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[Continued on next page]

(54) Title: WINDING FOR A ROTATING ELECTRICAL MACHINE AND METHOD FOR DESIGNING SUCH A WINDING

(57) Abstract: The invention provides a winding (40) for a rotating electrical machine (1) comprising a flexible PCB (45) having a plurality of conductors (60) on a first surface and a plurality of conductors (60) on a second surface, said conductors having a shape optimizing the performance of the machine, and a method for designing such a winding.

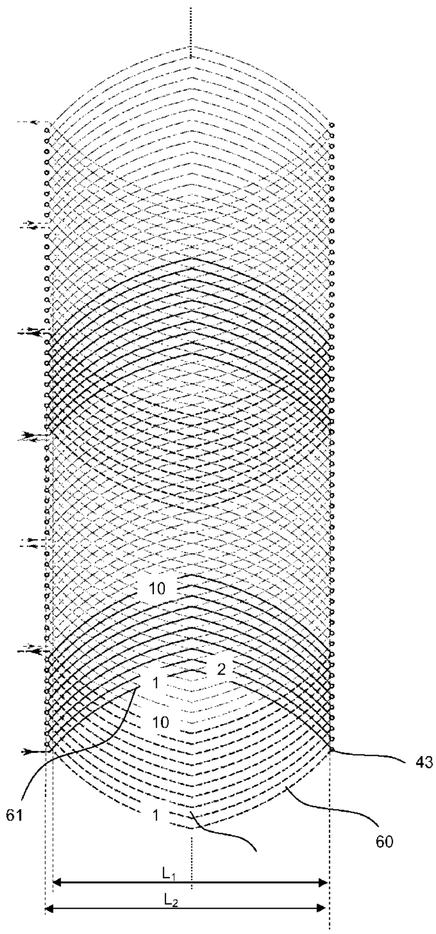

Fig. 7a

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Winding for a Rotating Electrical Machine and Method for Designing such a Winding

Field of the invention

[0001] The invention relates to a winding for a rotating electrical machine, the machine comprising an inductor, an iron core, and an air gap in between, the winding comprising a flexible PCB having a plurality of conductors on a first surface and a plurality of conductors on a second surface of a substrate, said conductors being tracks printed on said PCB, a conductor of the first surface being connected through a via to a conductor of the second surface so as to form a turn, such that when rolled up one or more times, along the length, it is adapted for inserting into said air gap in an axial direction. The invention also relates to a method for designing such a winding.

Description of prior art

[0002] Traditional windings made of copper wire have been known and used for producing electric motors such as Brushless DC electric motors (BLDC motors). Windings printed on flexible circuit board (Flex-PCB) have also been used for producing such motors, offering the opportunity to improve the performance of these BLDC motors since, compared with windings made from copper wire, they are easier to produce, and less expensive and give more flexibility in shape and design.

[0003] Document FR76288 discloses a planar DC motor, where the useful magnetic field of the magnets is axial, whose windings are printed on a rigid planar PCB with conductors on a first surface of the PCB, and circuits on the second surface of the PCB, connected through vias. This document discloses the use of windings with curved shape conductors. The use of windings with a curved shape in planar motors is well known to improve the performances of the machine. However, despite the fact that curved shape windings are well known in planar motors, these windings are not known as improving the performances of the Brushless DC electric motors (BLDC motors) where the useful magnetic field of the magnets is radial.

Documents US20090072651 and FR2262880 both disclose slotless windings for rotating electric machines and a manufacturing method thereof. These documents disclose the use of a flexible PCB, with conductors on a first surface of the PCB, and conductors on the second surface of the PCB, connected through vias. However, these document do not address the problem of optimizing the performance, are limited to windings whose conductors on each PCB surface are made of two or three rectilinear segments, and do not describe how the connections between conductors on the first and second surface are implemented.

[0004] A flex-PCB slotless winding for a BLDC machine is known from "B. Dehez, M. Markovic, Y. Perriard, "Analysis and comparison of classical and flex-PCB slotless windings in BLDC motors," Electrical Machines and Systems (ICEMS), 2012 15th International Conference on, pp.1-6, 21-24 Oct. 2012". This document, hereafter referenced as **Reference 1**, describes the general structure of a BLDC motor. An analytical expression of two parameters characterizing the winding, i.e. the torque constant and the electrical resistance are given. A comparison is made between a classic copper-wire winding, and a Flex-PCB winding having a simple shape (a conductor on one side of the PCB having three segments from the bottom of the PCB to the top of the PCB, forming either a skewed or a rhombic winding, as shown on Fig. 2 and Fig. 3 respectively) showing a potential 30% improvement in power density of the Flex-PCB winding over the classic copper-wire winding. However, no attempt is made at finding a design with optimal performance. No details are given as to how the conductors on the first surface are arranged with the conductors of the second surface so as to form coils or series of turns.

Summary of the invention

[0005] It is an object of the present invention to provide a winding for a rotating electrical machine having an improved performance and a method for designing such a winding.

[0006] The invention is defined by the independent claims. The dependent claims define advantageous embodiments.

[0007] According to a first aspect of the invention, there is provided winding for a rotating electrical machine, said machine comprising an inductor, an iron core, and an air gap in between, said winding comprising a flexible PCB having a plurality of conductors on a first surface and a plurality of conductors on a second surface of a substrate, said conductors being tracks printed on said PCB, a conductor of the first surface being connected through a via to a conductor of the second surface so as to form a turn, said PCB having an height and a length, such that when rolled up one or more times, in one or more layers, along the length, it is adapted for inserting into said air gap in an axial direction. According to the invention, a conductor has a shape extending from a bottom height of said flexible PCB to a top height of said PCB in an axial direction, along a continuous curve or a number n of rectilinear segments, n being larger than 3. The applicant has found, that, by giving the conductors a more complex shape, i.e. a continuous curve or a more than three rectilinear segments, unexpectedly good results could be obtained as to increase the performance of the electrical machine.

[0008] Preferably, the shape has a variable width such that the gap between a conductor and a neighboring conductor is equal to a predetermined constant along the length of said conductor. The predetermined constant distance is selected so as to achieve a good electrical insulation between two adjacent conductors located on the same side of the PCB. In other words, the conductors have a variable width.

[0009] When the shape of the conductors is extending along a number n of rectilinear segments, n is advantageously larger than 6 and smaller than or equal to 100. The applicant has found that 6 or more segments still improve the performance, but than no significant improvement can be obtained by using more than 100 segments.

[0010] According to a first preferred embodiment, the conductors have a line symmetric shape, the symmetry axis being a line along the length of the PCB, at mid-height of the PCB. This kind of winding is know in the art as a lap winding.

[0011] Preferably, a plurality of turns is connected in series so as to form a coil.

[0012] In a first connection mode, a conductor on the first surface of one turn is extended along its length and connected trough a via to a conductor on the second surface, having a corresponding extension, so as to form a connection between two successive turns of said coil, the two successive turns being at a distance in the length direction.

[0013] In a second connection mode, said plurality of turns is a number t of turns, conductors of the first surface being numbered from 1 to t in the length direction, conductors of the second surface being also numbered from 1 to t in the length direction, conductor i on the first surface being connected at the upper end of the PCB to conductor t-i of the second surface through a track extending along the length direction of the PCB, at decreasing heights, for i=1 to i=t-1;

and conductor i on the first surface being connected at the lower end of the PCB to conductor t-i+1 of the second surface through a track extending along the length direction of the PCB, at increasing heights, for i=1 to i=t. Conductors number t of first and second surface are connected to terminals. By using this second connection mode, the same torque as in the first connection mode is obtained. However, as the overall length of the conductors is shortened, the resistance is lower and the performance is improved.

[0014] According to a second preferred embodiment, said conductors have point symmetric shape, the reflection point being at mid-height of the PCB This kind of winding is know in the art as a wave winding.

[0015] Preferably, a plurality of turns are connected in series and forming a series of turns.

[0016] In a first connection mode, a plurality of adjacent series of turns are arranged at a distance in the length direction, a conductor on the first surface of one turn of one series is extended along its length and connected trough a via to a conductor of a successive series on the second surface, having a corresponding extension, so as to form a connection between two successive series, the two successive series being at a distance in the length direction.

[0017] In a second connection mode, a plurality of adjacent series of turns are arranged successively at a distance in the length direction, said plurality of series is a number t of series, adjacent conductors being numbered from 1 to t on both the first and second surface, and conductors 1 to t on the first surface are connected at the upper end of the PCB to conductors t to 1 respectively on the second surface through t tracks extending along the length direction of the PCB, at decreasing heights, and conductor 1 to t on the second surface being connected at the lower end of the PCB to conductor t to 1 of the first surface through t tracks extending along the length direction of the PCB, at increasing heights. For one serie of adjacent turns of the said plurality of series, conductors 1 to t-1 on the first surface are connected at the upper end of the PCB to conductors t-1 to 1 respectively on the second surface through t-1 tracks extending along the length direction of the PCB, at decreasing heights. Conductors number t of first and second surface are connected to terminals. By using this second connection mode, the same torque as in the first connection mode is obtained. However, as the overall length of the conductors is shortened, the resistance is lower and the performance is improved.

[0018] The tracks of the second connection mode, in the first and in the second embodiment may advantageously be located on both the first and the second surface of the PCB. This will further reduce the resistance of the winding and improve the performance of the machine.

[0019] In this case, the tracks on both sides of the PCB may be connected through a plurality of vias.

[0020] The shape of the winding/conductors may advantageously be designed for optimizing the ratio k_p of the torque constant k_T over the square root of the phase resistance R_{ph} of said winding.

$$k_p = \frac{k_T}{\sqrt{R_{ph}}}. \qquad (1)$$

Other objective functions to be optimized may be selected: the efficiency, i.e. the ratio of power output to power input, or the power density, or the size of the electrical machine.

[0021] According to a second aspect of the invention, there is provided method for designing a winding for a rotating electrical machine, said machine comprising an inductor, an iron core, and an air gap in between, said winding comprising a flexible PCB having a plurality of conductors on a first surface and a plurality of conductors on a second surface, said conductors being tracks printed on said PCB, a conductor of the first surface being connected through a via to a conductor of the second surface so as to form a turn, said PCB having an height and a length, such that when rolled up one or more times, in one or more layers, along the length, it is adapted for inserting into said air gap in an axial direction. A conductor extends from a bottom height of the flexible PCB to a top height of the PCB in an axial direction, along a continuous curve or a number n of rectilinear segments, n being larger than 3, and has a variable width such that the gap between a conductor and a neighboring conductor is equal to a predetermined constant along the length of said conductor.

According to the invention, the method comprises the steps of

a) determining the torque constant k_T of said rotating electrical machine in dependence of the geometric parameters of the shape of said conductor;
b) determining the phase resistance R_{ph} of said winding in dependence of the geometric parameters of the shape of said conductor;
c) varying the shape parameters for optimizing the objective function

$$k_p = \frac{k_T}{\sqrt{R_{ph}}}.$$

for obtaining the optimal shape of said conductors

The other objective functions discussed above may also be selected.

[0022] The optimization may advantageously be performed using a genetic algorithm.

Short description of the drawings

[0023] These and further aspects of the invention will be explained in greater detail by way of example and with reference to the accompanying drawings in which:

Fig.1 is a schematic section along a plane perpendicular to the axis of a rotation electrical machine according to the invention.

Fig.2a and 2b are a schematic representation of a PCB of a winding according to the invention, in a rolled up, and in a flat configuration, respectively, a turn having a lap configuration.

Fig.3a and 3b are a schematic representation of a PCB of a winding according to the invention, similar to Fig.2a and 2b, where the conductors have more rectilinear segments and therefore a still more improved shape.

Fig.4a and 4b are a schematic representation of a PCB of a winding according to the invention, in a rolled up, and in a flat configuration, respectively, a turn having a wave configuration.

Fig.5a and 5b are a schematic representation of a PCB of a winding according to the invention, similar to Fig.4a and 4b, where the conductors have more rectilinear segments and therefore a still more improved shape.

Fig.6a represents the shape of a conductor of a winding according to the invention, having a number of rectilinear segments.

Fig.6b represents the relative gain on the performance ratio k_p in dependence of the number n of rectilinear segments of a conductor.

Fig. 7a and 7b represent the winding of machines according to a first embodiment and second embodiment of the invention respectively, in a first mode of inter-turn connections.

Fig. 8a and 8b represent the winding of machines according to a first and second embodiment of the invention respectively in a second mode of inter-turn connections.

Fig. 9a and 9b is a view and a detailed enlarged view of the inter-turn connections according to the first mode of inter-turn connection, in the first embodiment of the invention.

Fig. 10a and 10b is a view and a detailed enlarged view of the inter-turn connections according to the second mode of inter-turn connection, in the first embodiment of the invention.

[0024] The drawings of the figures are neither drawn to scale nor proportioned. Generally, identical components are denoted by the same reference numerals in the figures.

Detailed description of embodiments of the invention

[0025] Fig.1 is a schematic section along a plane perpendicular to the axis of a rotation of a rotating electrical machine 1 according to the invention. Starting from the centre, there is a shaft 10 which may be made of iron or other ferromagnetic material, having radius R_r. On the shaft, there is an inductor, which may be a permanent magnet 20, which may be a 2-pole magnet, extending from radius R_r up to radius R_m, producing a magnetic field in a direction perpendicular to the axis of rotation, whose magnetization is directed along the arrow at azimuthal angle θ. The inductor may also be a coil fed with a DC current. There is an air gap 30, extending from radius R_r up to radius R_m, separating the rotor and the stator of the electrical machine. The winding according to the invention 40 is arranged between radius R_w and R_s. An iron housing 50, extending from radius R_s to radius R_e, which may be made of iron or other ferromagnetic material closes the magnetic circuit.

[0026] Fig.2a is a schematic representation of a PCB 45 of a winding 40 according to a first embodiment of the invention, in a rolled up configuration. Fig.2b shows the same PCB 45 in a flat configuration. The length φ corresponds to the azimuthal angle when the PCB is wound up. The height L_w of the PCB extends along the axis of the electrical machine when the PCB is wound up and inserted into the air gap. A conductor 61, printed on one side (visible side) of the PCB 45, is represented as a continuous line. Another conductor 60, printed on the other side of the PCB 45 is represented as a dashed line. Conductors 60 and 61 have a line symmetry (or mirror symmetry) with respect to a line at mid-height of the PCB 45. Conductors 60 and 61 are mirror images of each other with respect to a vertical line. Conductors 60 and 61 may be connected through a via 43 at the bottom, and form a lap turn 41. Although the conductors 60,61are represented on the drawings as extending upon the whole of the height L_w, the substrate of the PCB may extend a little so as to provide a margin. When a current flows in the turn 41, a magnetic field is generated perpendicular to the plane of the drawing. Each of the conductors 60 and 61 are comprised of n=4 rectilinear segments. The winding of Fig.2b may be rolled up in one turn, the right-hand side of the turns overlapping the left hand-side of the turns. The PCB of Fig.2b may also be extended a number of times in the length direction, and either rolled up said number of times, for forming a winding having a plurality of layers, or rolled up in one turn, for forming a winding having more poles and a larger diameter. Combinations of multi-layer, multiple poles windings may also be designed.

[0027] Fig.3a and 3b are similar to Fig.2a and 2b, but the number n of rectilinear segments is equal to 10. By increasing the number of rectilinear segments, a practically continuous curve can be obtained.

[0028] Fig.4a, 4b, 5a, and 5b are similar to Fig2a, 2b, 3a, 3b, but the conductors 60, 61 have point symmetry with respect to a point at mid-length. Conductors 60 and 61 are also mirror images of each other with respect to a vertical line. Conductors 60 and 61 may be connected through a via 43, and form a wave turn 42.

[0029] Fig.6a represents the shape of a conductor of a winding according to the invention, having a number of rectilinear segments. The conductor 60 comprises a number of rectilinear segments, with edges joined as shown in Fig.6a, in a continuous manner. By increasing the number n of segments, a continuous curve can be approached as close as desired. A segment s_i is defined by the coordinates of its extremities, (φ_{i-1}, z_{i-1}) and (φ_i, z_i). The width W_i of a segment depends on its slope and on the distance between the conductor and a neighbouring conductor. By using the PCB technology, a winding of any shape may be designed. The applicant of the present invention has shown that, by carefully designing the shape of the conductor, a significant improvement in the performance of an electrical machine both in terms of power density and electrical efficiency can be obtained.

[0030] Fig. 7a represents the winding for a rotating electrical machine according to a first embodiment of the invention and a first connection mode of turns. A plurality of successive turns are connected in series so as to form a coil. A first conductor 61 (number 1) on the front side of the PCB is linked at the top to a current entry terminal represented by a down arrow and at the bottom to the first conductor 60 (also number 1) on the back surface of the PCB through a via. The first conductor 60 then crosses first conductor 61 at an height indicated by L_1, and is extended up to an height indicated by L_2 so as to cross and connect through a via 43 with conductor number 2 of the front surface. These extensions ensure that the conductors of the second turn are located at a distance from the conductors of the first turn. The length of theses extensions are such that the distance between turns is equal to a predetermined constant. Conductors on the front surface and back surface are similarly connected in series up to the last (10^{th}) conductor 60 of the back surface, which arrives at a current exit terminal represented by an up arrow. Three phases are represented. When the right-hand end of the winding is rolled up one time so as to cover the left-hand end of the winding, a three-phase, two-poles winding is formed. The winding may also be extended, as suggested by the dotted lines, and rolled-up one or more times so as to form any number of phases, poles and layers.

[0031] Fig. 7b represents the winding for a rotating electrical machine according to a second embodiment of the invention and a first connection mode of turns. Turns are connected in series so as to form a series of turns. Starting from the current entry terminal represented by a down arrow, a first conductor 61 is connected through a bottom via 43 to a first conductor 60 of the back surface and the again through a top via 43' at height L_1 to a first conductor 61' of the front surface. When the winding is rolled up, the bottom end of this conductor is connected to the bottom end of a first conductor 60, forming a first series of turns. Successive series of turns are connected, through vias 44, relying on extensions up to height L_2, so that successive series of turns are separated a predetermined distance in the length direction. The upper end of last (10^{th}) conductor 60 is connected to a current exit terminal represented by an up arrow. Vias 44 are at a height L_2 between the two current terminals and vias 43' are at a height L_1 elsewhere. When the right-hand end of the winding is rolled up one time so as to cover the left-hand end of the winding, a three-phase, two-poles winding is formed. The winding may also be extended, as suggested by the dotted lines, and rolled-up one or more times so as to form any number of phases, poles and layers.

[0032] Fig. 8a represents the winding of a machine according to a first embodiment of the invention in a second mode of inter-turn connections. Starting from the current entry terminal represented by a down arrow, a last (10^{th}) conductor 61 on the front surface is connected to a horizontal track 65 at the bottom of the PCB, and extending up to the first conductor 60 of the back surface. Conductors, vias, and horizontal tracks succeed as represented on Fig.8a in a spiral fashion up to last (10^{th}) conductor 60 of the back surface which is connected to a current exit terminal represented by an up arrow.

Successive horizontal tracks 65 are shorter and shorter, and nearer to mid-horizontal line of the PCB. The last track, i.e. the connection between first conductor 61 of the front surface and last conductor (conductor number 10) of the back surface at the bottom and conductor number 9 at the top may be very short or even non-existing. As discussed with reference to Fig.7a, when the right-hand end of the winding is rolled up one time so as to cover the left-hand end of the winding, a three-phase, two-poles winding is formed. Also, the winding may be extended, as suggested by the dotted lines, and rolled-up one or more times so as to form any number of phases, poles and layers.

[0033] Fig. 8b represents the winding of a machine according to a second embodiment of the invention in a second mode of inter-turn connections. It is similar to Fig.7b, and uses the inter-turn connection of Fig.8a.

[0034] Fig. 9a is a view of a single coil of the winding of Fig.7a. Fig.9b is an enlarged view of the upper part of Fig.9a. The two arrows represent the currents in corresponding portions of conductors 60 of the back and 61 of the front surface. As is well known by the man skilled in the art, only the axial component of currents will generate a torque in a motor. Therefore, in the nearly triangular regions where the conductors 60 of the back surface and 61 of the front surface overlap, the resulting torque will be nil (the vector resulting from the two arrows is in the horizontal direction, without axial component). This explains why the second mode of inter-turn connection, represented in Fig.10a and 10b represents no loss in torque when the electrical machine is a motor. For a same geometry and currents, the winding of Fig 10a will produce the same torque as the winding of Fig.9a. Compared to the winding of Fig.9a, the winding of Fig.10a has and shorter tracks, and therefore a reduced phase resistance R_{ph}. For the same reasons, when the electrical machine is a generator, the emf generated with the winding of Fig.10a will be equivalent.

[0035] Two parameters determine essentially the performance of an electrical machine: the torque constant k_T, i.e. the ratio of torque to current, and the phase resistance R_{ph}, i.e. the overall resistance of the conductors. The relation of these parameters to the geometric, shape parameters of the winding have been given in reference 1, and more specifically for the torque constant at equations 16 for a wave winding (skewed winding) and at equation 17 for a lap winding (rhombic winding). Theses parameters depend also on other parameters, such as voltage, current, shape of field created by the permanent magnet. These parameters have not been varied in the optimization process. The phase resistance has been given at equation 29, with reference to equations 17 and 18 for a wave winding, and equation 21 and 22 for a lap winding.

The parameter k_p of equation 1 is an image of the torque density of a motor of given size. Indeed, multiplying the numerator and denominator of the ratio by the current amplitude, the parameter k_p appears to be nothing else than the ratio between the motor torque and the root square of the Joule losses. For the same dimensions, and therefore, pretty much, for the same capacity of evacuating the heat losses, the motor with the highest k_p will then be able to develop the highest nominal torque.

A search has been performed for finding the geometric parameters of a conductor, as discussed in relation to Fig.6a, giving the higher value of k_p. For different values of the number n of rectilinear segments of the conductor, the following relative values of k_p have been found:

n	k_p
2	100%
3	109,5%
4	112%
10	114%

These results show a significant increase in performance of the improved shapes of the invention with respect to the know shapes. Fig.6b shows the dependence of the performance ratio on n. A substantial increase is obtained with n=10. No significant improvement is observed for higher values of n.

[0036] The present invention has been described in terms of specific embodiments, which are illustrative of the invention and not to be construed as limiting. More generally, it will be appreciated by persons skilled in the art that the present invention is not limited by what has been particularly shown and/or described hereinabove. More specifically, the winding of the invention may be provided on the stator or the rotor of the electrical machine. The electrical machine may be a motor or a generator. The conductors on the first and second surfaces of a PCB described above may equivalently be on two or more layers of a multi-layer PCB. Although in the above examples, the successive turns of a coil or of a series of turns have been represented as having the same shape and width, the shape and width of each conductor of a coil or series of turns can be considered as parameters for optimizing further the performance of the machine.

[0037] Reference numerals in the claims do not limit their protective scope. Use of the verbs "to comprise", "to include", "to be composed of", or any other variant, as well as their respective conjugations, does not exclude the presence of elements other than those stated. Use of the article "a", "an" or "the" preceding an element does not exclude the presence of a plurality of such elements.

[0038] The invention may also be described as follows: the invention provides a winding for a rotating electrical machine comprising a flexible PCB having a plurality of conductors on a first surface and a plurality of conductors on a second surface, said conductors having a shape optimizing the performance of the machine, and a method for designing such a winding.

Claims

1. Winding (40) for a rotating electrical machine (1), said machine comprising an inductor (20), an iron core (50), and an air gap (30) in between, said winding (40) comprising a flexible PCB (45) having a plurality of conductors (60) on a first surface and a plurality of conductors (61) on a second surface of a substrate, said conductors (60, 61) being tracks printed on said PCB (45), a conductor (60) of the first surface being connected through a via (43) to a conductor (61) of the second surface so as to form a turn (70, 80), said PCB (45) having an height and a length, such that when rolled up one or more times, in one or more layers, along the length, it is adapted for inserting into said air gap (30) in an axial direction,
characterized in that
a conductor (60, 61) has a shape extending from a bottom height of said flexible PCB (45) to a top height of said PCB (45) in an axial direction, along a continuous curve or a number n of rectilinear segments, n being larger than 3.

2. Winding (40) according to claim 1 characterized in that said conductor has a variable width such that the gap between a conductor (60, 61) and a neighbouring conductor (60, 61) is equal to a predetermined constant along the length of said conductor (60, 61).

3. Winding (40) according to claim 1 or 2 characterized in that said conductor (60, 61) extends along a number n of rectilinear segments, n being larger than 6 and smaller than or equal to 100.

4. Winding (40) according to any of claims1 to 3, characterized in that said conductors (60, 61) have a line symmetric shape, the symmetry axis being a line along the length of the PCB (45), at mid-height of the PCB (45).

5. Winding according to claim 4, characterized in that a plurality of turns are connected in series so as to form a coil.

6. Winding according to claim 5, characterized in that a conductor (60) on the first surface of one turn is extended along its length and connected trough a via (43) to a conductor (61) on the second surface, having a corresponding extension, so as to form a connection between two successive turns of said coil, the two successive turns being at a distance in the length direction.

7. Winding according to claim 5, characterized in that said plurality of turns is a number t of turns, conductors (60) of the first surface being numbered from 1 to t in the length direction, conductors (61) of the second surface being also numbered from 1 to t in the length direction, and conductor i on the first surface being connected at the upper end of the PCB (45) to conductor t-i of the second surface through a track (65) extending along the length direction of the PCB, at decreasing heights, for i=1 to i=t-1;
and conductor i on the first surface being connected at the lower end of the PCB to conductor t-i+1 of the second surface through a track (65) extending along the length direction of the PCB, at increasing heights, for i=1 to i=t.

8. Winding according to claim 1 to 3, characterized in that said conductors have point symmetric shape, the reflection point being at mid-height of the PCB (45).

9. Winding according to claim 8, characterized in that a plurality of turns are connected in series and forming a series of turns.

10. Winding according to claim 9, characterized in that a plurality of series of turns are arranged successively at a distance in the length direction, a

conductor on the first surface of one turn of one series is extended along its length and connected trough a via (44) to a conductor of a successive series on the second surface, having a corresponding extension, so as to form a connection between two successive series, the two successive series being at a distance in the length direction.

11. Winding according to claim 9, characterized in that a plurality of series of turns are arranged successively at a distance in the length direction said plurality of series is a number t of series, adjacent conductors being numbered from 1 to t on both the first and second surface, and conductors 1 to t on the first surface are connected at the upper end of the PCB to conductors t to 1 respectively on the second surface through t tracks (65) extending along the length direction of the PCB, at decreasing heights, and conductors 1 to t on the second surface being connected at the lower end of the PCB to conductor t to 1 of the first surface through a track (65) extending along the length direction of the PCB, at increasing heights, except for one of the said plurality of series where conductors 1 to t-1 on the first surface are connected at the upper end of the PCB to conductors t-1 to 1 respectively on the second surface through t-1 tracks (65) extending along the length direction of the PCB, at decreasing heights, conductors t of the first and second surface being connected to terminals.

12. Winding according to claim 7 or 11 characterized in that said tracks extending along the length of the PCB are located on both the first and the second surface of the PCB

13. Winding according to claim 12 characterized in that a plurality of vias (43) are connecting said corresponding tracks on the first and second surface of the PCB.

14. Winding according to any of claims 1 to 13 characterized in that said shape is designed for optimizing the ratio k_p of the torque constant k_T over the square root of the phase resistance R_{ph} of said winding,

$$k_p = \frac{k_T}{\sqrt{R_{ph}}}.$$

15. Method for designing a winding (40) for a rotating electrical machine (1), said machine comprising an inductor (20), an iron core (50), and an air gap (30) in between, said winding (40) comprising a flexible PCB (45) having a plurality of conductors (60) on a first surface and a plurality of conductors (61) on a second surface, said conductors (60,61) being tracks printed on said PCB, a conductor (60) of the first surface being connected through a via (43) to a conductor (61) of the second surface so as to form a turn, said PCB having an height and a length, such that when rolled up one or more times, in one or more layers, along the length, it is adapted for inserting into said air gap in an axial direction,

wherein a conductor extends from a bottom height of said flexible PCB to a top height of said PCB in an axial direction, along a continuous curve or a number n of rectilinear segments, n being larger than 3, and has a variable width such that the gap between a conductor (60,61) and a neighbouring conductor (60, 61) is equal to a predetermined constant along the length of said conductor,

comprising the steps of

a) determining the torque constant k_T of said rotating electrical machine in dependence of the geometric parameters of the shape of said conductor;
b) determining the phase resistance R_{ph} of said winding in dependence of the geometric parameters of the shape of said conductor;
c) varying the shape parameters for optimizing the objective function

$$k_p = \frac{k_T}{\sqrt{R_{ph}}}.$$

for obtaining the optimal shape of said conductors

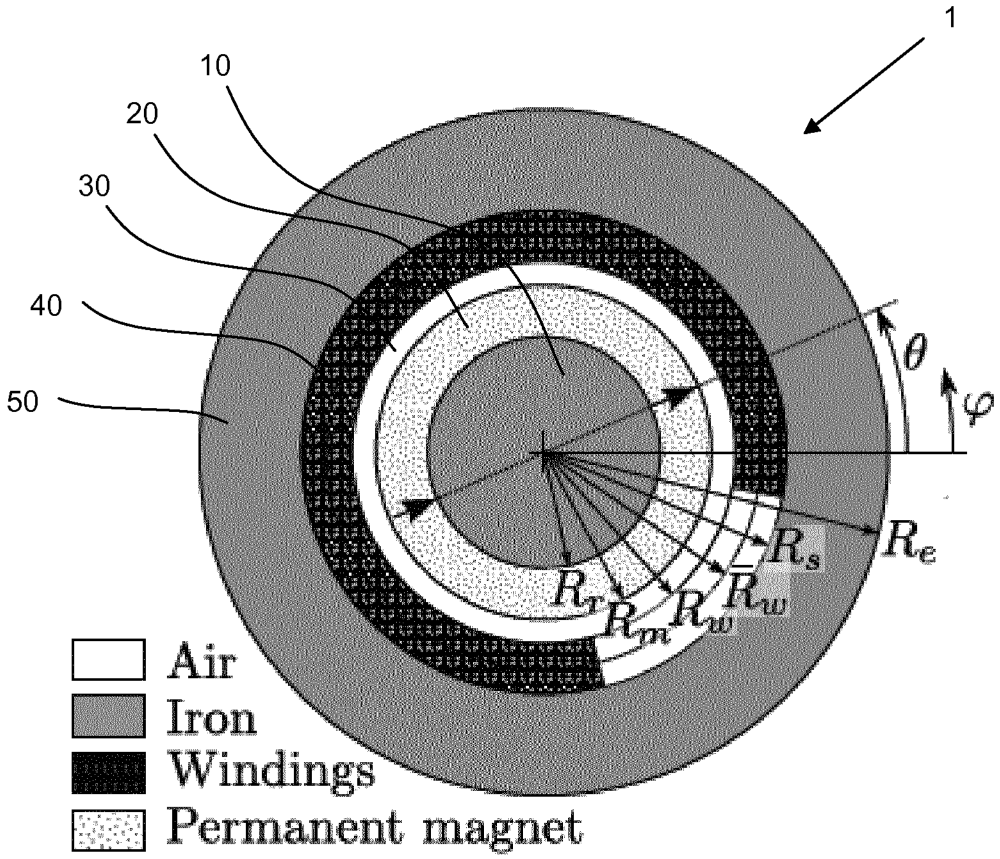

1
10
20
30
40
50
θ
φ
R_s
R_e
R_r
R_m
R_w
$\bar{R}_w$
Air
Iron
Windings
Permanent magnet

Fig. 1

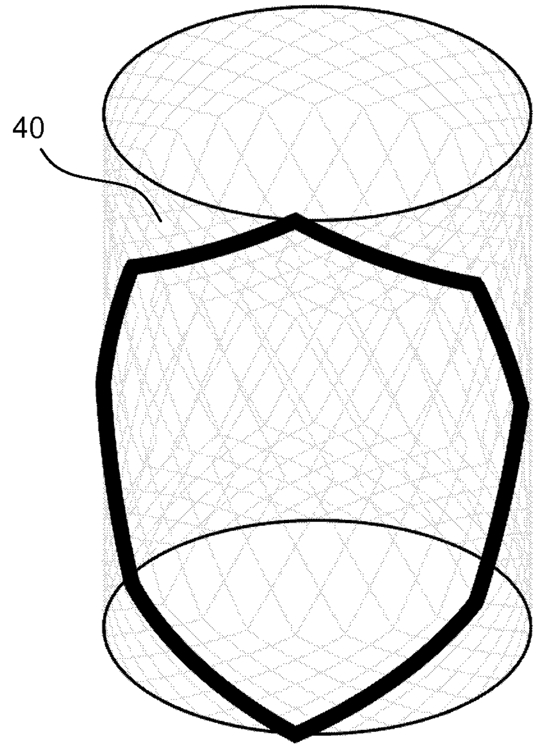


Fig. 2a

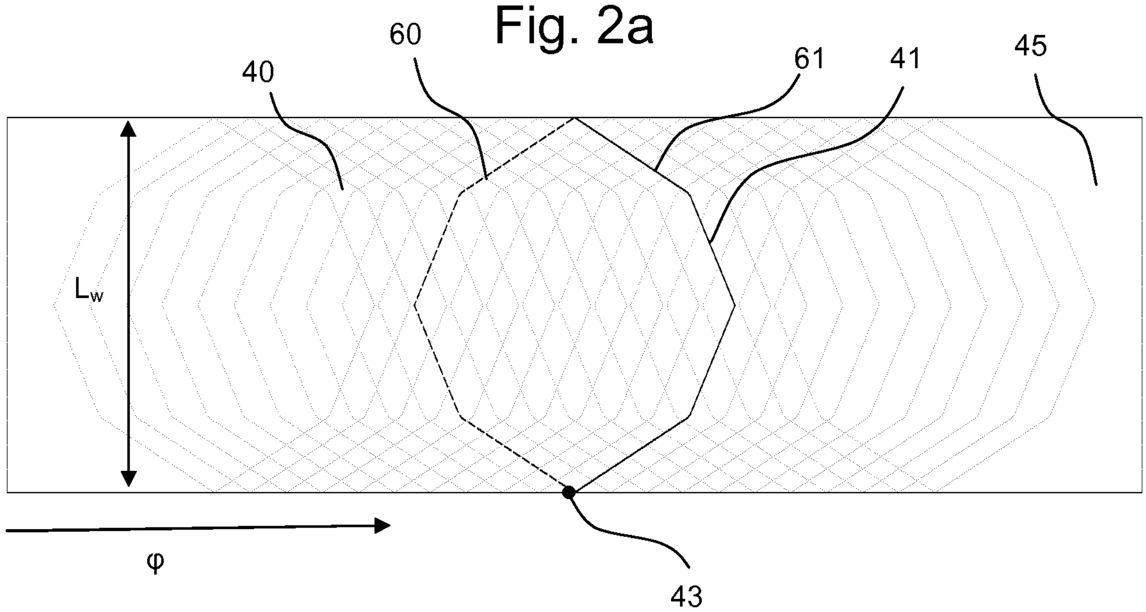


Fig. 2b

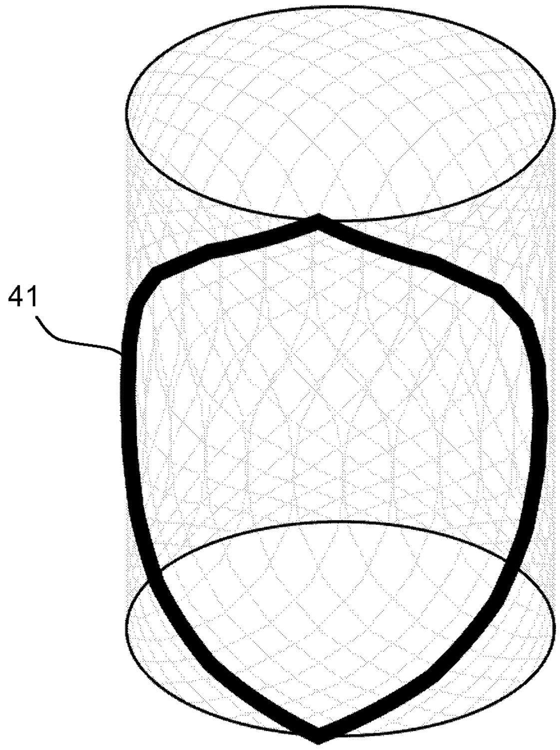


Fig. 3a

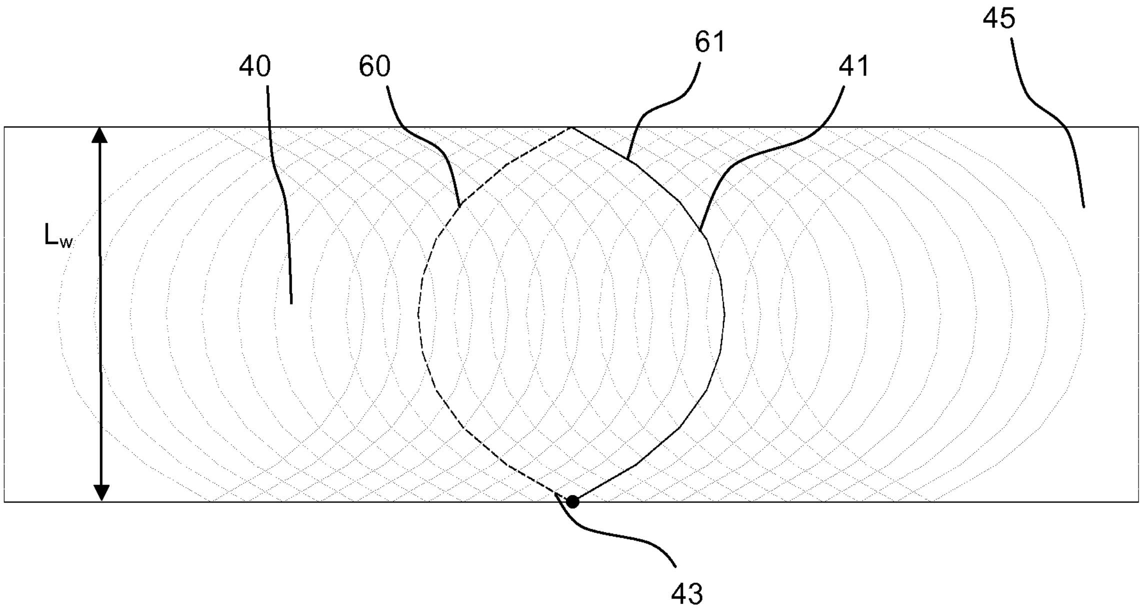


Fig. 3b

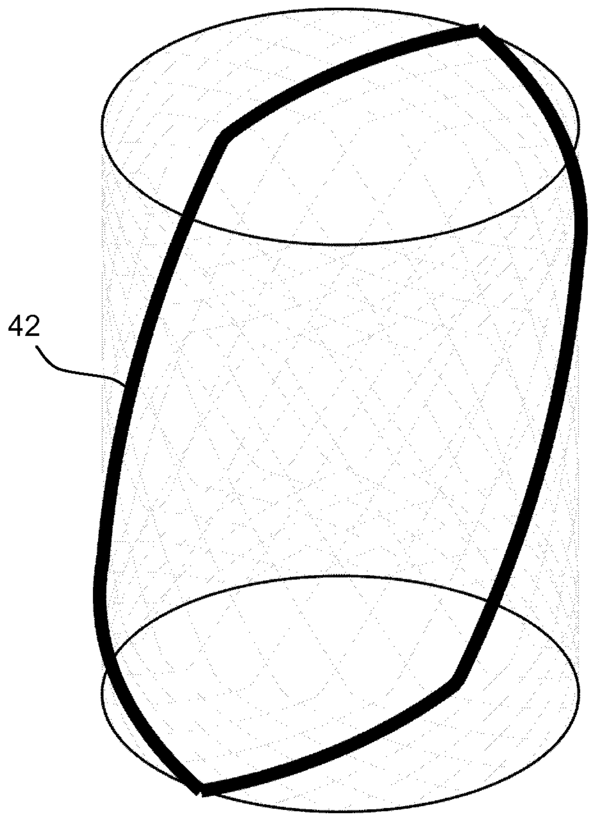


Fig. 4a

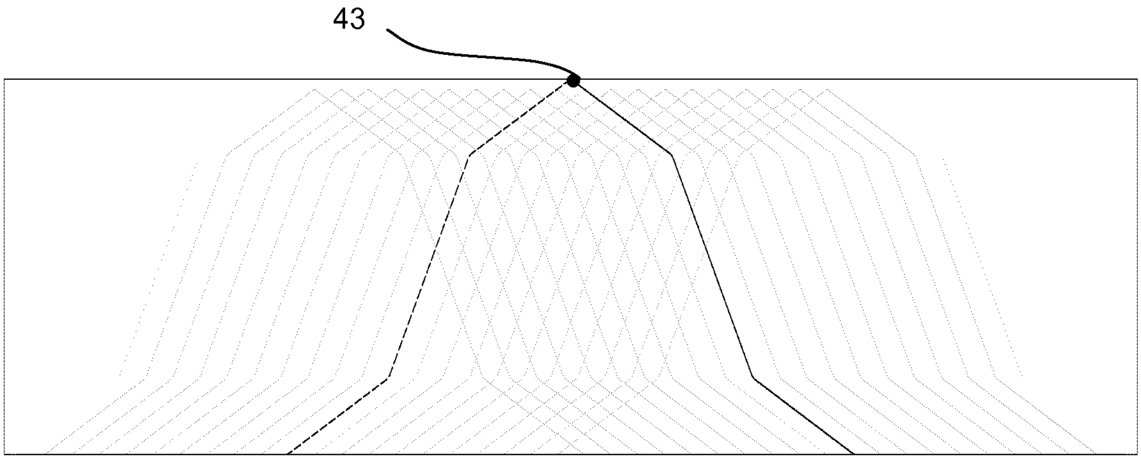


Fig. 4b

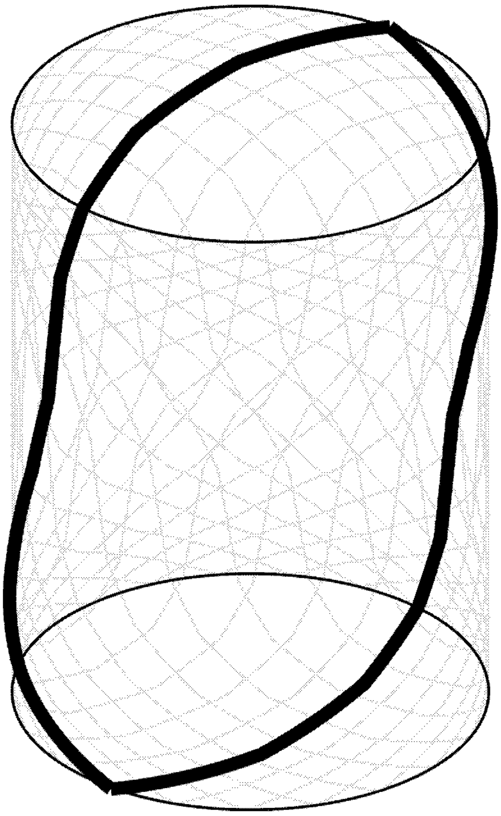


Fig. 5a

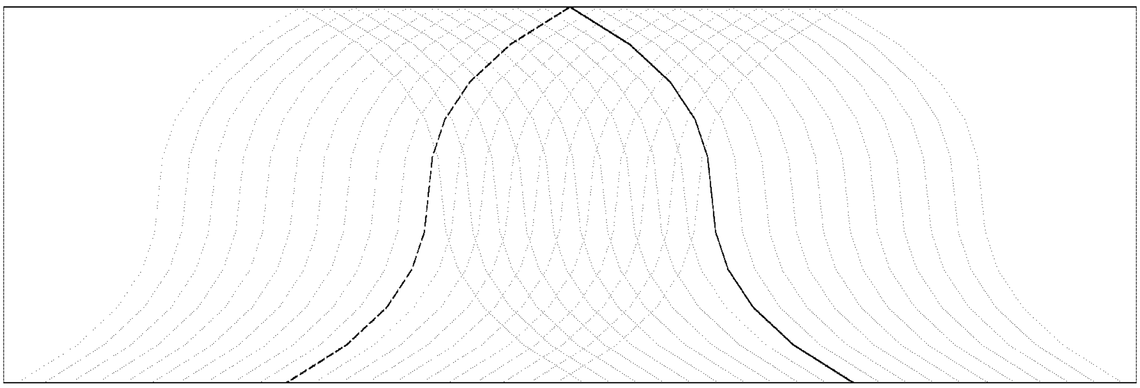
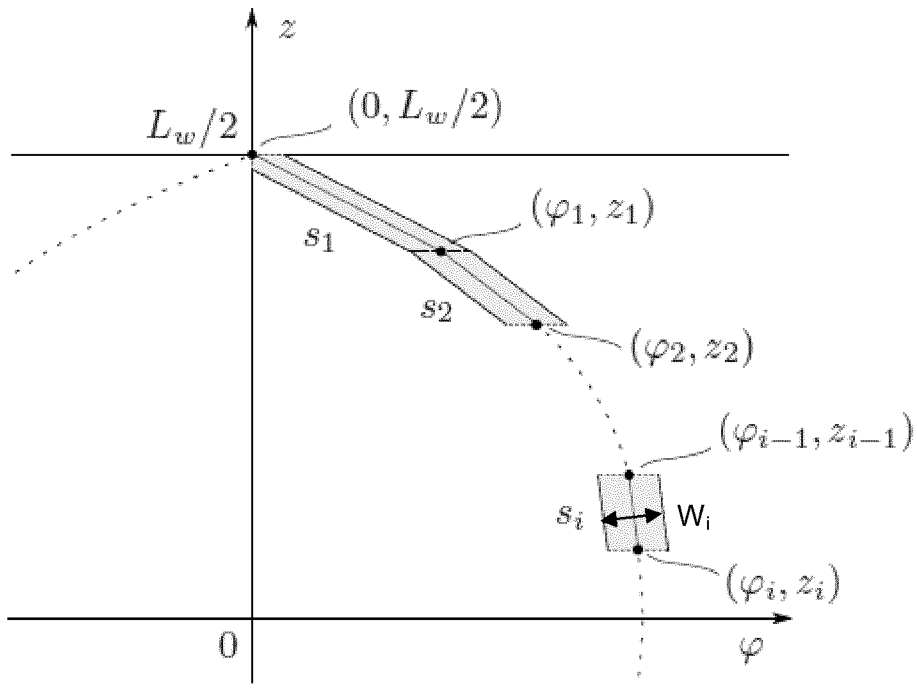
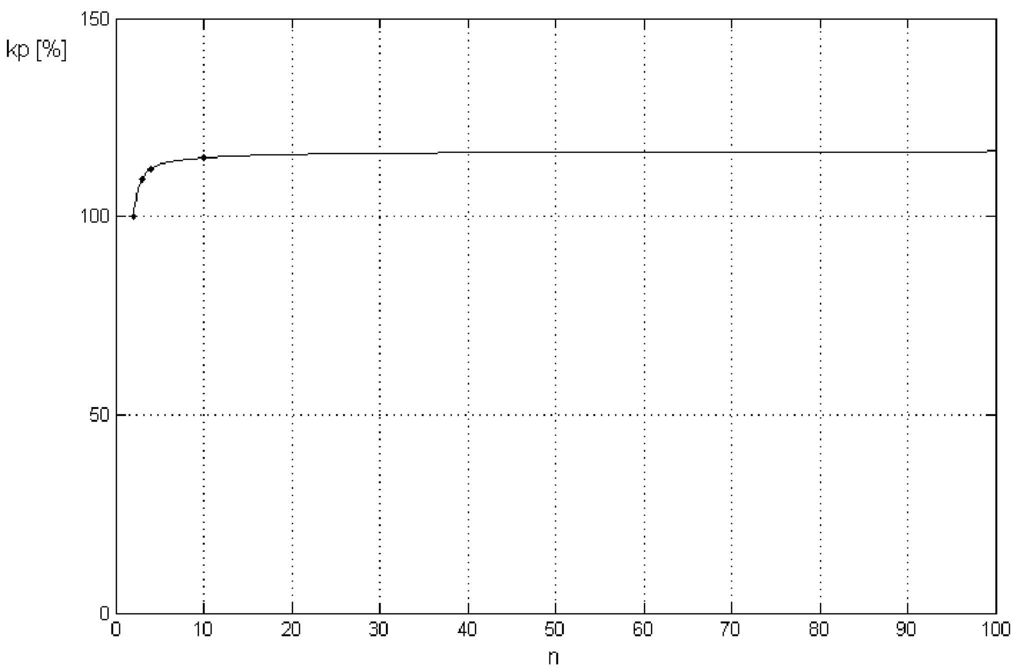


Fig. 5b



z
$L_w/2$
$(0, L_w/2)$
(φ_1, z_1)
s_1
s_2
(φ_2, z_2)
(φ_{i-1}, z_{i-1})
s_i
W_i
(φ_i, z_i)
0
φ

Fig. 6a



kp [%]
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
n

Fig. 6b

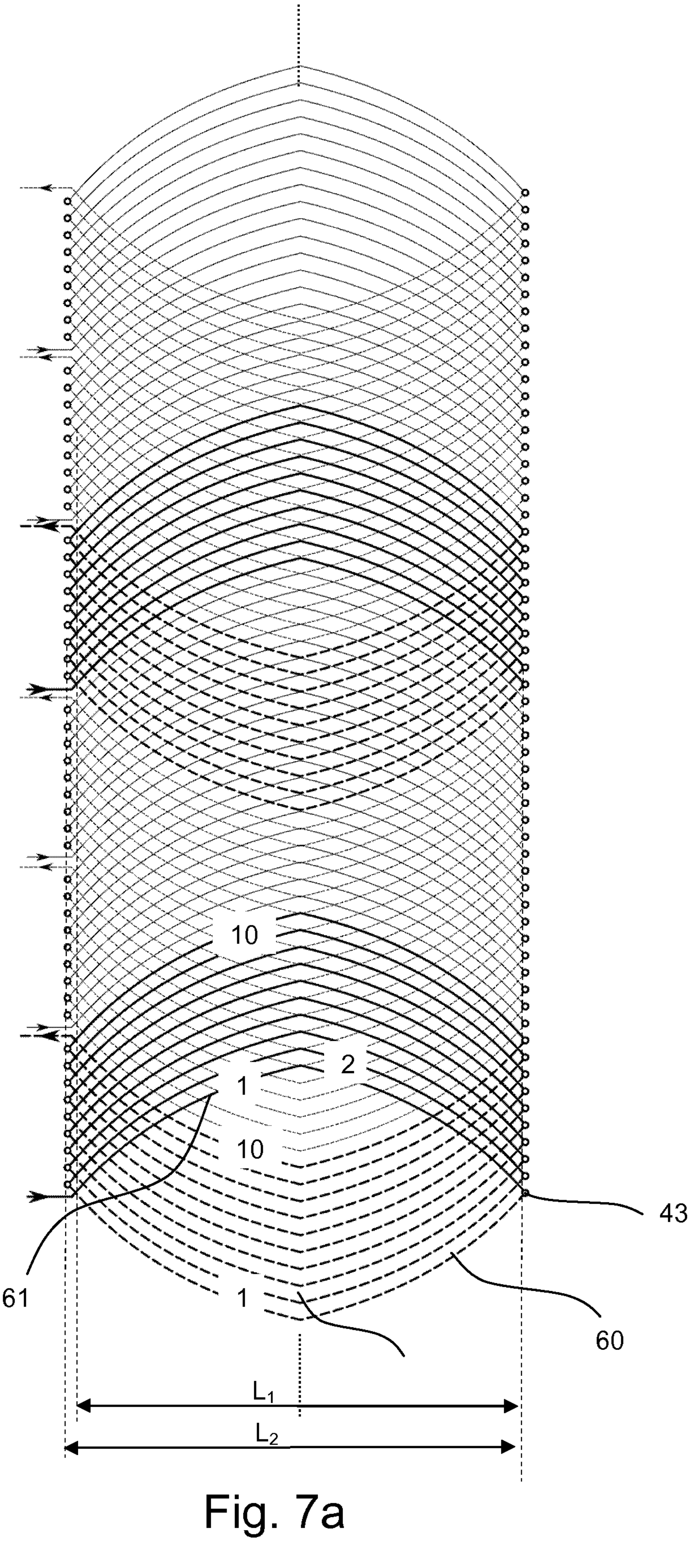


Fig. 7a

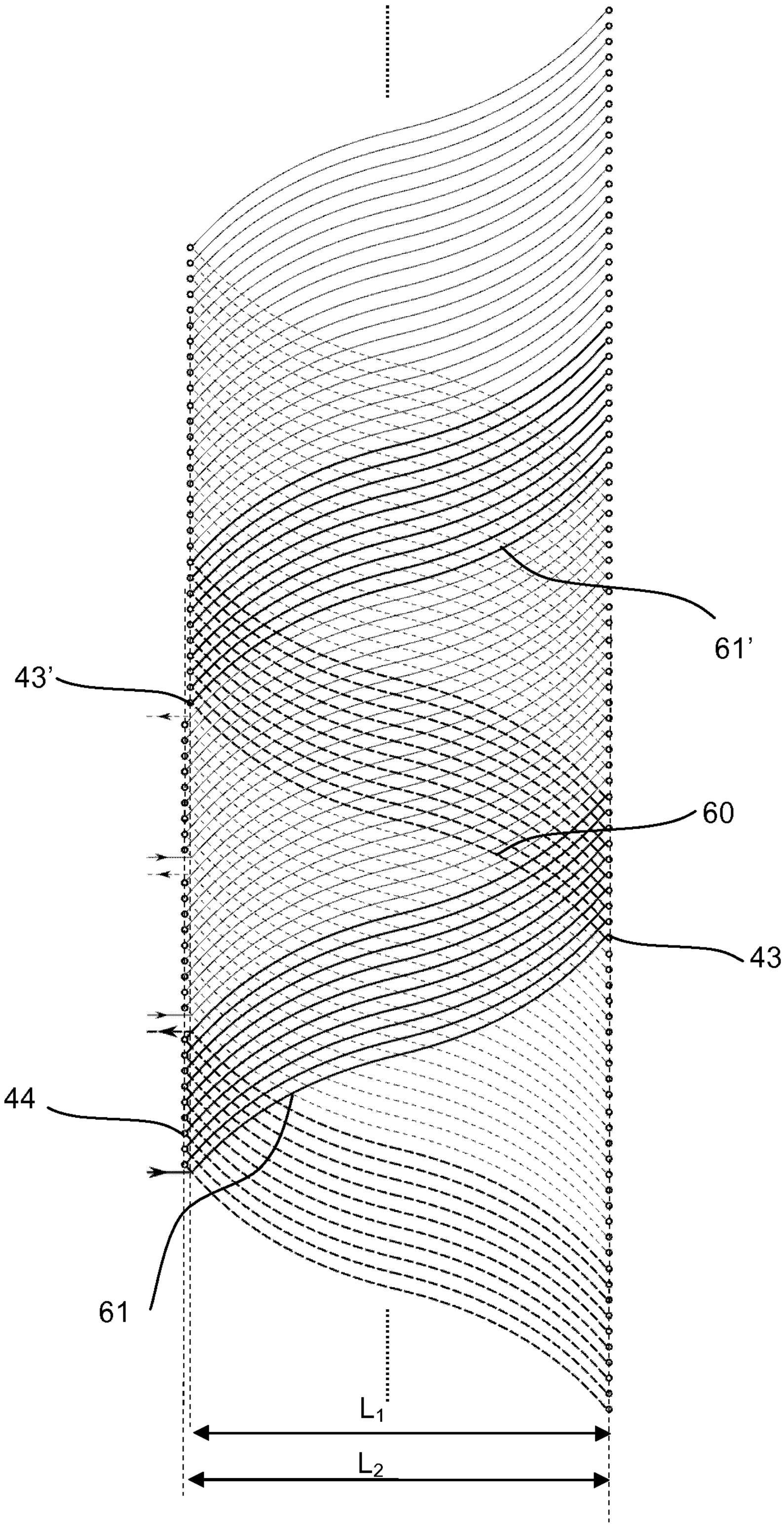


Fig. 7b

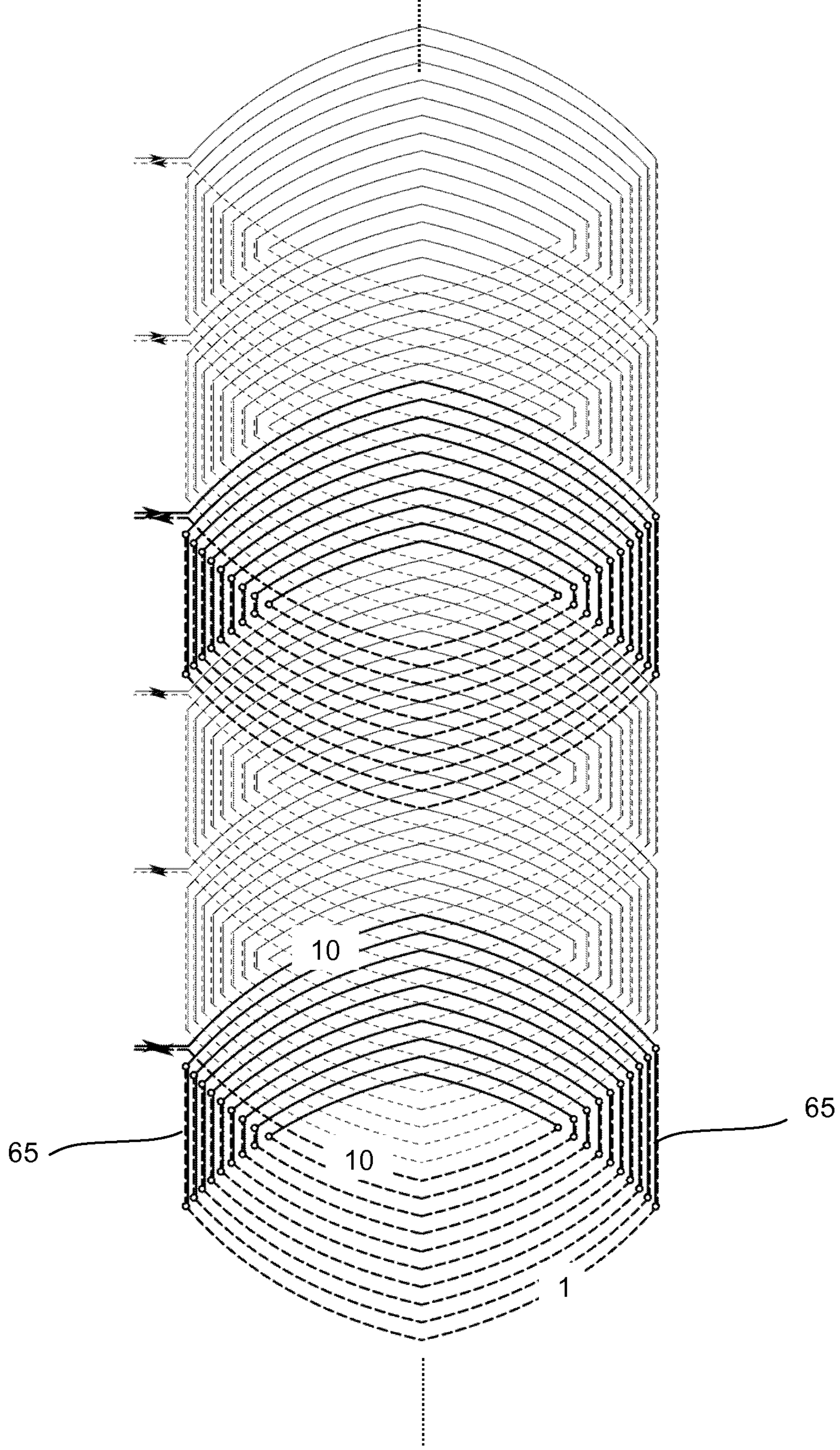


Fig. 8a

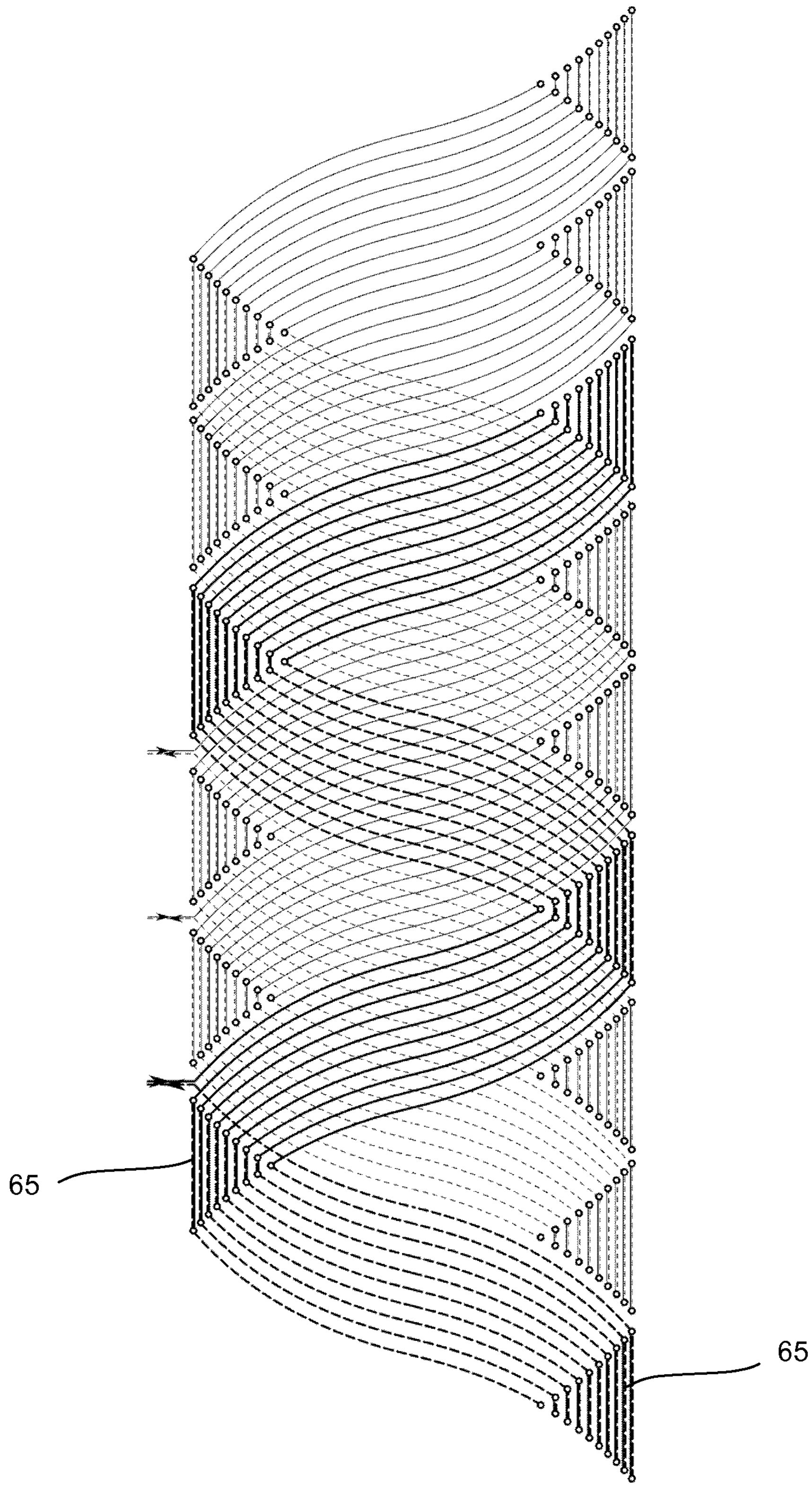


Fig. 8b

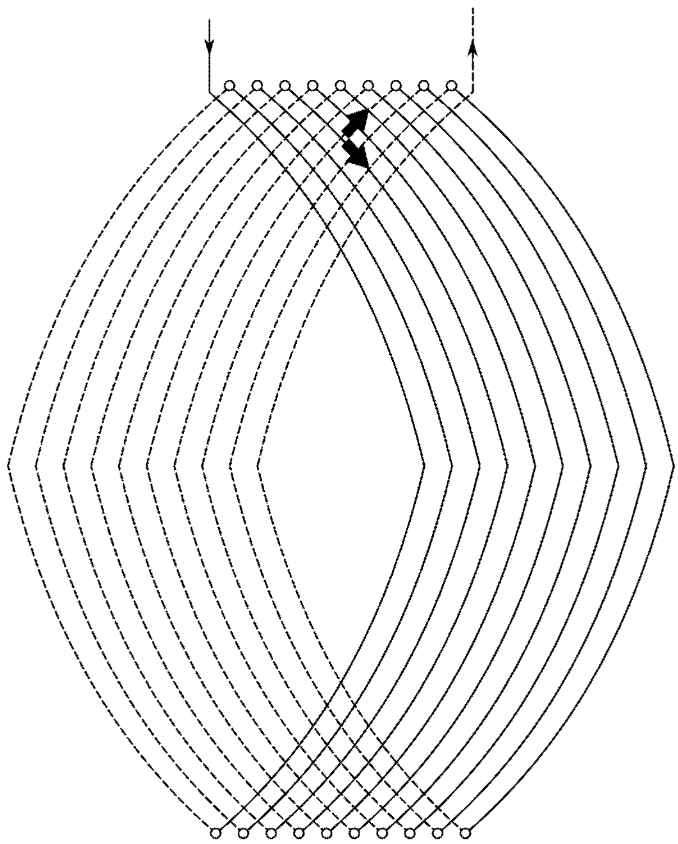


Fig. 9a

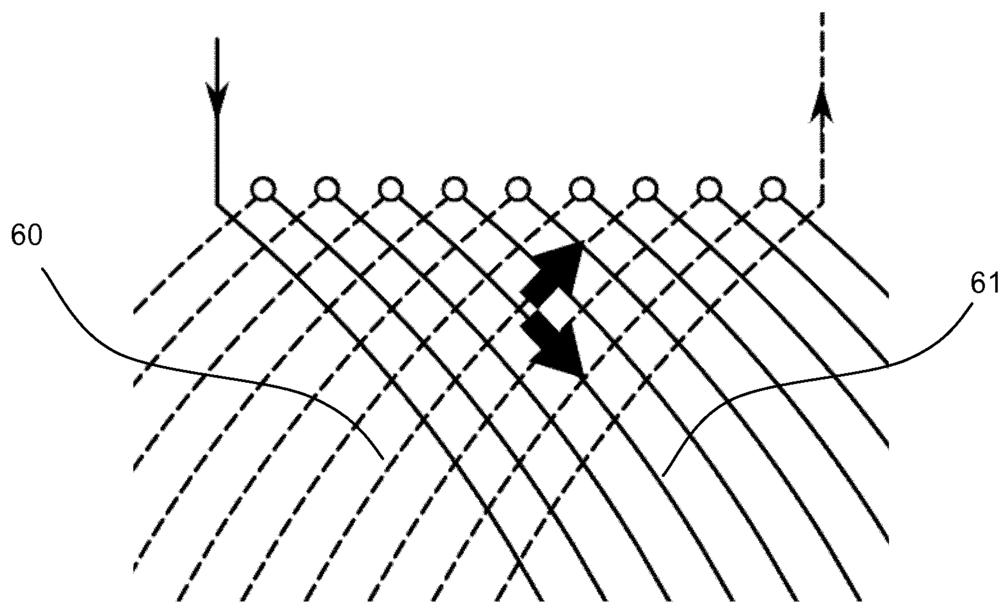


Fig. 9b

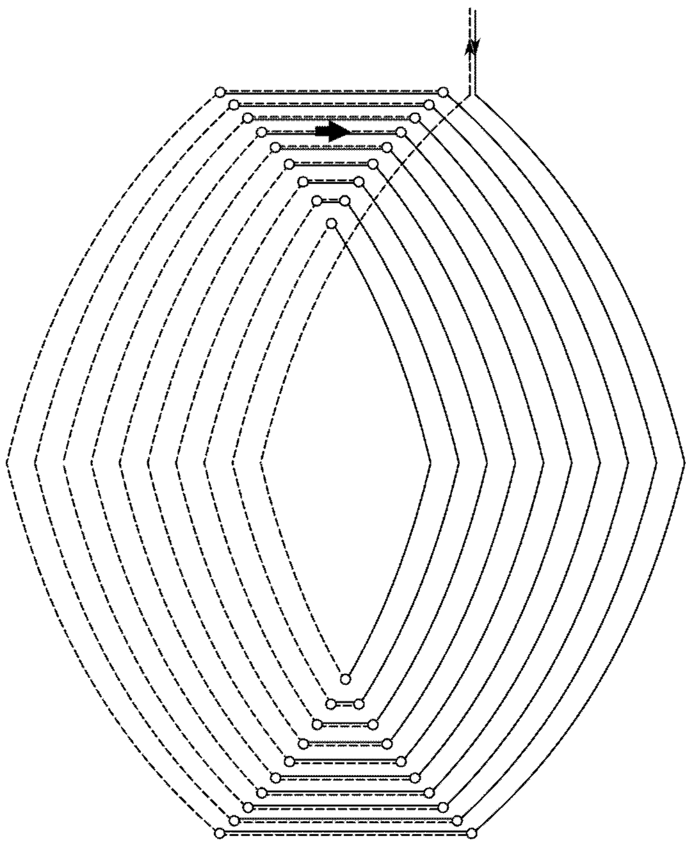


Fig. 10a

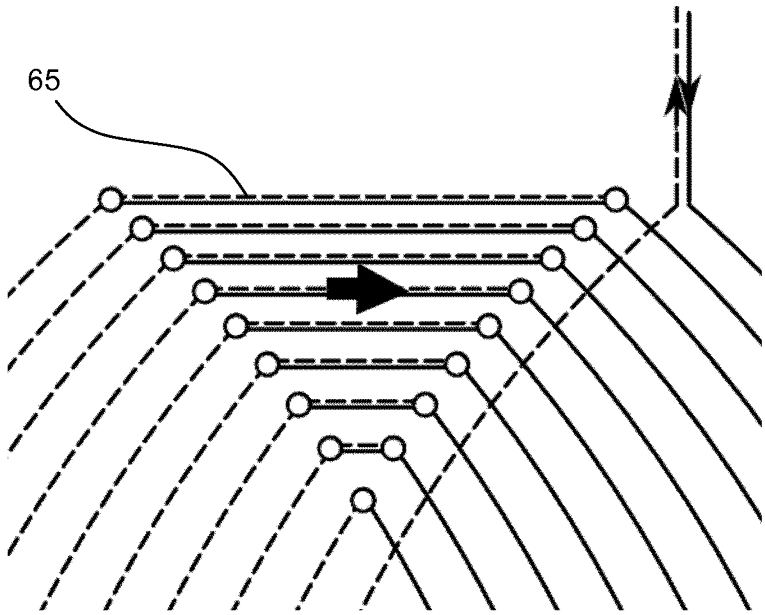


Fig. 10b