 4 radially outwards;
iv) extruding a second semi-conducting layer 8 comprising a polyethylene-based base polymer and optionally a cross-linking agent to be in contact with the insulation layer 6 and to surround the insulation layer 8 radially outwards;
v) subjecting the cable 1 to a curing procedure.
The conductor may be of the kind described above. The extrusion may be performed by using any of the available common extrusion technologies, which are well known for the skilled person and not described in detail herein. The extrusion steps ii) to iv) may be performed simultaneously or in sequence. To facilitate the control of the process, the extrusion steps are preferably performed simultaneously.

In the step iii), the base polymer in the insulation layer 6 can be cross-linked by using dicumyl peroxide as a cross-linking agent. The dicumyl peroxide cross-linking agent provides improved mechanical and thermal properties for the insulation layer.

In the step iv) a cross-linking agent is preferably added to cross-link the base polymer in the second semi-conducting layer 8. The cross-linking agent may be the same kind or different from the cross-linking agent used to cross-link the insulation layer 6. Preferably, the base polymer in the second semi-conducting layer 8 is cross-linked by using a highly active bisperoxide-compound, bis(tert-butyldioxyisopropyl)benzene. Thus, different properties to the insulation layer and the second semi-conducting layer can be rendered by the use of different cross-linking agents.

Preferably, the process comprises a further step of:

vi) heat treating and degassing the cable to remove cross-linking by-products.

Heat treating and degassing may be performed during the production process when deemed necessary. The heat-treating may be performed in an oven or by using any other technology known in the art and apparent to the skilled person. In this way, the amount of by-products can be decreased. It is known that e.g. polar chemicals, such as water and cross-linking by-products, affect the conductivity in insulation polymeric materials. Thus, there is a desire to limit the amount of such chemicals in the insulation system of the power cables.

The inventors of the present invention have noted that since the chemicals can leave the insulation system only through the outer semi-conducting layer of the cable, it will lead to a non-uniform distribution of by-products in the insulation system so that the radially inner parts of the insulation system in the cable, i.e. layers in close proximity to the conductor will contain a higher amount of by-products than the radially outer parts of the cable, i.e. for example the outermost semi-conducting layer of the power cable. The by-products may
redistribute by time and heat and the distribution may become more uniform, but problems with non-uniform distribution of the by-products lead to e.g. problems with locally high electric field before the by-products are redistributed uniformly.

For example, different peroxides used for cross-linking produce different set of by-products which may have different effects on conductivity. For example, an insulation system comprising an insulation layer comprising a cross-linked polyethylene polymer (XLPE) cross-linked with dicumyl peroxide DCP, known as Di-Cup®, CAS number 80-43-3, is provided. The polyethylene base polymer may be low density polyethylene, LDPE. The XLPE which is used as semi-conducting material layer in the cable contains another type of peroxide, for example a bisperoxide, bis(tert-butyldioxyisopropyl)benzene, which is highly active and on the market known as Vul-Cup® peroxide, CAS number 25155-25-3. Since there are two different peroxides, the cross-linking by-products produced in the insulation layer and semi-conducting layer during the cable production are different. After extrusion and cross-linking that occurs during curing, the cables are usually heat-treated which helps to remove a portion of the cross-linking by-products from the cable insulation system. However, not all of the cross-linking by-products can be removed, especially from the inner parts of the cable, whereby the electrical properties of the cable are negatively affected.

Most of the by-products in the outer semi-conducting layer can be degassed during the heat treatment. But the by-products in the first (inner) semi-conducting layer will diffuse into the innermost parts of the insulation layer adjacent to the inner semi-conducting layer. The by-products originating from the first, inner semi-conducting layer in the cable insulation can be measured. This will be shown below in Example 1.
Example 1

In this example, the first (inner) and the second (outer) semi-conducting layers of the insulation system were cross-linked with a bisperoxide bis(tert-butyldioxyisopropyl)benzene known with a trade name Vul-Cup® peroxide, CAS 25155-25-3. Different by-products after cross-linking were identified, namely:

1.3-diacetyl benzene
1.4-diacetyl benzene
1,3-dihydroxy isopropyl benzene
1,3-acetylhydroxy isopropyl benzene
1,4-dihydroxy isopropyl benzene

As it is shown in Fig. 4, the concentration of the by-products from semi-conducting layers is as expected highest in the inner parts and negligible in the outer parts. The graph shows the radial concentration distribution of the above-mentioned by-products from Vul-Cup®, as measured in a cable using GC-FID (gas chromatography with flame ionization detector). The measurement point at the smallest radius is in the inner semiconducting layer and the measurement point at the largest radius is in the outer semiconducting layer. The intermediate points are within the insulation layer. The measured by-products have obviously diffused from the inner semiconducting layer into the insulation layer. In the outer semiconducting layer and in the insulation layer nearby, the by-products could not be detected, so the by-products that were formed during cross-linking of the outer semiconducting layer have been removed during the manufacturing process, such as during degassing.

Example 2

In this example the effect of a peroxide cross-linking agent, namely Vul-Cup®, originating from the semi-conducting layers was studied. The apparent conductivity as function of time was measured using the method described in Nordic Insulation Symposium 2009 (Nord-IS 09), Gothenburg, Sweden, June 15-17, 2009, page 55-58: Olsson, CO, Kallstrand, B., Ritums, J., and Jeroense, M., "Experimental determination of DC conductivity for XLPE insulation".

A series of tests were performed with three different samples.
- 1 mm thick pressed XLPE (cross-linked polyethylene-based base polymer) insulation plate, was degassed for 24 hours at 70 °C as a reference sample.

- 1 mm thick pressed XLPE, was degassed and then heat treated for 24 hours at 70 °C in contact with 2 semi-conducting plates produced from a polyethylene-based base polymer with semi-conducting material without cross-linking.

- 1 mm thick pressed XLPE, which is degassed and then heat treated for 24 hours at 70°C in contact with 2 semi-conducting plates produced from a polyethylene-based base polymer with semi-conducting material with added Vul-Cup® peroxide to obtain concentrations representative of typical semi-conducting materials.

In the experiment behind Fig. 5 and Fig. 6, the applied voltage across a 1 mm thick XLPE plate was 30 kV, and the temperature was varied according to the curve shown in Fig. 5. This means that the temperatures illustrated as a function of time in Fig. 5 were used in the conductivity measurements as shown in Fig. 6. The measured current was converted to conductivity, and the results for the three different XLPE plates are shown in Fig. 6. The reference sample was kept in an oven at 70°C for 24 h before the measurement in order to remove the by-products from the peroxide of the insulation material. The two other plates were prepared in another way. After a first degassing similar to the reference plate, each of these plates was placed between two semiconducting plates of the same dimensions as the XLPE plate, wrapped in a diffusion barrier and placed in an oven at 70°C for 24 h. This step was performed in order to allow chemical substances from the semiconducting plates to diffuse into the XLPE plate. Subsequently, each XLPE plate was separated from the semiconducting plates and the conductivity measurements were made.

As described above, for one of these XLPE plates, the semiconducting plates were made of a material containing the Vul-Cup®. For the other XLPE plate, the semiconducting plates were made of a similar material but without the Vul-Cup®. As seen in Figure 6, the measured conductivity is higher due to the substances originating from the inner semi-conducting material with Vul-Cup®.

The leakage current was measured for each sample and apparent conductivity was calculated for each sample as illustrated in Fig. 6. An arrow 61 points at a line which shows a reference degassed XLPE. An arrow 65 points at a line which shows a degassed XLPE heat treated with
thermoplastic semi-conducting material without peroxide and this corresponds to the cable comprising an insulation system according to the present invention. An arrow 63 points at a line which shows a degassed XLPE heat treated with semi-conducting material including Vul-Cup® by-products.

Comparing the apparent conductivity of the samples the following observations were made:

- The sample heat treated with thermoplastic semi-conducting material, i.e. material without peroxide cross-linking agent (arrow 65), shows a conductivity level which is slightly higher at 70 °C but it is similar or even lower at lower temperatures.
- The sample heat treated with semi-conducting material containing Vul-Cup® peroxide shows (arrow 63) considerably higher conductivity than the reference sample at all temperatures.
- The sample semiconducting material with Vul-Cup® affects the conductivity of XLPE much more than the thermoplastic semiconducting material without peroxide.
- The sample heat treated with semiconducting material containing Vul-Cup® shows an abnormal increase of apparent conductivity during cooling, which is pointed with an arrow 60.

Considering the facts and problems the present inventors have realized and the measurement results shown above, the effect of using different inner semi-conducting materials can be evaluated and conclusions can be made.

Since the by-products concentration originating from the inner semi-conducting layer is normally higher in the inner parts of a cable insulation system, this can cause a local increase of conductivity in the inner parts of the cable insulation system. As it is shown in the results, chemicals from semi-conducting layer cross-linked with Vul-Cup® affect the apparent conductivity of XLPE considerably. This means that in the cable with an inner semi-conducting layer containing Vul-Cup®, the conductivity of the inner parts of the insulation system will be much higher than the conductivity of the outer parts. This will lead to more non-uniform electric field in which the field at the inner parts is reduced and instead the field at the outer parts will increase. This will increase the local field at the outer parts of the insulation system, specifically in the interface to the outer semi-conducting layer. Hence the risk of failure is increased.
Besides, considering the abnormal increase of apparent conductivity during cooling in the XLPE in contact with the semi-conducting material with cross-linking agent Vul-Cup®, will lead to dynamics, i.e. variations, in the electric field and to increased risk of instability in the insulation system.

Considering the results mentioned above, and comparing the conductivity of XLPE in contact with a semi-conducting material with and without the peroxide cross-linking agent Vul-Cup®, it is clear that using a semi-conducting material without Vul-Cup® (or very low concentration of Vul-Cup®) as the inner semi-conducting layer, i.e. the first semi-conducting layer, will help to make the electric field in the cable more uniform. This will lead to a cable with better field distribution and therefore a more robust insulation system.

It should be understood that the above description of preferred embodiments has been made in order to exemplify the invention, and that alternative solutions will be obvious for a person skilled in the art, however without departing from the scope of the invention as defined in the appended claims supported by the description and the drawings.
1. Electric power cable (1) comprising a metal conductor (2) and an electric insulation system (12) radially surrounding the conductor (2), which insulation system (12) comprises:
   - a first semi-conducting layer (4) comprising a polyethylene-based base polymer, wherein the first semi-conducting layer (4) surrounds the conductor (2);
   - an insulation layer (6) comprising a polyethylene-based base polymer, wherein the insulation layer (6) is in contact with and surrounds the first semi-conducting layer (4) radially outwards; and
   - a second semi-conducting layer (8) comprising a polyethylene-based base polymer, wherein the second semi-conducting layer (4) is in contact with and surrounds the insulation layer (6) radially outwards, characterized in that the base polymer in the first semi-conducting layer (4) is non-cross-linked, and wherein the base polymer in the insulation layer (6) is cross-linked.

2. Electric power cable according to claim 1, wherein the base polymer in the insulation layer (6) is cross-linked with dicumyl peroxide cross-linking agent.

3. Electric power cable according to any one of claims 1 or 2, wherein the base polymer in the second semi-conducting layer (8) is cross-linked.

4. Electric power cable according to claim 3, wherein the base polymer in the second semi-conducting layer (8) is cross-linked with a cross-linking agent that is different from the cross-linking agent used to cross-link the insulation layer (6).

5. Electric power cable according to claim 4, wherein the cross-linking agent is bis(tert-butylidioxyisopropyl)benzene.

6. Electric power cable according to any one of the preceding claims, wherein the polyethylene-based polymer is a low density polyethylene, ultra-low density polyethylene, linear low density polyethylene, high density polyethylene, ultra high density polyethylene, ultra high density polyethylene, or other suitable polyethylene type.
density polyethylene, or a mixture thereof.

7. Electric power cable according to claim 6, wherein the polyethylene polymer is a low density polyethylene.

8. Electric power cable according to any one of the preceding claims, wherein the first and the second semi-conducting layers (4, 8) comprise conductive particles in an amount of from 10 to 40 % by weight, based on the total weight of the first and/or the second semi-conducting layer, respectively.

9. Electric power cable according to claim 8, wherein the conductive particles comprise carbon black.

10. Electric power cable according to any one of the preceding claims, wherein the cable (1) is a power transmission cable having a rated voltage of 50 kV or higher.

11. Electric power cable according to any one of the preceding claims, wherein the cable (1) is a high voltage direct current (HVDC) cable.

12. Process for the production of an electric power cable (1) according to any one of claims 1-11 comprising the steps of:
   i) providing a conductor (2);
   ii) extruding a first semi-conducting layer (4) comprising a polyethylene-based base polymer to surround the conductor (2) radially outwards, wherein no cross-linking agent is added to the base polymer in the first semi-conducting layer (4);
   iii) extruding an insulation layer (6) comprising a polyethylene-based base polymer and a cross-linking agent, to be in contact with the first semi-conducting layer (4) and to surround the first semi-conducting layer (4) radially outwards;
   iv) extruding a second semi-conducting layer (8) comprising a polyethylene-based base polymer and optionally a cross-linking agent, to be in contact with the insulation layer (6) and to surround the insulation layer (8) radially outwards;
13. Process according to claim 12, wherein in the step iii), the base polymer in the insulation layer (6) is cross-linked by using dicumyl peroxide as a cross-linking agent.

14. Process according to claim 12 or 13, wherein in the step iv) the base polymer in the second semi-conducting layer (8) is cross-linked by using the same kind of cross-linking agent as used for the insulation layer (6).

15. Process according to claim 12 or 13, wherein in the step iv) the base polymer in the second semi-conducting layer (8) is cross-linked by using a cross-linking agent that is different from the cross-linking agent used to cross-link the insulation layer (6).

16. Process according to claim 15, wherein in the step iv) the cross-linking agent is bis(tert-butylidioxyisopropyl)benzene.

17. Process according to any one of claims 12-16 comprising a further step of:

vi) heat treating and degassing the cable to remove cross-linking by-products.
Fig. 4

- 1,3-Diacetyl benzene
- 1,4-diacetyl benzene
- ▲ 1,3-dihydroxy isopropylbenzene
- × 1,3-acetylhydroxy isopropylbenzene
- × 1,4-dihydroxy isopropylbenzene
- ● Sum by-products
**INTERNATIONAL SEARCH REPORT**

**A. CLASSIFICATION OF SUBJECT MATTER**

INV. H01B3/44 H01B9/02

ADD.

According to International Patent Classification (IPC) and both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

H01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal , WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<td>wo 2015/090643 AI (ABB TECHNOLOGY LTD [CH]) 25 June 2015 (2015-06-25) page 6, line 11 - page 12, line 40; claims 1-10; table 1</td>
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Further documents are listed in the continuation of Box C. See patent family annex.

*Special categories of cited documents:

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Date of the actual completion of the international search

21 September 2015

Date of mailing of the international search report

29/09/2015

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