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(54) **Coaxial fluid cooled high frequency high power cable.**

(57) Coaxial fluid cooled high frequency high power cable having a flexible central metal fluid duct and at least two coaxial conductors designed to minimize the skin effect, and the resultant cable current. Two cables may be interconnected with the individual conductors arranged antisymmetrically.

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Description

COAXIAL FLUID COOLED HIGH FREQUENCY HIGH POWER CABLE

The present invention relates to cables for transmission of high frequency high power from a power supply such as a power generator to a load such as a movable induction coil in connection with high frequency induction heating of an object.

For transmission of high frequency high current power special attention much be paid to the distribution of current over the available conductor cross section area. At induction heating frequencies the current distribution is governed by inductance rather than resistance which tend to force the current to flow in the smallest available current loop and only penetrate to the so called skin depth into the conductors. The skin depth in solid copper is 1.1 mm at 3 kHz, 0.5 mm at 20 kHz and 0.2 mm at 100 kHz. To transmit 1 kA with a current density of 10 A/mm^2 at 100 mm^2 effective cross section is needed. At 20 kHz with a skin depth of 0.5 mm this requires a conductor with a 200 mm circumference or 63 mm diameter.

The power loss for a solid copper conductor of this diameter will be great and it would require direct forced cooling. Together with the conductor for return current it would constitute a rather large and open current loop which would leak a very strong and dangerous high frequency magnetic field. A solution like this is clearly not satisfactory for many reasons.

The object of the present invention is to obtain a cable which is much more compact, flexible and well shielded and which can transmit the same current with only slightly higher loss.

The features of the cable of the present invention are defined in the claims.

The cable is flexible and combines supply of electrical power and fluid cooling to the load, such as an induction coil. The main advantages of the cable compared to simpler constructions are high power rating, low losses, low self inductance, efficient cooling, compactness and its complete shielding against leakage of magnetic and electric fields. The design is suitable for transmitting 1 MVA or more at frequencies ranging from 3 kHz to 100 kHz over distances in the range of 10 m. Such rating is necessary to handle a large reactive load with sufficient flexibility for system lay-out and mobility for the induction coil.

The basic idea for the design is to have conductors with a large circumference and a thickness approximately given by the skin depth at the design frequency. By arranging the tour and retour conductors insulated from each other in alternative layers in a coaxial geometry the net current in the cable will be zero and so avoiding any external magnetic field. In the hollow inner conductor the magnetic field will also be zero which facilitates material choice for the central cooling duct.

The specific construction with inner diameter, thickness and number of conductor layers, insulation thickness and total cross section will depend on the required current and voltage rating and frequency and on the permissible operating temperature.

For a given rating the losses will decrease for increasing total cross section and number of layers (i.e. decreasing layer thickness). On the other hand the radial thermal resistivity of the cable will be determined by the number and thickness of the insulation layers. For a given maximum operating temperature of the outer layer this will limit the number of conductor layers such that a practical feasible optimum will be from 2 to 5 conductor layers.

For a cable with only two conductor layers the effective conductor cross section will be given by the skin depth measured from the interface between the two conductors. For a cable with three or more conductor layers the middle conductor or conductors will be exposed to return current on both sides and the skin depth will be measured from both sides of the layer thereby doubling the effective conductor cross section for such layers. For protection and electrostatic shielding the cable should have an outer layer of insulation and an earthed metallic screen with an insulating protective covering.

The central cooling duct can be made of any material, but an all stainless steel armoured corrugated hose is preferred due to its good thermal conductivity, ruggedness and nonmagnetic properties. The magnetic properties are not important for the cable itself, but at the terminations there will be leakage fields which could otherwise increase losses.

The conductor layers should preferably be made of copper braid with a long pitch length to reduce the longitudinal current path. The braiding will tend to increase the effective skin depth, especially if each individual strand is laquer insulated. The same braided conductor can be used for all conductor layers by applying a double braid for the middle conductor layers.

The insulation layers between the conductor layers should be of a high quality material capable of operating at a high electric field strength at high frequency and temperature.

Due to the thermal resistance, but also to the self inductance of the cable it is important that the insulation layer is thin. An operating field strength above 1 kV/mm, but below the threshold for partial discharges and dielectric loss less than 10 W/m at the operating frequency and temperature should be a guideline for material choice. Suitable materials may be teflon or glass fibre tape with a temperature rating of up to 180°C.

Above mentioned and other features and objects of the present invention will clearly appear from the following detailed description of embodiments of the invention taken in conjunction with the drawings, where

- Figure 1 schematically shows a cable installation,
- Figure 2 shows one embodiment of the

invention,

- Figure 3 shows an alternative embodiment of the invention,
- Figures 4 and 5 show a power cable installation using two of the power cables of the present invention.

In Fig. 1 is schematically illustrated a power generator 1 supplying power via a flexible cable 2 to a load (not shown) arranged on or within a movable apparatus 3.

The cable 2 should in order to minimize losses contain at least one conductor for forward current as well as at least one conductor for return current.

In Fig. 2 is schematically illustrated the crossection of a cable according to the present invention. A fluid duct 10 in the center of the cable may be made of stainless steel preferably in the form of a corrugated hose, to make the duct sufficiently flexible. Over and in thermal contact with the duct 10 there is arranged a first cable conductor 11 which could be made from a number of braided copper wires. A heat resistive insulation layer 12 is placed over the conductor 11. This layer could be made from glass fiber tape, teflon tape or the like. The conductor 11/insulation 12 structure is duplicated in a second conductor 13 similar to the conductor 11 with an insulation layer 14 similar to the insulation layer 12. Externally the cable may include an electrostatic screen 21 made of metal wires or tapes and an outermost sheath 22 of insulation material.

The cable 2 described above has two coaxial conductors which will carry forward current and return current between a power supply 1 and a load 3. The cable is compact but flexible so that the load 3 may be movable. Efficient cooling is possible by forcing a fluid such as water or air through the duct 10. Furthermore the cable is completely shielded magnetically and electrostatically, when provided with a screen 21. The cable has low power losses due to the coaxial arrangement of the conductors. The power losses are further reduced due to the braided conductor construction.

In Figure 3 is illustrated a cable having three sets of conductors 11, 13, 15 with insulation 12, 14, 16. The crossection of the conductors 11, 13 and 15 should be chosen so that the sum of the crossection of conductors 11 and 15 corresponds to that of conductor 13. Thereby conductors 11 and 15 may carry current in one direction while conductor 13 carries current in the opposite direction.

A cable made according to the invention for carrying 1 kA at 1 kV and 20 kHz can be made as follows:

Central cooling duct 10: 13 mm (1/2") all stainless steel armoured hose.
First conductor 11: 50 mm^2 copper braid
Insulation 12: Double layer Teflon tape
Double layer glassfiber tape
Total thickness approx. 0,6 mm
Second (middle) conductor 13: 2x50 mm^2 copper braid
Insulation 14: as 12.
Third (outer) conductor 15: as (1)
Insulation 16: as 12.
Metallic screen and armouring 21: 50 mm^2 copper braid.
Sheath 22: Glassfiber tape.

The total diameter of such a cable may be 40-45 mm. A cable like this will operate at ca. 100°C overtemperature at the rated current.

When there is used one cable 2 between a power supply 1 and a load 3 there could be used an external return duct (not shown) for the cooling fluid.

It will, however, be practical to combine cooling of the cable with cooling of the load, such as an induction coil 3, and to use two parallel cables 2, 4 as illustrated in Fig. 4 and Fig. 5. In that case the respective conductor layers should be connected antisymmetrically to each other. The total rating of such a connection would be 2 MVA.

In the arrangement of using two parallel cables 2, 4 having conductors 30, 31 and 32, 33 as well as fluid ducts 34 and 35 respectively between the power supply 1 and the load 3, the duct 35 of the second cable 4 could be used as return fluid duct. When using two cables, each having at least two concentrical conductors 30, 31 and 32, 33, Fig. 5, the conductors within each cable should still be connected so as to carry current in both directions. As an example the inner conductor 30 of one cable 2 could be connected in parallel with the outer conductor 33 of the second cable 4, whereas conductor 31 is connected in parallel with conductor 32. The fluid ducts 34,35 are in direct contact with the conductors 30 and 32 respectively and with the load (the induction coil) 3.

When the cables contain three coaxial conductor layers 11, 13, 15, the conductors 11 and 15 of cable 2 could be connected in parallel with the conductor 13 of cable 4 to carry the foreward current, whereas the other conductors of the cables would carry the return current.

The above detailed description of embodiments of this invention must be taken as examples only and should not be considered as limitations on the scope of protection.

Claims

1. Coaxial fluid cooled high frequency high power cable (2, 4) capable of transmitting 1 MVA or more at a frequency in the range of 3 kHz to 100 kHz comprising a central cooling fluid duct (10), a coaxial conductor having suitable electrical insulation and possibly an outer metallic electrostatic screen (21) as well as insulation protective jacket(s) (22), **characterized in this t hat** it includes at least one additional coaxial conductor (11, 13, 15) and insulation (12, 14, 16).

2. Cable according to claim 1, **characterized in this that** the central cooling duct (10) is an armoured metallic hose, preferably all stainless steel.

3. Cable according to claim 1 or 2, **characterized in this that** at least one of the conductor layers (11, 13, 15) has a thickness given by the effective skin depth at the operating frequency.

4. Cable according to claims 1, 2 or 3, **characterized in this that** at least one of the layers (11, 13, 15) consists of a plurality of braided conductor strands.

5. Cable according to claim 4, **characterized in this that** the braided conductor strands are insulated from each other.

6. Cable according to claim 1, **characterized in this that** the middle (13) of three or more conductor layers have twice the thickness of the inner (11) and outermost (15) conductor layers.

7. Cable according to claim 1, **characterized in this that** the conductor layers (30, 31, 32, 33) are so connected as to carry current in alternating opposite directions, in order to reduce the resultant current in the cable.

8. Cable according to claim 7, **characterized in this that** the conductor layers are connected so that the total current of the cable is zero.

9. Power cable installation including a cable according to any of the preceeding claims, **characterized in this that** the cable (2) is operating in pair with an identical cable (4) and that the individual conductor layers (30, 31, 32, 33) are antisymmetrically connected.

10. Cable according to claim 1, characterised in this that the insulating layers (12, 14, 16) are made of thin high quality insulation material with high operating field strength, low dielectric losses and high temperature rating such as teflon and glassfiber tapes.

FIG.1

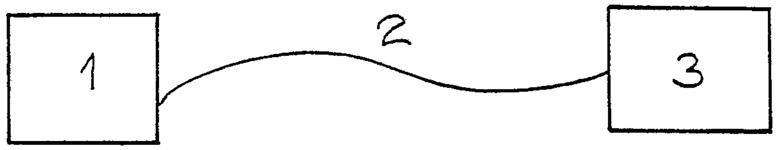

FIG.2

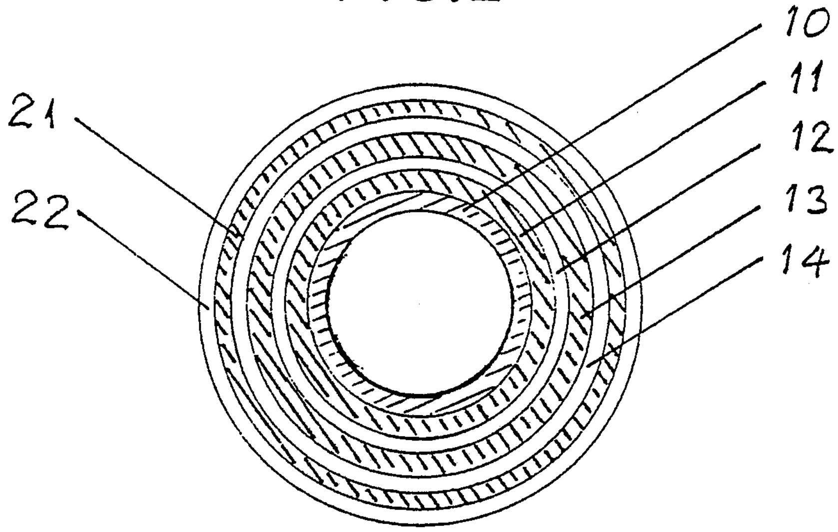

FIG.3

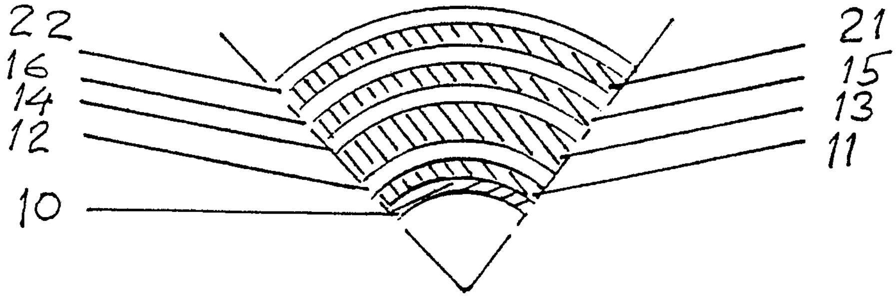

FIG.4

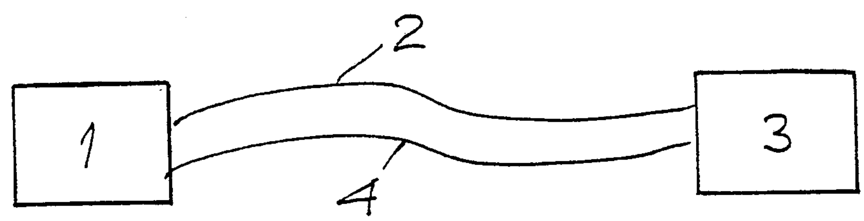

FIG.5