(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 2 833 378 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
04.02.2015 Bulletin 2015/06

(51) Int Cl.:
H01F 27/32 *(2006.01)*

(21) Application number: **13178808.5**

(22) Date of filing: **31.07.2013**

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME

(71) Applicant: **ABB Technology AG**
8050 Zürich (CH)

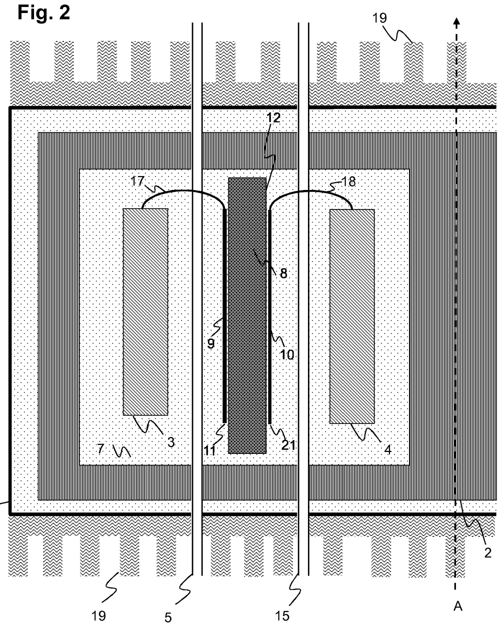
(72) Inventors:
- **Drofenik, Uwe**
  8053 Zürich (CH)
- **Brem, Franziska**
  8700 Küsnacht (CH)
- **Schuderer, Jürgen**
  8047 Zürich (CH)

(74) Representative: **ABB Patent Attorneys**
c/o ABB Schweiz AG
Intellectual Property CH-IP
Brown Boveri Strasse 6
5400 Baden (CH)

(54) Transformer

(57) The present invention is concerned with the field of power electronics, such as an induction electric apparatus, in particular a medium frequency transformer 1. The transformer 1, at least comprises a core 2, a primary winding 3, a secondary winding 4, at least one cooling channel 5, and an enclosure 6, wherein the enclosure 6 accommodates the core 2, the primary winding 3, the secondary winding 4, and the cooling channel 5 and the enclosure 6 is filled with an insulating medium 7. The least one cooling channel 5 is provided for cooling of the primary winding 3, the secondary winding 4, the enclosure 6 and/or the insulating medium 7. An insulating element 8 is placed between the primary winding 3 and the secondary winding 4, wherein a first conducting shield 9 is placed between the insulating element 8 and the primary winding 3 and a second conducting shield 10 is placed between the insulating element 8 and the secondary winding 4. Further the first conducting shield 9 is electrically connected to the primary winding 3 and the second conducting shield 10 is electrically connected to the secondary winding. The first cooling channel 5 is placed between the first conducting shield 8 and the primary winding 3.

Fig. 2



Printed by Jouve, 75001 PARIS (FR)

Description

FIELD OF THE INVENTION

[0001] The invention relates to the field of power electronics, such as an induction electric apparatus, in particular a transformer.

BACKGROUND OF THE INVENTION

[0002] An induction electric apparatus such as a transformer is part of a general power network system, in particular for transmitting power from a power plant to consumers. However, the transformer may be located in an environment where space is limited. Thus, the transformer needs to be designed to fit the limited space. An issue arising from said limited space is an required insulation between a primary and a secondary winding of the transformer starting to dominate the transformer size at high frequencies and/or small power. This issue may be resolved by filling the transformer, i.e. its enclosure, with a solid insulating material such as silicone.

[0003] At the same time a power density of the transformer needs to be increased to put large amounts of power through said apparatus. However, the power density of the transformer is generally limited by a maximum operating temperature. The maximum operating temperature depends on ambient temperature, energy losses during operation of the apparatus, and a thermal energy transfer of a region from an internal hot spot region. By filling the transformer with a solid insulating material the heat transfer away from said hot spots within the transformer is limited. Therefore, improving the heat transfer through the transformer components is critical to reduce volume as well as weight of the transformer and its components.

[0004] For medium frequency transformers by increasing the operating frequency size and weight of its components may be reduced. However, for said transformers the operating frequency can only be increased up to a maximum operating frequency due to several limiting factors such as an increasing operating temperature with increased frequency-dependent losses and reduced transformer size, required frequency-independent minimum insulation distances, or minimum insulation distances between the primary and the secondary winding. In particular, the minimum distances between the primary and secondary winding is determining the size of the transformer if its size is reduced by employing high frequencies. In addition, the increasing loss density and the maximum operating temperature require improved cooling of the transformer.

[0005] Document GB 853,913 describes a transformer, including a high-voltage layer winding, having one or more stress-distributing shields arranged between winding layers which are parallel connected. Electrically conductive shields are provided between the layers and are connected to the start and finish of the winding respectively. Electrostatic rings are provided in which the space between the layers forms a cooling duct. However, the optional cooling ducts in the prior art are located in the electric field between the shields, and the electric field will concentrate in said cooling ducts. This effect is intensified for a solid insulation between the windings for instance silicone gel. This will result in partial discharge within the cooling ducts leading to damage of the insulation of the transformer.

DESCRIPTION OF THE INVENTION

[0006] It is therefore an objective of the invention to provide a transformer with an increased power density. This objective is achieved by a transformer with an insulating element between a primary and a secondary winding, a conducting shield, and a cooling channel according to claim 1. Preferred embodiments are evident from the dependent patent claims, wherein the claim dependency shall not be construed as excluding further meaningful claim combinations.

[0007] According to the invention, a transformer is at least comprising a core, a primary winding, i.e. a coil, a secondary winding, at least one cooling channel, i.e. a pipe or duct, and an enclosure such as a casing, shell, or hull. The enclosure accommodates, i.e. receives or contains, the core, the cooling channel, and the primary winding and the secondary winding for instance such that the primary winding and the secondary winding are entirely enclosed, i.e. received or contained, by the enclosure. The enclosure is further filled with an electrically insulating medium or agent, i.e. an insulation medium, enabling heat transfer from the primary winding and the secondary winding to the cooling channel which acts as a thermal conductor guiding the heat from inside the enclosure to the ambient or a further cooling system outside the enclosure. This way the cooling channel provides cooling for the primary and secondary winding, the core, the insulating medium, and the enclosure.

[0008] Further an insulating element for instance a solid insulating element, i.e. a core, base, or kernel, is placed between the primary winding and the secondary winding. The insulating element may be suited to receive a large electric field for instance due to a potential difference, i.e. voltage difference, between the primary and secondary winding. In order to confine the electric field in the insulating element a first conducting shield, i.e. an element, unit, screen, or buffer is placed between the insulating element and the primary winding and a second conducting shield is placed between the insulating element and the secondary winding. To limit or confine the electric field in the insulating element, the first conducting shield is electrically connected to the primary winding and the second conducting shield is electrically connected to the secondary winding. This way the potential between the primary and secondary winding is transferred to the first and second conducting shield such that the electric field is confined in or limited to the insulating element.

[0009] Eventually, to allow proper cooling of the transformer, the first cooling channel is placed between the first conducting shield and the primary winding. The cooling channel may therefore be in direct contact with the insulating medium. This way the first cooling channel may transfer heat produced in the transformer, e.g. by the primary and secondary windings, to the outside of the transformer for instance the cooling channel may be part of a larger cooling system. By confining the electric field in the insulating element large electric fields are not present in the cooling channel and thus no partial discharges with subsequent damage for instance to the insulating medium is possible. This leads to an increased reliability and a prolonged lifetime of the transformer.

[0010] In order to allow for a robust design with minimal volume, controlling electrical stress at a periphery of the conducting shields is necessary. The periphery of the conducting shield gives rise to two major issues to be considered, first an increased or enhanced surface electric field from the conducting shield along an interface with the insulating element leading to surface and corona discharges with a risk for flashover breakdown, i.e. a voltage breakdown along the surface; and second an increased or enhanced electric field penetrating into the insulating element leading to heightened stress and discharges in the insulating element and eventually to dielectric breakdown.

[0011] In one embodiment of the invention, the periphery, i.e. border or boundary, of the first and the second conducting shield is drawn-in, i.e. retracted or recessed with respect to a periphery of the insulating element and wherein one of the first or second conducting shields is drawn-in further than the other conducting shield. For instance the conducting shield may be drawn-in on one side for roughly the width, i.e. thickness, of the insulating element, wherein the other conducting shield on the opposite side of the insulating element is drawn-in twice or more the width, i.e. thickness, of the insulating element. This way an easy to build design is provided to reduce the stress on the periphery of the conducting shield. However, in order to improve the stress reduction a further insulating element may be placed on the periphery of the insulating element covering the periphery of the conducting shields.

[0012] A further embodiment of the invention includes a nonlinear resistive field grader or a field grading material placed between at least one of the first or second conducting shields. The field grader is drawn-in with respect to the periphery of the insulating element and is drawn-in less than said conducting shield in the periphery. i.e. covers a greater area than the conducting shield. In this embodiment surface and bulk electric fields are effectively reduced. The nonlinear material of the field grader must have the correct switching field strength, which is the electric field strength at which the material switches from the insulating to the conductive mode. The switching field strength must be in the order of the ratio between maximum voltage applied and length or area of the field grading layer on the insulating element.

[0013] In this embodiment the width, i.e. thickness, of the insulating element may be significantly reduced compared to the design without the field grader. The conducting shield on one side may be placed on top of the field grader and its periphery may be drawn-in about twice as much a periphery of the field grader with respect to the periphery of the insulating element. At the same time the second conducting shield may be drawn-in less than the width, i.e. thickness, of the insulating element. However, in order to improve the stress reduction a further insulating element may be placed on the periphery of the insulating element covering the periphery of the conducting shields.

[0014] An exemplary design of the nonlinear resistive field grading layer is mixing ZnO microvaristor for instance in a polymer matrix. As ZnO microvaristor electrical characteristics can be widely tailored by specific doping and processing, e.g. the switching field strength ranging from 50V/mm up to 5000V/mm, and high nonlinearity is achieved with ZnO microvaristors. The nonlinearity is important since the higher the nonlinearity coefficient of the material, the better is its field grading performance, i.e., the lower a leakage current, and the less its frequency dependence. Other material or fillers for nonlinear resistive field grading may be SiC, doped SnO_2 or carbon black. Alternatively, other field grading methods such as linear resistive field control or refractive field grading may be considered.

[0015] In yet a further exemplary embodiment of the invention a periphery of at least one of the first and second conducting shields is curved away from the insulating element and wherein the insulating element has an enlarged periphery section, i.e. T-section or T-shaped periphery, supporting the curved periphery of said conducting shield. This way geometric field control via curved shields is provided. This is an effective field control to lower bulk and surface electric fields. However, in order to improve the stress reduction a further insulating element may be placed on the periphery of the insulating element covering the periphery of the conducting shields. The distance from the periphery of the first and second conducting shields is around the width, i.e. thickness, of the insulating element in the center of the insulating element. In this embodiment the width, i.e. thickness, of the insulating element at least in the center of the insulating element may be significantly reduced compared to the design without the curved conducting shields.

[0016] In a further variant of the invention, the transformer is a medium frequency transformer, wherein the primary winding and the secondary winding are formed of Litz wire and/or foil winding and wherein further the primary winding and the secondary winding are placed on the core forming a gap between the primary winding and the secondary winding.

[0017] In an advantageous embodiment of the invention, the cooling channel and/or the core are in direct contact with the insulating medium. In other words no gap, i.e. an air gap, is in between the core and the insulating medium. This way partial discharges, thus damage to the transformer, are avoided. In addition, heat transfer from the insulating medium to the cooling channel and the core is improved through the direct contact. The direct contact between the insulating medium and the cooling channel and the core may be particularly relevant for a medium frequency transformer, where high voltages may cause partial discharges and high frequencies may cause high amounts of heat.

[0018] In a variant of the invention, the cooling channels are part of a circulation system, e.g. comprising a pump and further supply and drain channels, provided with a cooling medium, i.e. liquid or gas, flowing through the cooling channel. This way the transformer may be actively cooled. For better cooling a more dense cooling liquid may be used. However, for a less dense cooling liquid, e.g. gas, the circulation system such as the pump may be a less sophisticated device for instance for air no tight sealing may be necessary.

[0019] In yet a further embodiment of the invention a second cooling channel is placed between the second conducting shield and the secondary winding. This way the cooling properties may be further improved and more heat may be transferred away from the hot spots of the primary and secondary windings. This may be necessary for applications causing a large amount of heat in the transformer. For other applications the transformer may be implemented more simple with only the first cooling channel.

[0020] In another variant of the invention a cooling element such as cooling plates, e.g. heat sink, cold plate, or two-phase cooling, is placed on the core, the insulating element, the insulating medium, and/or the enclosure for cooling of the transformer. This way the cooling element may provide a further way of transporting heat away from hot spots in the transformer and may be combined with the cooling channels and the circulation system.

[0021] In an advantageous embodiment of the invention, the insulating medium is one of a silicone gel, transformer oil, silicone-based or fluorinated hydrocarbons, polyurethane, synthetic rubber, any mix of these materials or any other similar material suited for cooling. A suited material may be for instance stable or suited for a temperature ranging between -40°C and +150°C and may have further a dielectric breakdown strength for instance from 15 to 22kV/mm. However, different parameters may apply for some applications.

[0022] In yet another embodiment of the invention, the insulating medium is a liquid and filled in the enclosure for instance from a top side of the enclosure. In this embodiment, the enclosure provides additional space for expansion of the insulating medium due to cycling and aging of the insulating medium within the enclosure. Silicone Gel used for power electronic modules is specified generally for temperature ranges between -40° and +150°C, i.e. for usage in 6.5kV power electronics modules with an expected 25 years of lifetime. Dielectric breakdown strength is typically 15 - 22kV/mm. Breakdown strength itself is not dependent on aging as the chemical structure is not changed, it is much more dependent on filling quality, voids and moisture uptake and partial discharge which depend mainly on processing and operation conditions. In order to prevent mechanical constraints for the silicone gel filling, the enclosure containing the silicone gel is filled from the top side with space provided for material expansion and contractions due to cycling and aging. This way the lifetime of the insulating medium may be improved.

[0023] In one embodiment, the transformer may be a single-phase, three-phase, or multi-phase transformer, i.e. a shell-type or core-type transformer.

[0024] In yet another embodiment, a cross-section of the insulating medium in an opening, i.e. a winding window or cut, of the core is greater than the cross-section of the primary winding and the secondary winding in said winding window, i.e. a copper-filling-factor of a winding window of the core is below 50%.

[0025] The invention improves the cooling of the transformer, thus, the power density of said transformer may be increased or at a given power and insulation voltage the transformer may be designed with a reduced weight and with reduced size compared to the prior art. The invention further provides a significant cost-, weight- and volume-reduction for a transformer in particular for a medium frequency transformer, especially if there are high voltages between primary- and secondary winding. Further yet a simple and effective cooling of the windings via convection very close to the windings and significantly reduced reliability problems associated with partial discharge in solid insulation materials and/or the cooling system are provided by the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] The subject matter of the invention will be explained in more detail in the following text with reference to preferred exemplary embodiments which are illustrated in the attached drawings, in which:

- Fig.1 schematically shows the a cross-section of a shell-type transformer along a horizontal plane through transformer with an insulating element between primary and secondary winding;
- Fig.2 schematically shows a another view along the section II-II of the shell-type transformer of Fig.1 with the insulating element, the cooling channels and cooling elements;
- Fig.3 schematically shows an insulating element of the transformer of Fig. 1 and 2 and having conducting shields;
- Fig.4 schematically shows another embodiment of an insulating element with a nonlinear resistive field grader and
- Fig.5 schematically shows another embodiment of an insulating element with a curved periphery.

[0027] The reference symbols used in the drawings, and their meanings, are listed in summary form in the list of designations. In principle, identical parts are provided with the same reference symbols in the figures.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0028] Fig.1 schematically shows a cross-section of a transformer 1 along horizontal plane of the transformer. The transformer, i.e. medium frequency transformer of a shell-type, at least comprising a core 2, a primary winding 3, a secondary winding 4, at least one cooling channel 5, and an enclosure 6. The windings 3, 4 may be formed from Litz wire and/or foil winding, in particular for a medium frequency transformer. The enclosure 6 accommodates the core 2, the primary winding 3 and the secondary winding 4 such that the primary winding 3 and the secondary winding 4 is entirely enclosed by the enclosure 6. Further the enclosure 6 is filled with an insulating medium 7 enabling heat transfer from the primary winding 3 and the secondary winding 4 to the cooling channel 5.

[0029] Between the inner primary winding 3 and the surrounding secondary winding 4 an insulating element 8 is placed as dielectric barrier. In the shown embodiment the insulating element 8 fully surrounds the secondary winding 4, where the primary winding 3 surrounds the insulating element 8. On the sides facing the primary winding 3 and the secondary winding 4 insulating shields 9 and 10 are placed on the insulating element 8. Said conducting shields 9 and 10 are ring shaped as well. Further said conducting shields 9 and 10 are electrically connected to the primary winding 3 and the secondary winding 4 respectively such that the conducting shield 9 is at the same potential as the primary winding 3 and the conducting shield 10 is at the same potential as the secondary winding 4. This way the electric field caused by the potential difference between the primary winding 3 and the secondary winding 4 is transferred to be between the conducting shields 9 and 10. By placing the conducting shields 9 and 10 on the insulating element 8 the electric field is further confined in the insulating element 8. Conducting shields 9 and 10 are placed on the insulating element 8 without an air gap, in between, thus avoiding partial discharges in the gap. This way no partial discharges may occur in the cooling channel 5 or the insulating medium 7, thus avoiding damage to the transformer 1 and increasing reliability of the transformer 1 and further prolonging its lifetime.

[0030] The insulating medium 7 may be in direct contact with the cooling channel 5 and the primary and secondary winding 3 and 4. The insulating medium also serves as a heat conductor to transfer heat away from hot spots in the transformer 1, i.e. the primary and secondary winding 3 and 4. By directly contacting the insulating medium 7 with the cooling channel 5 and the primary and secondary winding 3 and 4 it is ensured that heat is properly conducted away from the hot spot and transferred away from the transformer 1 by the cooling channel 5. For improved cooling properties a second cooling channel 15 may be placed on the opposite side of the insulating element 8, i.e. facing the secondary winding 4. This way an improved heat transport away from the secondary winding 4 is enabled.

[0031] The cooling channels 5 and 15 may be implemented as pipes or ducts, or as shown in Fig.1 as a plurality of pipes. The plurality of the pipes allows to increase the surface area which is cooled, and allows to adjust the pressure drop in the pipes for optimizing the coolant flow. This way any cooling liquid may be used to be pumped through the cooling channels 5 and 15. An alternative would be the use of air ducts in the insulating medium 7 as cooling channels 5 and 15. For instance in this case the insulating medium 7 may have gaps extending through the transformer 1. This may be a simple way of providing cooling channels 5 and 15 by forcing for instance air or any other suitable cooling gas through said gaps. This simple cooling option may be suitable for some applications with less heat production in the transformer 1.

[0032] Further the cooling channels 5 and 15 may surround or may be surrounded by the insulating element 8 along all sides. This may be balanced by the ratio of necessary insulation between the primary and secondary winding 3 and 4 and the necessary cooling provided by the cooling channels 5 and 15. For an application requiring high power density and high efficiency, the volume of the cooling channels 5 and 15 may be reduced by confining the cooling channels 5 and 15 to only one or two main sides of the insulating element 8 or by reducing its width over one side of the insulating element 8 as shown in Fig. 1.

[0033] Fig. 2 schematically shows a view as marked by the arrow along the section II-II of the shell-type transformer 1 of Figure 1 with the insulating element 8, the cooling channels 5 and 15 and in addition to what is shown in Figure 1 with cooling elements 19. The view of the transformer 1 is however for simplicity shown only partly in Fig. 2, where the shell-type transformer 1 is symmetrical and the shown features are to be mirrored on the right side of the core 2. The conducting shields 9 and 10 are placed on the insulating element 8 symmetrically, i.e. on one side facing the primary winding 3 and on another side facing the secondary winding 4. The insulating element 8 and the conducting shields 9 and 10 are ring shaped and surround the central leg of the transformer core 2. The conducting shields 9 and 10 are further drawn-in direction of the axis A and with respect to a periphery 11, 21 of the conducting shield respectively and to a periphery 12 of the insulating element 8. The axis A is defining the vertical direction of the transformer 1. With other words, the conducting shields 9 and 10 are of reduced length in direction of axis A in respect of the extension of the insulating element 8 in the direction of axis A. This way peak fields on the periphery 12 of the insulating element 8 are avoided and the lifetime of the insulating element 8 is increased.

[0034] Further the conducting shields 9 and 10 are electrically connected to the primary and secondary windings 3 and 4. For this an electrical connection 17 connects the primary winding 3 with the conducting shield 9 and an electrical connection 18 connects the secondary winding 4 with the conducting shield 10. This way the conducting shield 9 is on the same electrical potential as the primary winding 3 and the conducting shield 10 is on the same electrical potential as the secondary winding 4 . The electric field caused by the potential difference of the primary and secondary winding 3 and 4 is then confined between the conducting shields 9 and 10, where the insulating element 8 is made of a suitable material to further confine the electric field only to the insulating element 8. In addition the insulating medium 7 is in direct contact with the conducting shields 9 and 10, the insulating element 8, the cooling channels 5 and 15, the primary and secondary windings 3 and 4, the core 2, and with the enclosure 6 in order to avoid any gaps, i.e. air gaps between the components which may lead to partial discharges and damage to the transformer 1. This way the invention avoids partial discharges and damage to any parts of the transformer 1 and further prolonging the lifetime of the transformer 1.

[0035] In addition, the core 2 may be employed as a cooling element by serving as a heat sink which may be additionally cooled by the cooling channels 5 and 15. Further yet, an cooling element 19 such as cooling plates, e.g. a heat sink, cold plate, or a two -phase cooling maybe placed on the core 2, the insulating element 8, the insulating medium 7, and/or the enclosure 6 for cooling of the transformer 1. The cooling element 19 on the top and the bottom side of the enclosure 6 as shown in Fig. 2 is a heat sink with fins and a base, where the fins are increasing a surface area of the heat sink to increase the amount of dissipated heat via the heat sink to ambient. Other implementations of the cooling element 19 may be more sophisticated and require a cooling system with a cooling liquid, ducts, and a pump. Such a sophisticated cooling system may be necessary in some applications where large amounts of heat need to be dissipated from the transformer 1The cooling element 19 may be placed for instance on the core 2 or be in direct contact with the insulating medium 7.

[0036] The cooling channels 5 and 15 may be part of a larger cooling system as well. In this case a cooling liquid is forced through the cooling channels 5 and 15. The cooling liquid may be a liquid or gas, where a more dense liquid may provide better heat transport and thus better cooling of the transformer 1. However, tight sealing of supply and drain ducts connected to the cooling channels 5 and 15 may be necessary so that no cooling liquid spills. Further a pump may be necessary to force the cooling liquid through the cooling channels 5 and 15 and the supply drain ducts respectively.

[0037] Further for increased heat transfer from the primary winding 3 and the secondary winding 4 to the cooling channels 5 and 15, the insulating medium 7 may be one of a silicone gel, transformer oil, silicone-based or fluorinated hydrocarbons, polyurethane, synthetic rubber. For instance, a thermal conductivity of silicone gel can be higher than 20 times the thermal conductivity of air. Further, compared to oil, the thermal conductivity may be about a factor 8 higher. Further yet, epoxy filling has a thermal conductivity comparable to silicone gel, but as a solid material, serious reliability problems may occur such as cracks due to thermal cycling, partial discharge in cracks and voids. However, in case these issues are controlled epoxy filling may also be a suitable insulating medium 7. An advantage of silicone gel over other material is its high breakthrough field strength which allows insulation distances within the transformer 1, especially between windings 3, 4 and core 2, to be reduced by about a factor three or more compared to air insulation.

[0038] The invention allows reducing size and further simplifying the cooling of a transformer 1. The heat, i.e. thermal losses, flows from the windings 3, 4 via thermal conduction through the insulating medium 7 to the cooling channels 5 and 15. This configuration not only allows shrinking the component size significantly but also allows improved cooling.

[0039] In one embodiment of the invention, the copper cross section of the windings 3, 4 fills less than 50% of the winding window of the core 2.

[0040] For instance the insulating medium 7 may be supplied initially as two liquid components for mixing. The two components start cross linking after mixing. In a following step the mixture of the two liquid components is further cured. However, other material may be supplied as a granulate which is filled in the enclosure 6 and is further distributed or melted in the enclosure 6, i.e. by applying heat for a specified period of time. This may be carried out while placing the enclosure 6 for instance on a table where the granulate or the melted insulating material 7 may not leak or may only get in contact with the table top. After a cooling period the insulating material 7 solidifies and tight sealing of the enclosure is not necessary. Any material on the outside of the enclosure that may have leaked can be removed easily after solidification. However, proper outgassing of the material is necessary

[0041] Fig. 3 shows a cross-section of another embodiment of the insulating element 8 with the conducting shields 9 and 10 as it may be implemented in the transformer 1 of Figure 1 and 2, where the conducting shields 9, 10 are placed on the insulating element 8 such that stress on the periphery 11 and 21 of the conducting shields 9 and 10 may be controlled. The periphery 11, 21 of the conducting shields 9 and 10 give rise to two major issues to be considered. At first a surface electric field of the surface of the conducting shields 9 and 10 along an interface with the insulating element 8 may be increased and thus leading to surface and corona discharges with a risk for flashover breakdown, i.e. a voltage breakdown along the surface. At second an electric field penetrating into the insulating element 8 may be increased and thus leading to heightened stress and discharges in the insulating element 8 and eventually to dielectric breakdown.

[0042] The embodiment shown in Fig. 3 shows the periphery 11 and 21 of the conducting shields 9 and 10 drawn-in or recessed with respect to the periphery 12 of the insulating element 8. This way peak electric fields on the periphery 12 of the insulating element 8 are avoided and this results in a longer lifetime of the insulating element 8. In difference to what is shown in Figure 2 , the periphery 11 of the conducting shield 9 in Figure 3 is drawn-in more than the periphery 21 of the conducting shield 10. Thus, resulting in a slight asymmetric placement of the conducting shields 9 and 10 on the insulating element 8. This way peak electric fields are further reduced. In addition, a insulating cover element 16 may be placed on one end of the insulating element 8 for further protection of the periphery 11, 21 of the conducting shields 9 and 10 and the periphery 12 of the insulating element 8. The s insulating cover element 16 is covering the periphery 11 and 21 of the conducting shields and may have a U-shaped cross-section. In this case another insulating cover element 20 is placed on the opposite side of the insulating cover element 16 on the insulating element 8 to cover both ends of the insulating element 8.

[0043] Fig 4. shows a cross-section of an insulating element 8 as shown in Figure 3 and having in addition a nonlinear resistive field grader 14 placed in between the insulating element 8 and the conducting shield 9. The field grader 14 covers an area greater than the conducting shield 9 and has therewith an larger extension in the vertical direction of the transformer 1 compared to the extension of the conducting shield 9 in this direction. The field grader 14 reduces surface and bulk electric fields effectively. At the transition of an electric field from one medium to another medium, electric stresses harmful to the electric equipment can ensue due to a discontinuity in the electric field. Field grading or field grading material is causing the capacitance and electric stress to be more uniformly distributed between the conducting shield 9 and the insulating element 8. The application of such a field grading material as a field grader 14 results for instance in an increase of the breakdown voltage.

[0044] The nonlinear material of the field grader 14 must be designed to have the correct switching field strength which is the electric field strength at which the material switches from the insulating to the conductive mode. The switching field strength must be in the order of the ratio between maximum voltage applied and length of or area covered by the field grader 14, i.e. field grading layer.

[0045] A preferred design of the nonlinear resistive field grading layer is mixing ZnO microvaristor into a polymer matrix. ZnO microvaristor electrical characteristics can be widely tailored by specific doping and processing where the electric field strength ranges from 50V/mm up to 5000V/mm and high nonlinearity is achieved with ZnO microvaristors. The latter is important since the higher the nonlinearity coefficient of the material, the better is its field grading performance, i.e., the lower the leakage current, and the less its frequency dependence. Other material or fillers for nonlinear resistive field grading are SiC, doped SnO2 or carbon black. Other field grading methods such as linear resistive field control or refractive field grading may be applied as well. In addition, an insulating cover element 16 may be placed on one end of the insulating element 8 for further protection of the periphery 11, 21 of the conducting shields 9 and 10 and the periphery 12 of the insulating element 8 as described with respect to Fig. 3.

[0046] Fig. 5 shows another embodiment of the insulating element 8 as shown in the Figures 3 and 4 and as it may implemented in the transformer 1 shown in the figures 1 and 2. In difference to what is hown in the figures 3 and 4, the insulating element 8 of Figure 5 having the periphery 12 being curved and having the periphery 11, 21 of the conducting shields 9 and 10 being curved. This is an effective field control to lower bulk and surface electric fields. The periphery 12 of the insulating element 8 is curved as to support the curved periphery 11, 21 of the conducting shields 9 and 10.

[0047] The insulating element 8 has a width or thickness depending on the actual embodiment. The embodiment according to Fig. 3 has the greatest thickness and requires the most material, where the embodiments according to Fig. 4 and Fig. 5 have a similar thickness at least in the center of the insulating element 8. The embodiment of Fig. 4 is more complex and costly to actually form but does not require any field grading material such as the field grader 14. The use of one or another embodiment may depend on the actual application of the transformer 1 and the electric field and stress present in the insulating element 8.

[0048] For comparison of insulating medium 7, i.e. for a Silicon gel based transformer 1 according to the invention with a conventional air-insulated transformer, medium frequency transformers are considered employing copper-litz wire and a Ferrite N87 magnetic core 2 for a power of 170 kVA, an operating frequency of 3.5 kHz, and a voltage insulation between primary and secondary winding of 50kV. The transformer 1 according to the invention allows a reduction of the transformer volume by more than 2/3 compared to transformer of the prior art employing the same ratings. The mass of windings 3, 4 plus core 2 is reduced by more than half compared to air insulation combined with convective air cooling.

LIST OF DESIGNATIONS

[0049]

1	Transformer
2	Core
3	Primary winding
4	Secondary winding

5	Cooling channel
6	Enclosure
7	Insulating medium
8	Insulating element
9	First conducting shield
10	Second conducting shield
11	Periphery
12	Periphery
14	Field grader
15	Cooling channel
16, 20	Insulating cover element
17	Electrical Connection
18	Electrical Connection
19	Cooling element
21	Periphery

Claims

1. A transformer (1) at least comprising a core (2), a primary winding (3), a secondary winding (4), at least one cooling channel (5), and an enclosure (6),
wherein the enclosure (6) accommodates the core (2), the primary winding (3), the secondary winding (4), and the at least one cooling channel (5) and the enclosure (6) is filled with an insulating medium (7),
wherein the at least one cooling channel (5) is provided for cooling of the primary winding (3), the secondary winding (4), the enclosure (6) and/or the insulating medium (7),
wherein an insulating element (8) is placed between the primary winding (3) and the secondary winding (4),
wherein a first conducting shield (9) electrically connected to the primary winding (3) is placed between the insulating element (8) and the primary winding (3) and a second conducting shield (10) electrically connected to the secondary winding (4) is placed between the insulating element (8) and the secondary winding (4),
4wherein the at least one cooling channel (5) is placed between the first conducting shield (9) and the primary winding (3).

2. The transformer (1) according to claim 1, wherein a periphery (11, 21) of the first and the second conducting shield (9, 10) is drawn-in with respect to a periphery (12) of the insulating element (8).

3. The transformer (1) according to claim 2, wherein the first or the second conducting shield (9, 10) is drawn-in further than the other conducting shield (9, 10).

4. The transformer (1) according any of the claims 1 to 3, wherein a nonlinear resistive field grader (14) is placed between at least one of the first or the second conducting shields (9, 10) and is drawn-in with respect to the periphery (12) of the insulating element (8) and is drawn-in less than said conducting shield (9, 10) in the periphery.

5. The transformer (1) according to claim 4, wherein the nonlinear resistive field grader (14) comprises doped ZnO, SiC, doped SnO_2, or carbon black.

6. The transformer (1) according to claim 1, wherein a periphery (11, 21) of at least one of the first and second conducting shields (9, 10) is curved away from the insulating element (8) and wherein the insulating element (8) has an enlarged periphery section supporting the curved periphery (11) of said conducting shield (9, 10).

7. The transformer (1) according to any of the claims 1 to 6, wherein the at least one cooling channel (5) is part of a circulation system provided with a cooling medium flowing through the at least one cooling channel (5).

8. The transformer (1) according to claim 1, wherein an insulating cover element (16) encloses the first conducting shield (9), the second conducting shield (10), and the insulating element (8) in the periphery (12) of the insulating element (8).

9. The transformer (1) according to any of the claims 1 to 8, wherein at least a cooling channel (15) is placed between the second conducting shield (10) and the secondary winding (4).

10. The transformer (1) according to any of the claims 1 to 9, wherein a cooling element (19) is placed on the core (2), the insulating element (5), the insulating medium (7), and/or the enclosure (6) for cooling of the transformer (1).

11. The transformer (1) according to any of the claims 1 to 10, wherein the insulating medium (7) is one of a silicone gel, transformer oil, silicone-based or fluorinated hydrocarbons, polyurethane, synthetic rubber.

Fig. 1

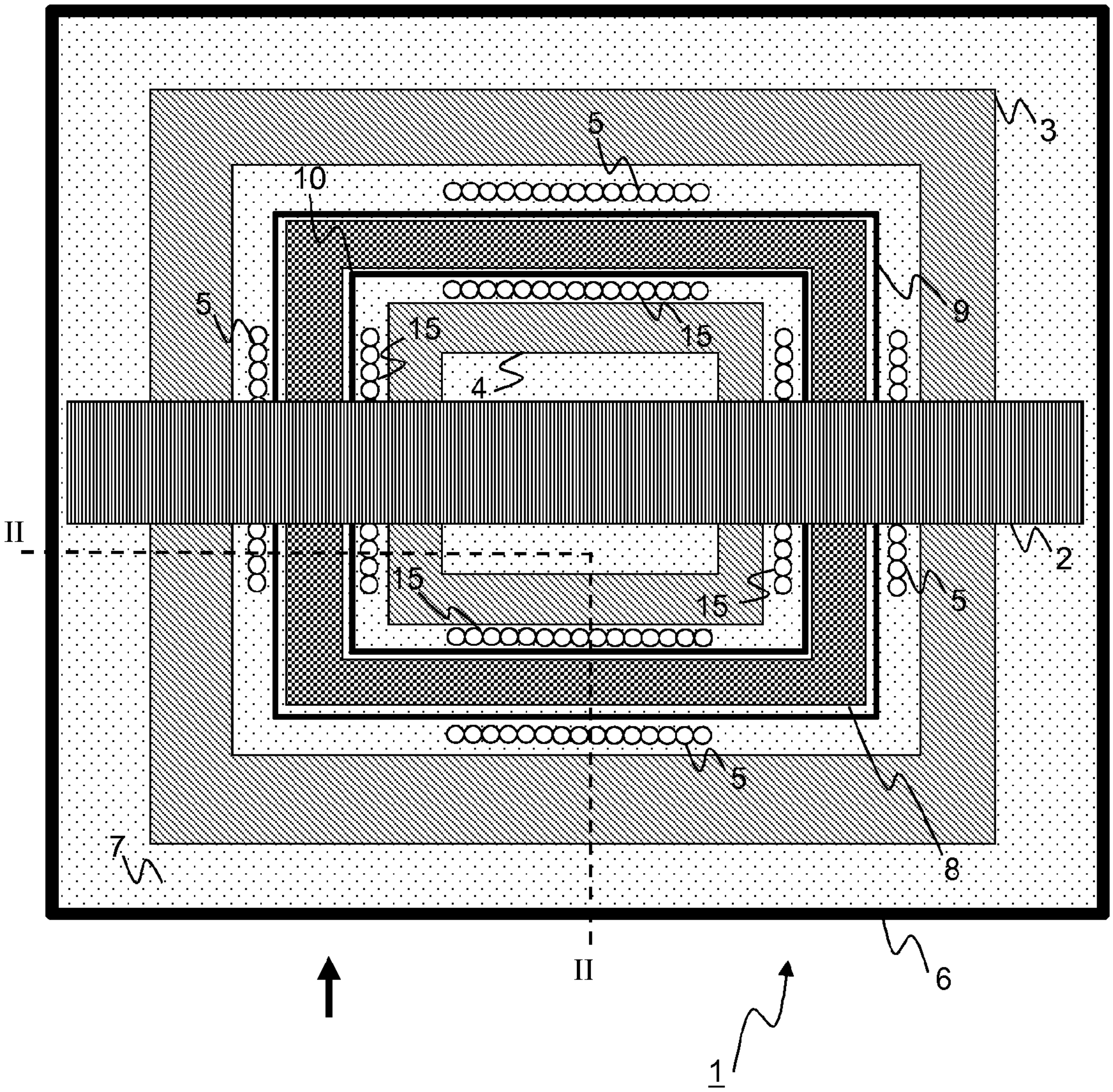


Fig. 2

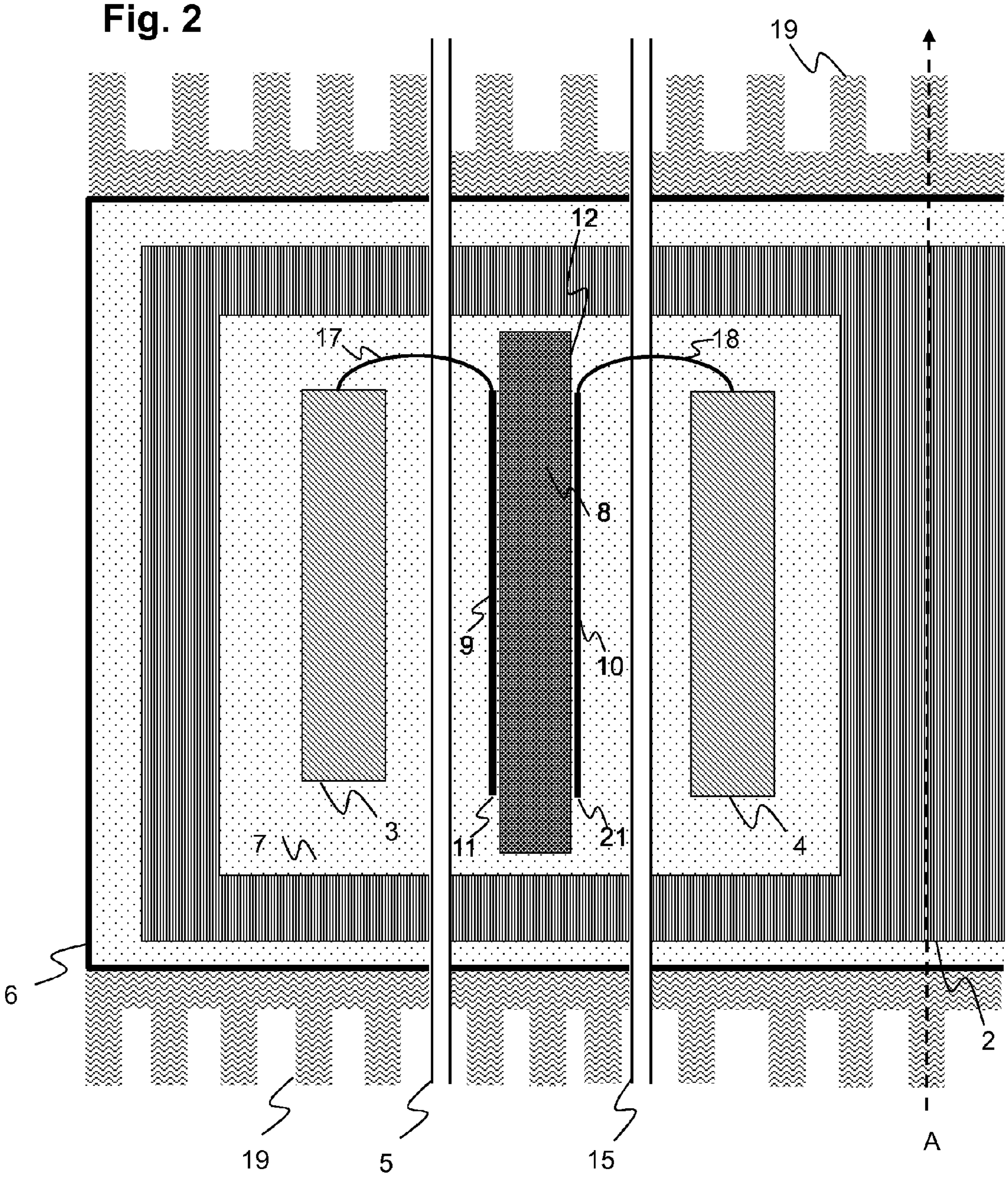


Fig. 3

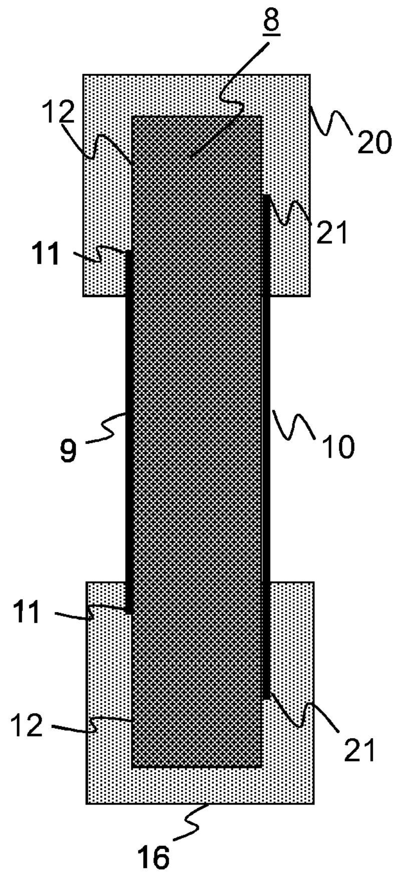


Fig. 4

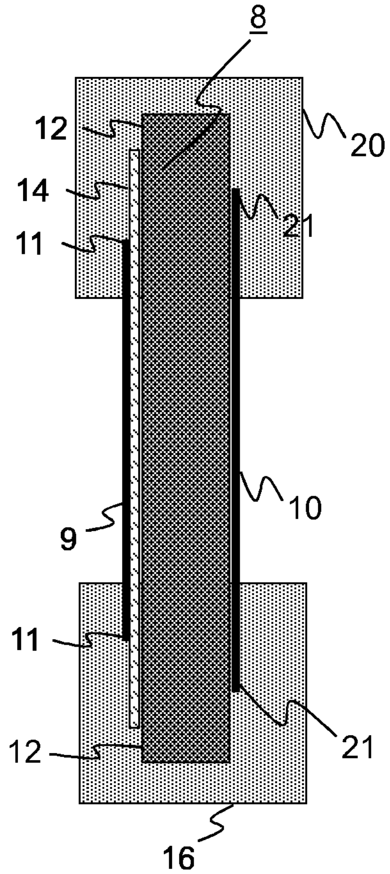
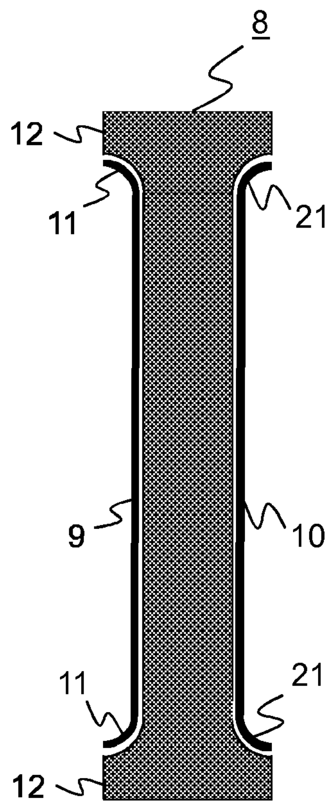


Fig. 5



Europäisches Patentamt
European Patent Office
Office européen des brevets

EUROPEAN SEARCH REPORT

Application Number
EP 13 17 8808

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	EP 0 061 608 A1 (SMIT TRANSFORMATOREN BV [NL]) 6 October 1982 (1982-10-06) * page 1, lines 11 - 16, 28 -34 * * page 2, lines 17 - 26 * * page 4, lines 1 - 24 * * page 5, lines 14 - 25 * * figure 1 * -----	1-11	INV. H01F27/32
A	EP 2 428 967 A1 (ABB TECHNOLOGY AG [CH]) 14 March 2012 (2012-03-14) * paragraphs [0001], [0009], [0016], [0022] * * figure 2 * -----	1-11	
A	US 4 725 804 A (YARPEZESHKAN HASSAN [US]) 16 February 1988 (1988-02-16) * column 1, lines 8-11 * * column 3, lines 8 - 27 * * figures 1, 2 * -----	1-11	
A	EP 2 075 806 A1 (ELETTROMECCANICA DI MARNATE S [IT]) 1 July 2009 (2009-07-01) * paragraphs [0001], [0014], [0031], [0032] * * figures 3, 4 * -----	1	TECHNICAL FIELDS SEARCHED (IPC) H01F

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	13 December 2013	Van den Berg, G

2

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons
....
& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 13 17 8808

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

13-12-2013

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0061608 A1	06-10-1982	DE 3113139 A1	21-10-1982
		EP 0061608 A1	06-10-1982
		JP S5812313 A	24-01-1983
EP 2428967 A1	14-03-2012	CA 2810416 A1	15-03-2012
		CN 103125003 A	29-05-2013
		EP 2428967 A1	14-03-2012
		ES 2406408 T3	06-06-2013
		US 2013181796 A1	18-07-2013
		WO 2012031646 A1	15-03-2012
US 4725804 A	16-02-1988	NONE	
EP 2075806 A1	01-07-2009	NONE	

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- GB 853913 A **[0005]**