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(71) Applicant: HÖGANÄS AB (PUBL) [SE/SE]; Bruksgatan 35, S-26383 Hoganas (SE).

(72) Inventors: WASHINGTON, Jamie; 20 Garden Croft, Forest Hall, Newcastle upon Tyne Tyne and Wear NE12 9LT (GB). ATKINSON, Glynn; 35 Mill Grove, Tynemouth, Newcastle upon Tyne Tyne and Wear NE30 2JP (GB). STANNARD, Nick; 13 Maidcroft Road, Oxford Oxfordshire OX4 3EN (GB).

(74) Agent: GUARDIAN IP CONSULTING I/S; Diplomvej, Building 381, 2800 Kgs. Lyngby (DK).

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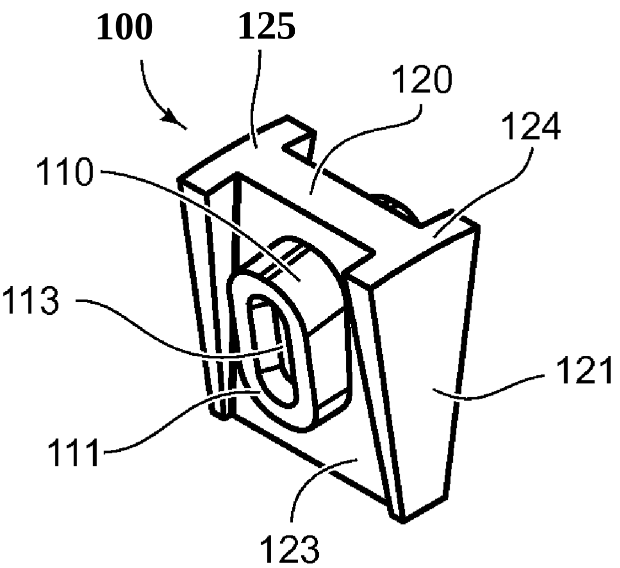

Fig. 1

(57) Abstract: A stator of an axial flux electric machine has a slotted stator core that is assembled from stator core segments (xOO), and coils with a toroidal winding topology. The stator core segment (xOO) comprises a yoke portion (xlO) and a tooth portion (x20). The tooth portion (x20) projects in at least one axial direction from the yoke portion (xlO), wherein the tooth portion (x20) comprises one or more pole pieces (x24, x25), and wherein each of the pole pieces (x24, x25) has a pole face (x21, x22) that is oriented in the axial direction. The yoke portion (xlO) has a first abutment face (xl l) facing towards a first circumferential direction and a second abutment face (xl2) facing in a second circumferential direction opposite to the first circumferential direction, wherein the yoke portion (xlO) is shaped and dimensioned such with respect to the tooth portion (x20) that the first abutment face (xl 1) of the core segment (xOO) abuts a second abutment face (xl2) of a circumferentially adjacent core segment (xOO) when these are assembled in a stator core assembly.

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STATOR ASSEMBLY FOR AN AXIAL FLUX MACHINE

The present invention relates in one aspect to a core segment for forming a slotted stator core of an axial flux electrical machine with a toroidal winding topology and a segmented stator core assembly for such an axial flux electrical machine formed from the core segments. In yet a further aspect, the present invention relates to a segmented slotted stator for an axial flux permanent magnet electrical machine and an axial flux permanent magnet electrical machine comprising such a segmented slotted stator.

BACKGROUND OF THE INVENTION

Dynamo-electrical machines, i.e. electrical generators or electrical motors, are electromechanical energy converters converting mechanical power into electrical power and/or vice versa. The conversion is based on the forces resulting from electromagnetic interaction between electrical currents and magnetic flux in a moving part and a stationary part called stator. In a permanent magnet type machine, usually the moving part is provided with permanent magnets generating a magnetic field, which is coupled to the stator via a flux carrying magnetic circuit across an air gap. The stator comprises coils made of an electrically conducting material for carrying an electrical current. Typically, the stator further comprises a stator core forming part of the magnetic circuit, and on which the coils are wound. Dynamo-electrical machines are in the following merely referred to as electrical machines. The electrical machines may e.g. involve a rotary movement or a linear movement. In the following reference is only made to rotary electrical machines. However, it will be understood that an equivalent linear translation geometry corresponding to a given rotary geometry may easily be conceived by a skilled person.

In a rotary electrical machine, the moving part is referred to as a rotor and the stationary part is referred to as the stator. In the rotary geometry, the rotor and the stator have rotational symmetry with respect to a common axis of rotational symmetry. The rotor is configured for rotating about the common axis of rotational symmetry, which in the following is referred to as the axis of rotation. Depending on the design, the rotary electrical machine may have one or more rotors and one or more stators. In the simplest design, the electrical machine comprises a single stator and a single rotor facing each other. While this design is conceivable, other designs are more advantageous. For example, an advantageous axial flux electrical machine with an internal rotor design may have an internal rotor sandwiched by two external stators; another advantageous axial flux electrical machine may have external rotors sandwiching an internal stator (internal stator design); furthermore, a multi-stage axial flux electrical machine may also have a plurality of internal rotors stacked in the axial direction with internal stators in an alternating manner, wherein the stack at either end terminates with an external rotor or an external stator. While the invention in the following is illustrated with reference to an internal stator axial flux electrical machine, the invention should not be construed as being limited to that design only, but as covering also the above-mentioned variations of the design.

In the rotary geometry, geometrical terms are defined as follows. Axial directions are parallel to the direction of the axis of rotation, radial directions are perpendicular to the axis of rotation, and circumferential directions are tangential to a circle about the axis of rotation, i.e. perpendicular to the axial directions and perpendicular to a radial direction at a finite radial distance from the axis of rotation. An angle between two circumferential directions is thus equal to the central angle between the corresponding radial directions. Planes, such as cross-sectional planes or planes of projection/elevation, are referred to by their orientation, i.e. an axial plane/cross-section is taken in a plane perpendicular to the axial direction, a radial plane/cross-section is taken in a plane perpendicular to the radial direction, and a circumferential plane/cross-section is taken in a plane perpendicular to the circumferential direction. In the context of the present invention, a toroid is to be understood as a torus-like three-dimensional body with a single central opening and rotational symmetry about a central axis (the axis of rotational symmetry of the toroid) defining the orientation of the toroid. A reference plane of the toroid is perpendicular to the axis of rotational symmetry of the toroid.

The magnetic circuit of the electrical machine comprises an air gap between the rotor and the stator. As mentioned above, in an axial flux electrical machine, the magnetic flux that is coupled across the air gap is oriented in an essentially axial direction. In a permanent magnet electrical machine the magnetic circuit comprises permanent magnets for generating a magnetic field. In one type of permanent magnet electrical machine, permanent magnets are distributed on the rotor in a circumferential direction wherein the permanent magnets form pole faces that are oriented in an axial direction to form a rotor side of the air gap, whereas the stator is provided with coils for interaction with the magnetic field emanating from the permanent magnets of the rotor.

In one configuration, the stator coils may be provided in a toroidal winding topology. A toroidal winding topology refers to windings running in a poloidal direction around a toroid-shape to form a coil with a coil axis pointing in a circumferential direction. Note, that a helical coil with a toroidal topology will have poloidal windings with circumferential components corresponding to the pitch of the helix. Typically, the toroid-shape is defined by a coil body which is made of a soft magnetic material acting as a flux guiding magnetic core. The core may be "slot-less". Advantageously, however, the core is "slotted", i.e. the core has a toroidal yoke running in a circumferential direction and teeth projecting from the yoke. Neighbouring teeth are spaced apart from each other so as to define a slot between them. The slot is for receiving a respective coil wound around the yoke in a poloidal direction. The teeth project in an axial direction, wherein the teeth have a proximal portion attached to the yoke, and a distal portion with pole faces facing towards the rotor so as to define the stator side of the air gap. The teeth may be shaped to have distal portions that are widened as compared to the proximal portions so as to at least partially cover the coils on the side facing towards the respective rotor. Despite the advantages of improved electromagnetic coupling in a slotted core configuration as compared to a slot-less configuration, such a complex stator core geometry for an axial flux electrical machine may be difficult to produce, and the winding of coils into the slots may be cumbersome, amongst others due to the risk of damaging the insulation of the wire forming the coils. Attempts have been made to address these issues by providing a segmented stator core geometry. WO 2010/070405 describes a slotted stator section of an axial flux electric machine which is assembled by fitting to a central ring acting as a magnetic core both a plurality of toroidal coils and a plurality of toroidal elements made of magnetic material. The toroidal coils and the toroidal elements each have a central through-hole whose shape matches the transversal profile of the central ring. Coils and toroidal elements are alternated and adjacent to each other along the annular centre line of the core. However, the construction requires the use of a stabilizing central ring as a backbone, which furthermore needs to match the inner shape of coils and toroidal element within narrow tolerances in order to provide the required stability. WO 2012/062710 relates to a rotary axial flux electrical machine with permanent magnets arranged on the rotor and a segmented stator core comprising toroidal coils wound onto a coil carrier having end faces that form the axially oriented pole faces. In one embodiment, a circumferential widening of the pole faces covers the coils in order to improve efficiency. However, such widening impedes the winding of the coil onto the coil body.

SUMMARY OF THE INVENTION

Object of the present invention is to provide an axial flux electrical machine with an improved slotted stator core that can be produced at a commercially viable cost and that overcomes at least some of the above-mentioned disadvantages or provides an alternative.

A first aspect of the invention relates to a stator core segment for forming a slotted stator core of an axial flux electric machine with a toroidal winding topology, the stator core segment comprising a yoke portion and a tooth portion; the tooth portion projecting in at least one axial direction from the yoke portion to form a pole face oriented in the axial direction; the yoke portion having a first abutment face facing towards a first circumferential direction and a second abutment face facing in a second circumferential direction opposite to the first circumferential direction, wherein the yoke portion is shaped and dimensioned such with respect to the tooth portion that the first abutment face of the core segment abuts a second abutment face of a circumferentially adjacent core segment when these are assembled in a stator core assembly. Most preferably, the tooth portion comprises one or more pole pieces, wherein each of the pole pieces has a pole face that is oriented in the axial direction. The yoke portion projects in at least one circumferential direction beyond the tooth portion as seen in an axial projection. The length of the yoke portion in a circumferential direction is dimensioned to be larger than the corresponding dimension of the tooth portion as seen in the axial projection. The tooth portions of circumferentially adjacent stator core segments in a stator core assembly are thus spaced apart from each other separated by a circumferential gap between circumferentially adjacent stator pole faces. To form a circular stator core arrangement, a plurality of such stator core segments are assembled, wherein on each stator core segment the first and second abutment faces are inclined towards each other in a radially inward direction, wherein corresponding points of contact on the first and second abutment faces define a segment angle covered by the stator core segment with respect to the axis of rotation. By ensuring that the yoke portions of adjacent stator core segments abut each other, a stable arrangement is achieved despite the segmented design. An additional shape defining element, such as an assembly ring for retaining the individual stator core segments in place in the stator core arrangement may be advantageous. Also in this case, the stator core segments, which are shaped and dimensioned to abut each other when they are assembled in a stator core assembly, are advantageous, since they stabilize each other and therefore relax the requirement of precision of the fit between such an assembly ring and the stator core segments. Since the first and second abutment faces are defined on the yoke portion rather than the tooth portions, the coils may easily be wound separately and mounted onto the yoke portions when producing the stator. Readily wound coils can, for example, merely be slipped over the yoke portions when mounting the stator core segments in an alternating manner with the coil elements.

Advantageously, the first and second abutment faces each comprise a flat area in a plane parallel to the respective radial direction, i.e. flat areas oriented in the circumferential direction. Thereby an arrangement of improved mechanical stability may be achieved wherein the circumferentially oriented flat areas are for taking up wedging forces in the circumferential direction.

Advantageously, the first and second abutment faces are shaped and dimensioned such that the first abutment face of the core segment mates with a second abutment face of a circumferentially adjacent core segment when these are assembled in a stator core assembly. By providing mating features on the abutment faces a further improved mechanical stability is achieved, in particular when these mating features interlock or at least engage each other upon assembly.

Further according to one embodiment of a stator core segment, the first and second abutment faces include cooperating first and second guide elements, respectively, said guide elements being configured such that the first and second abutment surfaces mate in a male/female relationship, in a female/male relationship, or in a hermaphroditic relationship. As mentioned above, by providing mating features on the abutment faces a further improved mechanical stability is achieved when these mating features interlock or at least engage each other upon assembly. These mating features may be configured hermaphroditic or female/male or male/female. A hermaphroditic design of the mating features may be shaped such that the stator core element is symmetric with respect to rotation by 180 degrees about the radial direction. This is particularly advantageous for assembly of a stator core arrangement in the case, where the yoke and tooth portions of the stator core segment are shape-invariant with respect to the same rotational symmetry operation, since the orientation of the stator core element does not matter. On the other hand, a male/female or female/male relationship between the first and second abutment faces may advantageously be used for dictating a particular orientation to avoid assembly errors, if the stator core segments are not symmetric, but have to have a particular orientation when assembled in a stator core arrangement.

Further according to one embodiment of a stator core segment, the yoke portion projects beyond the tooth portion in only one circumferential direction. As long as the yoke portion in a circumferential direction is longer than the tooth portion, a slotted design of the stator core assembly can be achieved. By having the yoke portion project in one circumferential direction, the oppositely oriented abutment face may be aligned with or even recessed with respect to a plane defined by the tooth portion. Such a shape is, for example, advantageous when the stator core segment is formed by compression moulding with a mould separation interface being oriented in the circumferential direction (e.g. circumferential draw line).

Further according to one embodiment of a stator core segment, the tooth portion has a rim with a proximal portion attached to the yoke portion and a distal portion carrying one or more pole pieces at a radial distance from the yoke portion, wherein each of the pole pieces have an axially oriented pole face. In a stator with coils, the rim portion is typically for abutting the coil elements in a circumferential direction, whereas the pole pieces project from the coil elements in at least an axial direction. Thereby a precise pole face defining the stator side of the axial air gap in an axial flux electrical machine is achieved.

Further advantageously the one or more pole pieces project at least in a circumferential direction from the rim so as to partially cover the yoke portion as seen in an axial projection.

Further according to one embodiment of a stator core segment, the rim and the one or more pole pieces of the tooth portion as seen in a radial cross-section form one of a T-shaped profile, an H-shaped profile, or a C-shaped profile. A T-shaped profile as seen in a radially oriented cross-sectional plane is achieved when the tooth portion projects only in one axial direction from the yoke portion, wherein the stem of the T forms the rim and wherein the bar of the T forms the pole piece. A T-shaped profile may be advantageous for use in an external stator of an axial flux electrical machine. An H-shaped profile as seen in a radially oriented cross-sectional plane is achieved when the tooth portion projects in both axial directions from the yoke portion, wherein the horizontal bar of the H forms the rim, wherein the vertical bars of the H form the pole pieces on the axial ends of the rim, and wherein the pole pieces project from the rim in both circumferential directions. The H-shaped profile may also be seen as a combination of two T-shaped profiles projecting in opposite axial directions from the yoke portion. The H-shaped profile may be advantageous for use in an internal stator of an axial flux electrical machine, due to the symmetry with respect to an axial mirror plane. The H-shaped profile is particularly advantageous for use in an axial flux electrical machine intended for operation in both directions of rotation, due to the symmetry of the H-shaped profile with respect to a plane oriented in the circumferential direction. A C-shaped profile as seen in a radially oriented cross-sectional plane is achieved when the tooth portion projects in both axial directions from the yoke portion, wherein the back of the C forms the rim, wherein the upper end lower end of the C form the pole pieces on the axial ends of the rim, and wherein the pole pieces project from the rim in only one circumferential direction. The C-shaped profile may be advantageous for use in an internal stator of an axial flux electrical machine, due to the symmetry with respect to an axial mirror plane. The C-shaped profile is particularly advantageous for use in an axial flux electrical machine intended for operation in a preferred direction of rotation, due to the asymmetry of the C-shaped profile with respect to a plane oriented in the circumferential direction.

Further according to one embodiment of a stator core segment, the core segment is made of a soft magnetic material. Magnetically "soft" refers to materials like annealed iron, which can be magnetized but do not tend to stay magnetized, i.e. materials having low coercivity. The soft magnetic material may e.g. be laminated sheet metal as commonly used for forming magnetic cores in electromagnets or electrical machines. However, owing to the higher complexity of the shape, the stator core segments according to the present invention are preferably made of a soft magnetic material that can be shaped by a moulding technique.

Further according to one embodiment of a stator core segment, the soft magnetic material is a soft magnetic composite (SMC). Using a soft magnetic composite material has the advantage that complex shapes of stator core segments may be produced at a high throughput using moulding techniques, such as compression moulding followed by stress relieving heat treatment. In contrast to sintering such stress relieving heat treatment is performed under conditions which will not destroy the electrically insulating coating of the soft magnetic composite particles. An advantageous example of a mouldable SMC is Somaloy available from Hoganas AB, 263 83 Hoganas, Sweden.

Further according to one embodiment, the stator core segment is formed by a compression moulding and stress relieving heat treatment process. By providing a segmented stator core design where the abutment faces determining the shape of the assembled stator core arrangement are located on the circumferential end faces of the yoke portion, the stator core segment may be produced in a mould that separates in a circumferential direction, e.g. using a straight draw mould allowing for a high pressure compaction in an SMC powder metallurgical process.

Further according to one embodiment, the stator core segment has a circumferential passage extending from the first abutment face through the yoke portion to the second abutment face. By providing an internal passage, penetrating the entire length of the yoke in a circumferential direction, the stator core assembly made from the stator core segments can be formed as a hollow toroid. The internal passage can advantageously be used for e.g. passing a cooling fluid, for passing wiring, and/or for receiving an internal assembly ring for further stabilizing the stator core arrangement. The internal assembly ring may advantageously be made of a soft magnetic material to further enhance the magnetic flux guiding properties of the stator core assembly along the circumferential direction.

Further according to one embodiment of a stator core segment, the first and second abutment faces are adapted to allow for a fluid tight connection between adjacent stator core segments. By shaping the first and second abutment faces such that they are adapted to seal when abutting against each other, optionally with a sealing element, such as an O-ring or gasket in between, a fluid tight internal channel may be formed, that is directly suited for passing a heat exchange medium (coolant) there through. The stator core assembly may for that purpose be provided with inlet and outlet ports in fluid communication with the internal channel formed by the abutting stator core segments.

Further according to one embodiment, the stator core segment has at least one of a radial or an axial passage for receiving fastening elements for securing the stator core segment to an assembly element. The stator core segments may be secured in place to a shape-defining assembly element, such as an assembly ring, thereby facilitating easy assembly and further enhancing the mechanical stability of a segmented stator core assembly.

Further according to one aspect of the invention, a stator core assembly for forming a slotted core of an axial flux electrical machine with a toroidal winding topology is provided, the stator core assembly comprising a plurality of stator core segments according to any of the preceding claims, wherein adjacent stator core segments are arranged to abut each other in a circumferential direction to form a circular arrangement, wherein the first abutment face of the yoke portion of each stator core segment contacts the mating second abutment face of the yoke portion of the adjacent stator core segment, and wherein the tooth portions of adjacent/neighbouring stator core segments define a slot for receiving a toroidal coil between them. Thereby an easy assembly of a slotted stator core assembly is achieved, wherein the stator core segments for forming the slotted stator core assembly further contribute to the advantages of the stator core assembly as discussed in detail above. Advantageously, the stator core assembly may comprise sub-assemblies of circle sections formed from a plurality of abuttingly mounted stator core segments. Thereby, a stator can be produced in circle-section shaped slotted stator core subassemblies, each sub-assembly comprising a plurality of stator core segments abutting each other and carrying toroidal coil elements on the yoke portions interleaved between the tooth portions of adjacent stator core segments.

Further according to one aspect, a stator for an axial flux electric machine with a toroidal winding topology is provided, the stator comprising a slotted stator core assembly according to any of the above-mentioned embodiments and toroidal coils arranged on the yoke portions in the slots defined between the tooth portions of adjacent stator core segments.

Further according to one embodiment of the stator circumferentially oriented end faces of the toroidal coils are parallel to each other.

Further according to some embodiments a stator has toroidal coils, wherein circumferentially oriented end faces of the toroidal coils are wedged towards each other in a radially inward direction.

Advantageously, an axial flux permanent magnet electrical machine comprises a stator with a segmented stator core assembly as described above, the stator being arranged together with a rotor carrying permanent magnets so as to form an axial air gap between the pole faces of the stator and cooperating pole elements of the rotor. In some embodiments of the axial flux permanent magnet electrical machine, the pole elements of the rotor are permanent magnets carried on a support disk and oriented in an axial direction. Alternatively, according to some embodiments, the rotor comprises permanent magnets that are oriented in the circumferential direction in contact with pole elements made of a soft magnetic material. The permanent magnets alternate with the pole elements and are arranged to form a rotor disk. The pole elements have pole surfaces oriented in an axial direction towards the pole faces of the stator, wherein the pole surfaces of the rotor pole elements define the rotor side of the axial air gap, and wherein the pole faces of the stator pole pieces define the stator side of the axial air gap. In a particularly advantageous arrangement the permanent magnets are recessed in an axial direction from the air gap, and the pole elements bulge towards the air gap. Thereby an improved flux coupling from the permanent magnets towards the air gap and to the stator is achieved and cogging forces of the axial flux permanent magnet electrical machine are reduced.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention will be described in more detail in connection with the appended drawings, which show in

Figs. 1-6 different views of a stator core segment according to a first embodiment,

Figs. 7-9 different views of a stator core segment according to a second embodiment,

Fig. 10 a stator core assembly with an outer retaining ring,

Figs. 11-13 different views of a stator core segment according to a third embodiment,

Fig. 14 a stator core assembly with an internal retaining ring,

Fig. 15 a perspective view of a stator core segment according to a fourth embodiment,

Figs. 16-17 a stator core assembly with an external retaining ring using stator core element according to the fourth embodiment,

Fig. 18-19, a wedge shaped coil element for use in a segmented stator according to the invention,

Fig. 20, an alternating arrangement of wedged coil elements and stator core segments for use in a segmented stator according to the invention,

Fig. 21-22, a coil element with plane parallel circumferential end faces for use in a segmented stator according to the invention,

Fig. 23, an alternating arrangement of plane parallel coil elements and stator core segments for use in a segmented stator according to the invention,

Fig. 24-25, different views of an advantageous configuration of an axial flux electrical machine with a segmented stator between two external rotor disks with axially oriented permanent magnets,

Figs. 26-28, different stator-rotor configurations of axial flux electrical machines,

Fig. 29, a rotor disk for an axial flux electrical machine with circumferentially oriented permanent magnets according to one embodiment,

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Figs. 1-6 show a first embodiment of a stator core segment 100. The stator core segment 100 is for producing a slotted stator core of a rotary axial flux electrical machine from a plurality of identical stator core segments 100 arranged in a circular geometry with respect to an axis of rotation Z. Fig. 1 and Fig. 2 show perspective elevations of the stator core segment 100 from two sides; Fig. 3 shows a projection of the stator core segment onto a plane oriented in a circumferential direction (circumferential projection); Fig. 4 shows a projection of the stator core segment onto a plane oriented in an axial direction (axial projection); Fig. 5 shows a projection of the stator core segment onto a plane oriented in a radial direction (radial projection); and Fig. 6 shows a radial projection of three adjacent stator core segments 100a, 100b, 100c as arranged for use in a circular stator core assembly for a rotary axial flux electrical machine.

Referring to Figs. 1-6, a stator core segment 100 comprises a yoke portion 110 and a tooth portion 120. The yoke portion 110 extends in a circumferential direction with a first abutment face 111 facing towards a first circumferential direction and a second abutment face 112 facing in a second circumferential direction opposite to the first circumferential direction. The first and second abutment faces 111, 112 of the yoke portion 110 are inclined with respect to each other by an angle corresponding to the segment angle ALPHA to be covered by the stator core segment 100. The outer surface of the yoke portion 110 facing in axial and radial directions is formed to receive a coil element with a toroidal winding, as further detailed below. The tooth portion 120 forms a first pole face 121 oriented in a first axial direction, and a second pole face 122 oriented in a second axial direction. The tooth portion 120 has a rim 123 projecting from the yoke portion 110 in axial and radial directions. The rim 123 has a proximal portion attached to the yoke portion 110 and a distal portion carrying respective first and second pole pieces 124, 125 at an axial distance from the yoke portion 110, wherein the pole pieces 124, 125 provide the axially oriented first and second pole faces 121, 122. In radial cross-section, the pole pieces 124, 125 and the rim 123 form an H-shaped profile, as for example shown in the radial projection of Fig.5. As best seen in the axial projection in Fig.4, the yoke portion 110 projects in circumferential directions beyond the tooth portion 120. When arranged in a stator core assembly, the abutment faces 111, 112 of adjacent stator core segments 100 contact each other, wherein the inclination of the abutment faces defines the angle of inclination between the adjacent stator core segments, as illustrated in Fig.6 by the arrangement of three adjacent stator core segments 100a, 100b, 100c. For example, the second abutment face 112a of the first stator core segment 100a contacts the first abutment face 111b of the clockwise adjacent second stator core segment 100b, and the second abutment face 112b of the second stator core segment 100b contacts the first abutment face 111c of the clockwise adjacent third stator core segment 100c. The first and second abutment faces 111a/b/c, 112a/b/c are shaped and dimensioned to form mating surfaces so as to support and stabilize each other in the circular arrangement. The abutment faces 111, 112 further comprise guide elements 113, 114. A first, female guide element 113 is provided on the first abutment face 111, and a second, male guide element 114 is provided on the second abutment face 112. The guide elements further stabilize the stator core assembly formed from a plurality of stator core segments.

Figs.7-9 show a second embodiment of a stator core segment 200. Like the first embodiment of a stator core segment 100, the second embodiment of a stator core segment 200 has a yoke portion 210 with circumferentially oriented abutment faces

211, 212, and a tooth portion 220 forming axially oriented pole faces 221, 222 on pole pieces 224, 225. The perspective elevation of Fig. 7 shows three adjacent stator core segments 200a, 200b, 200c as they will be arranged abutting each other in a stator core assembly at corresponding abutment faces 212a/211b, 212b/211c. Fig. 8 shows an axial projection of the stator core element 200, and Fig. 9 shows a radial projection of the stator core element 200.

The tooth portion 220 has a rim 223 carrying the pole pieces 224, 225 at an axial distance from the yoke portion 210. As seen in the radial projection of Fig. 9, the rim 223 and the pole pieces 224, 225 define a C-shaped profile in radial cross-sections, wherein the pole pieces 224, 225 project only in one circumferential direction from the rim 223.

The yoke portion 210 has a first abutment face 211 facing towards a first circumferential direction and a second abutment face 212 facing in a second circumferential direction opposite to the first circumferential direction, wherein the abutment faces 211, 212 are inclined with respect to each other to intersect at the rotation axis Z of the circular assembly to be formed at a segment angle ALPHA. The first and second abutment faces 211, 212 are shaped and dimensioned such that the first abutment face 211 of the core segment 200 mates with a second abutment face of a circumferentially adjacent core segment when these are assembled in a stator core assembly. The mating abutment faces 211, 212 stabilize the shape of the assembly. Female/male guide elements 213, 214 provided on the abutment faces 211, 212 further stabilize the assembly. As seen in the axial projection of Fig. 8, the yoke portion 210 projects in at least one circumferential direction beyond the tooth portion 220 so as to ensure a circumferential spacing between the pole pieces of adjacent stator core segments when these are assembled in a stator core assembly.

Fig. 10 shows a circular stator core assembly made from 21 stator core segments each covering a respective segment angle ALPHA of (360/21) degree. The stator core assembly is encased by an external assembly ring 10 with a radially inner surface of the assembly ring 10 abutting the radially outer surface of the stator core segments 100, thereby wedging the stator core segments 100 in place in the stable circular arrangement defined by the mating abutment faces 111, 112 of the yoke portions 110 of the stator core segments 100. Since the yoke portion 110 in a circumferential direction is longer than the tooth portion when measured along the same path, the pole pieces 124, 125 of adjacent stator core segments 100 are spaced apart from each other with a circumferential spacing/gap between them. Note that the assembly ring may be part of an external stator casing or machine housing providing an inner circular cylinder surface.

A third embodiment of a stator core segment is shown in Figs. 11-13. Fig. 11 shows the stator core element 300 in an axial projection; Fig. 12 shows the stator core segment 300 in a circumferential projection; and Fig. 13 shows the stator core segment 300 in a perspective view. The stator core segment 300 has a yoke portion 310 and a tooth portion 320 projecting from the yoke portion 310 in both axial and radial directions. The tooth portion 320 comprises two pole pieces 324, 325, wherein a first pole piece 324 has a pole face 321that is oriented in a first axial direction, and a second pole piece 325 has a pole face 322 that is oriented in a second axial direction opposite to the first axial direction. The tooth portion 320 has a rim 323 with a proximal portion attached to the yoke portion 310 and a distal portion carrying the pole pieces 324, 325 at an axial distance from the yoke portion 310. As can evident from the perspective view in Fig. 13, the rim 323 and the pole pieces 324, 325 of the stator core segment 300 form an H-shaped profile as seen in a radial projection. As in all embodiments, the yoke portion 310 has a first abutment face 311 facing towards a first circumferential direction and a second abutment face 312 facing in a second circumferential direction opposite to the first circumferential direction, wherein the distance between the abutment faces 311, 312 determines the length of the yoke portion in the circumferential direction. As seen in the axial projection of Fig. 11, when measuring along a circumferential direction, the arc length of the yoke portion 310 is longer than that of the tooth portion 320 at corresponding radial coordinates. In this particular embodiment, the yoke portion 310 projects in both circumferential directions beyond the tooth portion 320. The stator core segment 300 differs from the above-mentioned embodiments in that it comprises a circumferential passage 315 running from the first abutment face 311 through the entire yoke portion 310 to the second abutment face 312. The passage 315 can serve one or more different purposes, such as passing a cooling fluid for providing cooling to a stator of an axial flux electrical machine build from stator core segments 300, passing wiring, and/or for threading the stator core elements onto an internal assembly ring 30 for retaining the stator core segments 300 in the stable circular arrangement defined by the mating abutment faces 311, 312. In a particularly advantageous embodiment, the internal assembly ring 30 is made of a soft magnetic material, thus forming a circumferentially running yoke for improving the magnetic coupling between the stator core segments while at the same time adding mechanical stability to the stator core assembly. The assembly ring 30 may e.g. be made of a soft magnetic composite or, alternatively, from laminated sheets of a soft magnetic material. Fig. 14 gives an example of using stator core elements 300 for forming a stator core assembly with an internal assembly ring 30. The assembly ring has an opening 32 through which the stator core segments 300a/b are threaded one by one and abutting each other onto the assembly ring 30 passing through the respective circumferential passages 315. The circumferential cross-section of the assembly ring 30 has a profile 31 matching the axial and radial dimensions of the passages 315 so as to provide mechanical support for the stator core segments 300. Once all stator core segments 300 are threaded onto the assembly ring 30 the opening maybe closed by adequate means.

A fourth embodiment of a stator core segment is shown in Figs. 15-17. Fig. 15 shows the stator core segment 400 in a perspective view. The stator core segment 400 has a yoke portion 410 with a rectangular planar abutment face facing in a first circumferential direction, and an equivalent second rectangular abutment face 412 facing in a second circumferential direction opposite to the first circumferential direction. In a radial direction, the yoke portion 410 and the abutment faces 411, 412 extend over the full height of the stator core segment 400. The stator core segment has further a tooth portion 420 with pole pieces 424, 425 carried by rim sections 423 projecting axially from the yoke portion 410. The pole pieces 424, 425 have respective pole faces 421, 422 that are oriented in opposite axial directions.

Centrally of the yoke and tooth portions 410, 420, the stator core segment 400 has a passage 416 running in a radial direction over the full height of the stator core segment from the radially inner end to the radially outer end. The passage 416 is for receiving a fastening element 417 there through, for fixing the stator core element 400 to an assembly ring 40. Fig. 16 shows an axial elevation of the stator core segment 400 illustrating its attachment to a rib 41 on the inside of an assembly ring 40 by means of a fastening element 417 passing in a radial direction through the passage 416. Fig. 17 shows an axial elevation of a complete stator core assembly of stator core segments 400 attached from the inside to an assembly ring 40. The stator core elements 400 are wedged together to form a stable circular arrangement defined by the abutment faces 411, 412 and secured to the external assembly ring by fastening elements 417 as described above. Any suitable fastening elements may be used, such as bolts threading into the rib 41, or rivets passing through the rib 41 to engage the assembly ring 40. As also mentioned above, an external assembly ring 40 may form part of a stator casing and/or a machine housing.

To produce a stator for an axial flux electrical machine, the slotted stator core assembly is provided with coils wound onto the yoke portions and in the slots formed by the tooth portions of adjacent stator core segments, wherein the axes of the coils are oriented in the circumferential direction. Thereby a toroidal winding topology is achieved with the toroidal direction along the circumferential direction of the stator core assembly, and the windings of the coils running in a poloidal direction thereto. By way of example, this is illustrated for two differently shaped coil elements 130, 530 in Figs. 18-20 and Figs 21-23, respectively. Fig. 18 shows three stator core segments 100a/b/c arranged to abut each other in a circumferential direction by their mating abutment faces on the respective yoke portions 110a/b/c. The stator core segments 100a/b/c are interleaved with coil elements 130a/b/c arranged on the yoke formed by the abutting yoke portions 110a/b/c and border the circumferential faces of the rim of the tooth portions 120a/b/c. Fig. 19 shows a circumferential projection of a coil element 130 with an opening 135 having an inner contour 134, which is shaped and dimensioned to match the outer contour of the yoke portion 110 of a stator core segment 100. The yoke portion 110 thus supports the coil element 130 in a mechanically stable manner. Fig.20 shows an axial projection of the coil element 130. The coil element 130 has circumferential end faces 131, 132 that are inclined with respect to each other to form a wedge-shape that fits the inclined circumferential faces of the rims in the slot between abutting stator core segments 100a/b, 100b/c. As can be seen from Fig. 19, the coil is widened in the axial and radial directions at the radially inner end as compared to the radially outer end. This is for compensating for the wedge shape with a reduced length of the coil in the circumferential direction at the radially inner end as compared to the radially outer end, so as to maintain a constant cross-sectional area accommodating the windings. In an alternative embodiment, coil elements 530 have plane parallel circumferential end-faces 531 , 532, as best seen in the axial projection of Fig. 22. As shown in the circumferential projection of Fig. 21, the coil 530 has a central opening 535 with an inner contour 534 matching the outer contour of the yoke portions, and with an outer contour 533 that essentially follows the inner contour 534. Consequently, the cross-sectional shape of the winding of the coil element 530 is essentially constant along the poloidal direction. Fig.23 shows an arrangement of alternating coil segments 530a/b/c/d and stator core segments 500a/b/c abutting each other in a circumferential direction. The inner contour 534 of the coil segments 530 matches the outer contour of the yoke portions 510c such that the yoke formed by the yoke portions supports the coil elements 530 in mechanically stable manner. In the embodiment shown in Fig.23, the circumferential end faces 531 , 532 border the circumferential faces of the rim of the tooth portions 520a/b/c. Circumferentially opposite faces of the rim of the tooth portion of a stator core segment 530 are therefore inclined towards each other in a radially inward direction so as to form a wedge shape.

Fig. 24 and Fig.25 show an axial flux electrical machine with a stator 101 with a segmented stator core assembly of stator core segments 100 alternating with coil elements 130 arranged in circumferential orientation to form a toroidal winding topology as described above. The axial flux electrical machine has two external rotors 140 in axial alignment with the internal stator 101 . The rotors 140 each comprise a rotor disk 141 and permanent magnets 142 forming rotor pole faces that are oriented (N/S) in an axial direction so as to face the axially outward oriented pole faces 121 , 122 of the stator core segments 100 across an axial air gap. Note that any casing or assembly ring has been omitted in these drawings for illustrative purposes. Besides the internal stator configuration with two external rotors shown in Fig.24 and Fig.25, the segmented stator core design may advantageously also be used in other configurations of axial flux electrical machines, such as those shown schematically in Figs.26-28 in a radial projection corresponding to the radial projection of Fig.24, wherein "Ro" denotes a rotor, and "St" denotes a stator: Fig.26 is a single rotor - single stator configuration; Fig.27 is a single internal rotor configuration with two external stators; and Fig.28 is a multiple stage configuration with two internal stators and three rotors, one of which is an internal rotor sandwiched between the internal stators and two of which are external rotors.

Fig.29 shows an alternative arrangement of a rotor 150 for an axial flux permanent magnet electrical machine, wherein the permanent magnets 152 of the rotor 150 are oriented (N/S) in a circumferential direction. The permanent magnets 152 are separated from neighbouring permanent magnets 152 by abutting rotor pole elements 151 made of a soft magnetic material. The permanent magnets and the rotor pole elements 151 with axially facing rotor pole surfaces 153 are arranged in a planar disk geometry. As indicated by cut-lines 155, the rotor 150 may be produced in sectors 154 that are fabricated separately and then assembled. This is for convenience of production and the division may be any suitable integer number of sectors 154 to form a full rotor 150.

Fig.30 and Fig.31 show a further advantageous rotor 160 for use in an axial flux permanent magnet electrical machine. As in the embodiment of Fig.29, the permanent magnets 162 of the rotor 160 are oriented (N/S) in a circumferential direction with alternating polarity, and the flux is diverted into the axial direction by means of pole elements 161 with axial pole surfaces 163 separating neighbouring permanent magnets from each other. However, in contrast to the embodiment of Fig. 29, the axial surface of the rotor 160 is corrugated, wherein the permanent magnets 162 are recessed from the rotor surface facing the air gap, whereas the pole elements 161 are bulged towards the stator such that the axially oriented pole surfaces 163 protrude into the air gap. Fig.31 shows two corrugated rotors 160 sandwiching an internal stator 601 with a segmented slotted stator core made of stator core segments 600 carrying stator coils 630 in a toroidal winding topology in a manner as described in detail above.

List of reference numerals

xOO	core segment
x10	yoke portion
x11	first abutment face
x12	second abutment face
x13, x14	guide feature
x15	circumferential passage
x16	radial/axial passage
x20	tooth portion
x21, x22	pole faces
x23	rim
x24, x25	pole piece
x30	coil element

wherein x is one or more of the list {1, 2, 3, 4, 5, 6}

30	assembly ring
31	assembly ring profile
32	opening
40	assembly element/assembly ring/housing
41	mounting rib
140	rotor
141	rotor disk
142	permanent magnet
150, 160	rotor
151, 161	pole element
152, 162	permanent magnet
153, 163	pole surface
154	sector
155	out line

Ro	Rotor
St	Stator
N/S	magnetic poles

CLAIMS

1. Stator core segment (xOO) for forming a slotted stator core of an axial flux electric machine with a toroidal winding topology, the stator core segment (xOO) comprising a yoke portion (x10) and a tooth portion (x20);

the tooth portion (x20) projecting in at least one axial direction from the yoke portion (x10), wherein the tooth portion (x20) comprises one or more pole pieces (x24, x25), wherein each of the pole pieces (x24, x25) has a pole face (x21, x22) that is oriented in the axial direction;

the yoke portion (x10) having a first abutment face (x1 1) facing towards a first circumferential direction and a second abutment face (x12) facing in a second circumferential direction opposite to the first circumferential direction, wherein the yoke portion (x10) is shaped and dimensioned such with respect to the tooth portion (x20) that the first abutment face (x1 1) of the core segment abuts (xOO) a second abutment face (x12) of a circumferentially adjacent core segment (xOO) when these are assembled in a stator core assembly.

2. Stator core segment according to claim 1, wherein the first and second abutment faces (x1 1, x12) include cooperating first and second guide elements (x1 3, x14), respectively, said guide elements (x13, x14) being configured such that the first and second abutment surfaces (x1 1, x12) mate in a male/female relationship, in a female/male relationship, or in a hermaphroditic relationship.

3. Stator core segment according to any of the preceding claims, wherein the yoke portion (x10) projects beyond the tooth portion (x20) in only one circumferential direction.

4. Stator core segment according to any of the preceding claims, wherein the tooth portion (x20) has a rim (x23) with a proximal portion attached to the yoke portion (x10) and a distal portion carrying the one or more pole pieces (x24, x25) at an axial distance from the yoke portion (x10).

5. Stator core segment according to claim 4, wherein the rim (x23) and the one or more pole pieces (x24, x25) of the tooth portion (x10) as seen in a radial cross-section form one of a T-shaped profile, an H-shaped profile (123/124/125, 323/324/325, 423/424/425,), or a C-shaped profile (223/224/225).

6. Stator core segment according to any of the preceding claims, wherein the core segment is made of a soft magnetic material.

7. Stator core segment according to claim 6, wherein the soft magnetic material is a soft magnetic composite (SMC).

8. Stator core segment according to claim 7, wherein the stator core segment is formed by a compression moulding and heat treatment process.

9. Stator core segment according to any of the preceding claims, wherein the stator core segment (300) has a circumferential passage (315) extending from the first abutment face (31 1) through the yoke portion (310) to the second abutment face (312).

10. Stator core segment according to claim 9, wherein the first and second abutment faces (31 1, 312) are adapted to allow for a fluid tight connection between adjacent stator core segments (300).

11. Stator core segment according to any of the preceding claims, wherein the stator core segment (400) has at least one of a radial passage (416) or an axial passage for receiving fastening elements (417) for fastening the stator core segment (400) to an assembly element (40).

12. Stator core assembly for forming a slotted core of an axial flux electrical machine with a toroidal winding topology, the stator core assembly comprising a plurality of stator core segments (xOO) according to any of the preceding claims, wherein adjacent stator core segments (xOO) are arranged to abut each other in a circumferential direction to form a circular arrangement, wherein the first abutment face (x1 1) of the yoke portion (x1 0) of each stator core segment (xOO) contacts

the second abutment face (x12) of the yoke portion (x10) of the adjacent stator core segment (xOO), and wherein the tooth portions (x20) of adja-cent/neighbouring stator core segments (xOO) define a slot for receiving a toroi-dal coil between them.

13. Stator for an axial flux electric machine with a toroidal winding topology, the stator comprising a slotted stator core assembly according to claim 12 and toroidal coils (130, 530) arranged on the yoke portions (110, 510) in the slots defined between the tooth portions (120, 520) of adjacent stator core segments (100, 500).

14. Stator according to claim 13, wherein circumferentially oriented end faces (531, 532) of the toroidal coils (530) are parallel to each other.

15. Stator according to claim 13, wherein circumferentially oriented end faces (131, 132) of the toroidal coils (130) are wedged towards each other in a radially inward direction.

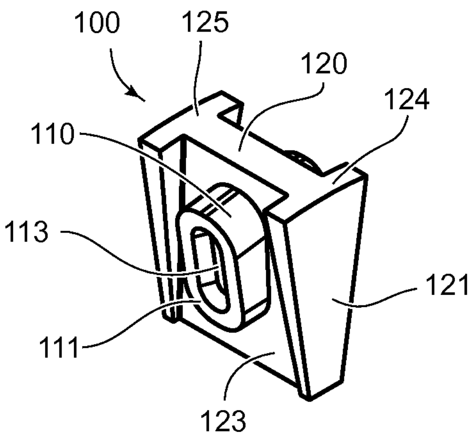


Fig. 1

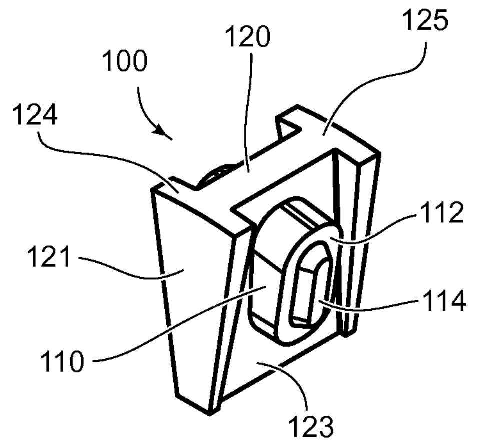


Fig. 2

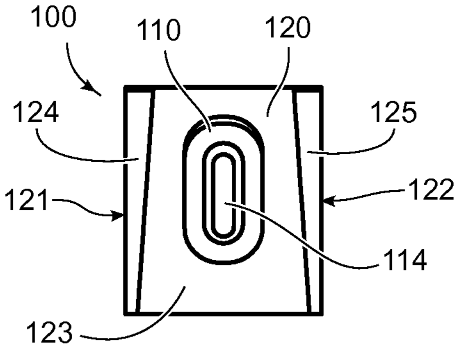


Fig. 3

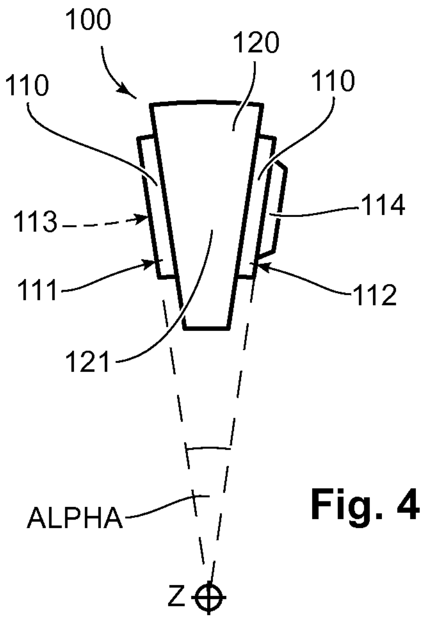


Fig. 4

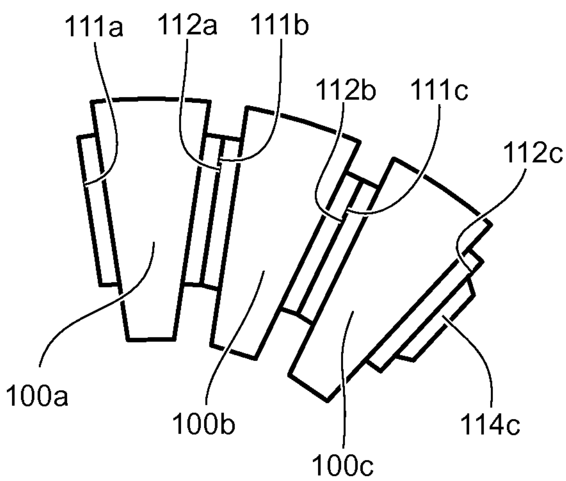


Fig. 6

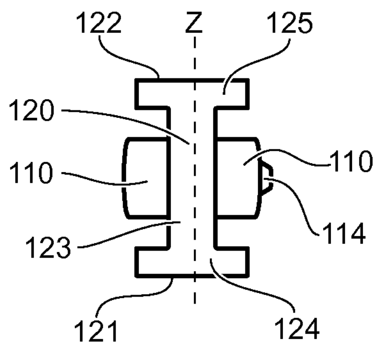


Fig. 5

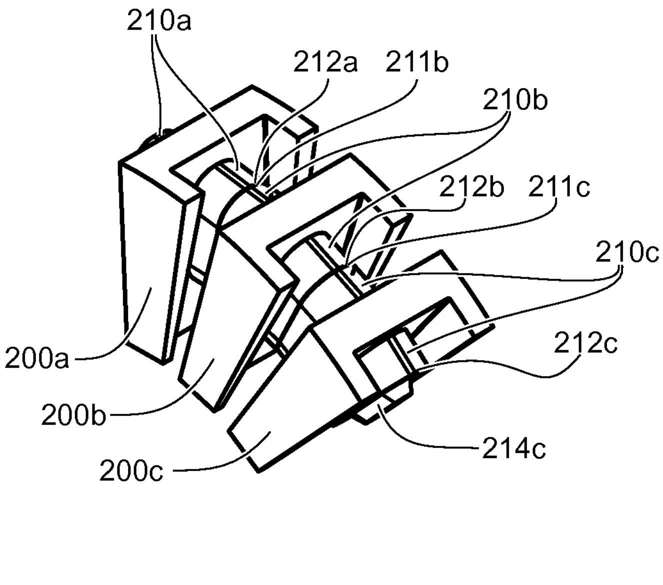


Fig. 7

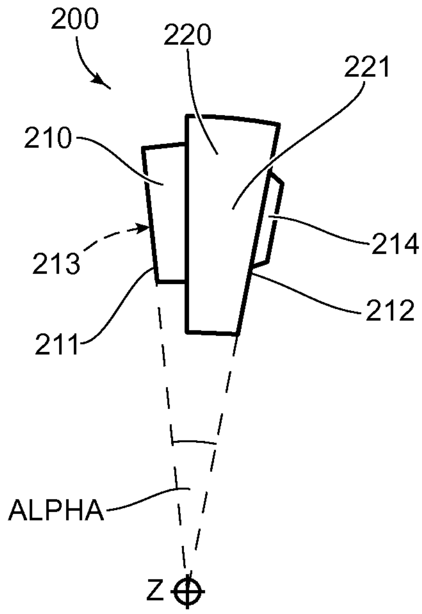


Fig. 8

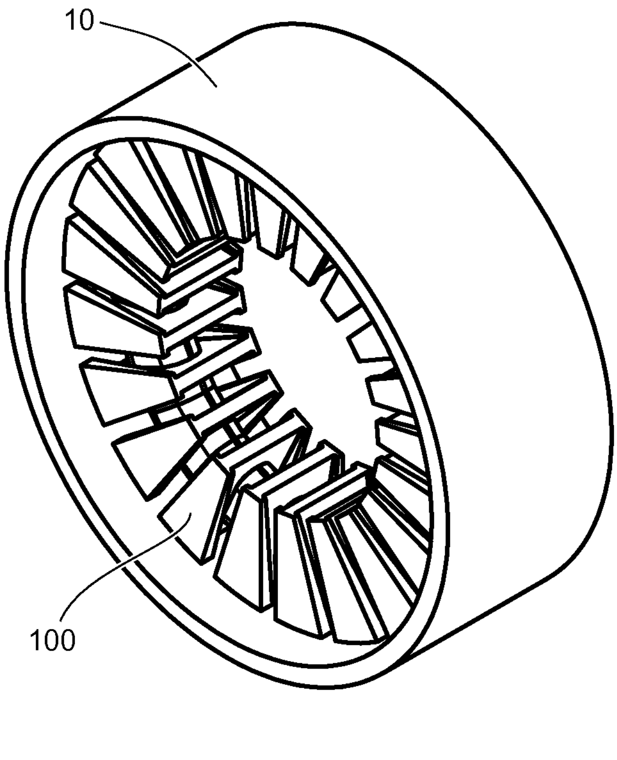


Fig. 10

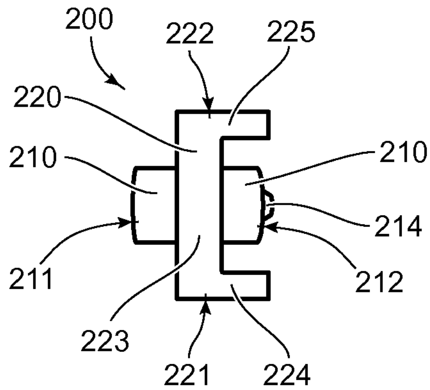


Fig. 9

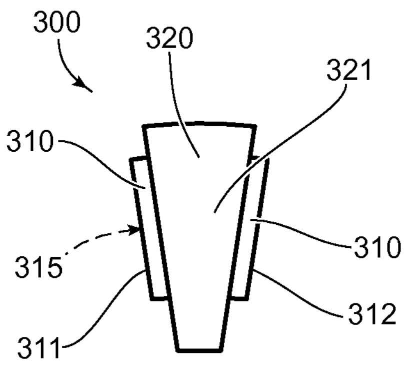


Fig. 11

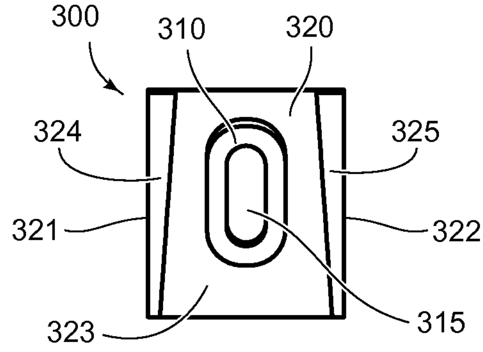


Fig. 12

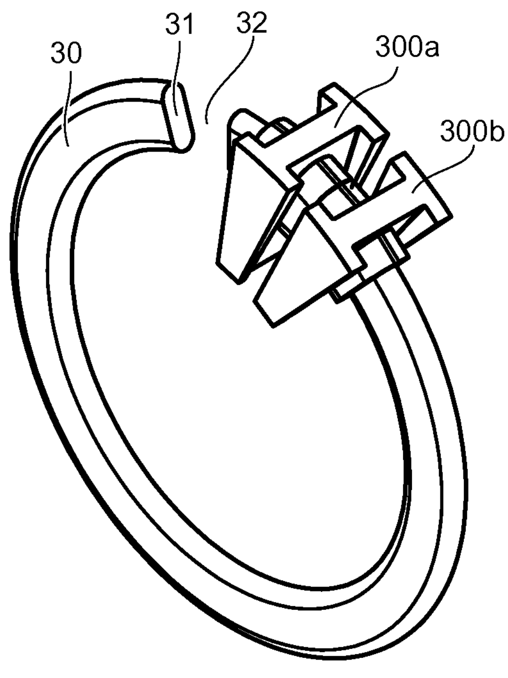


Fig. 14

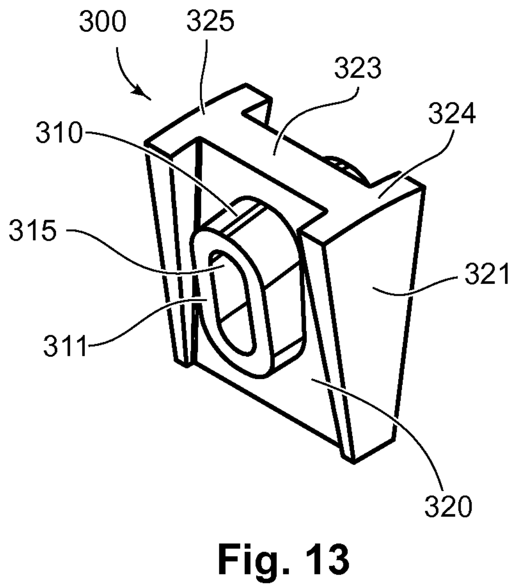


Fig. 13

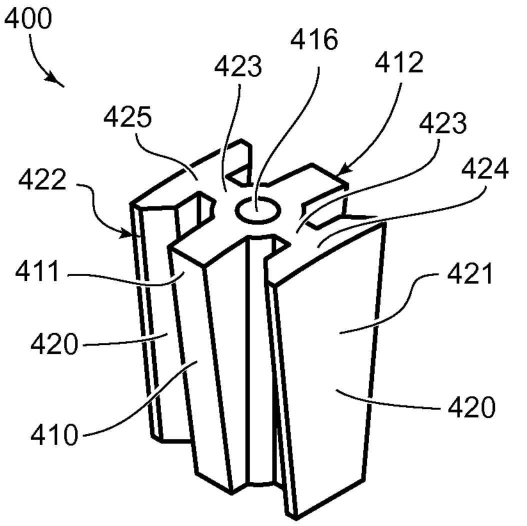


Fig. 15

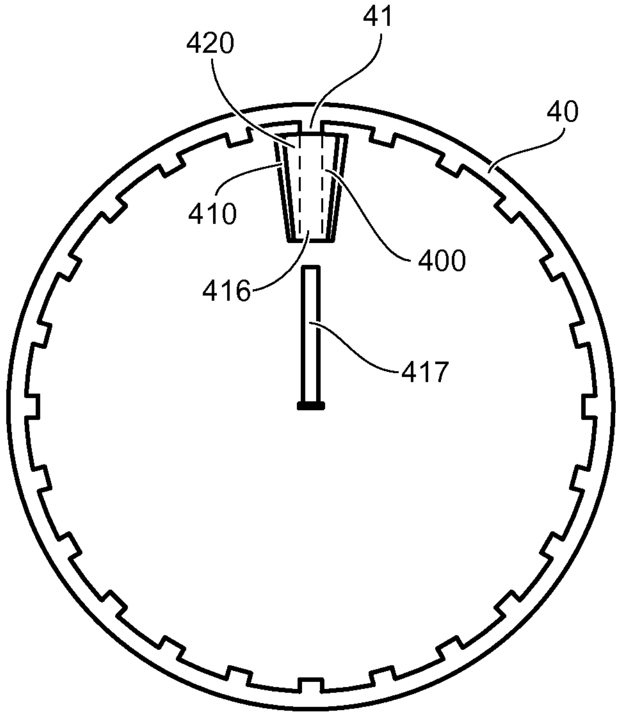


Fig. 16

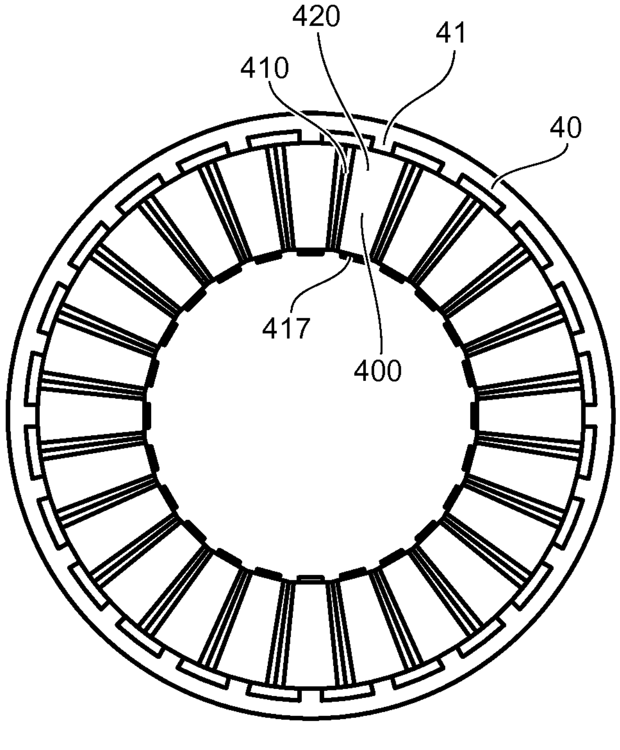


Fig. 17

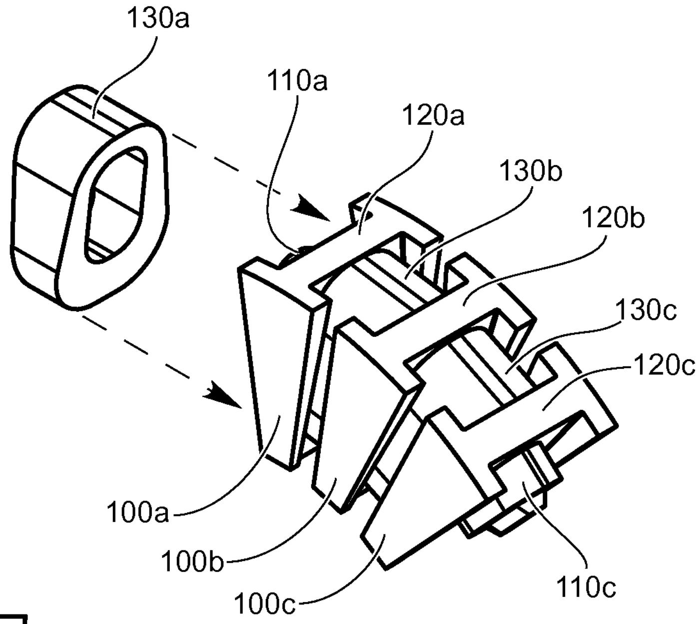
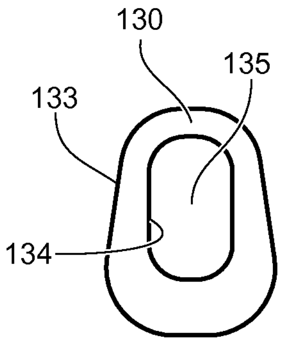


Fig. 18



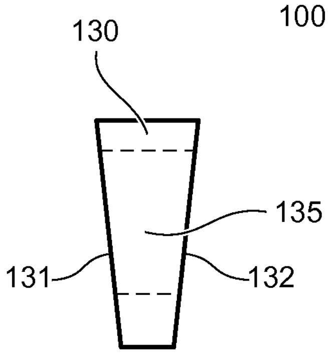
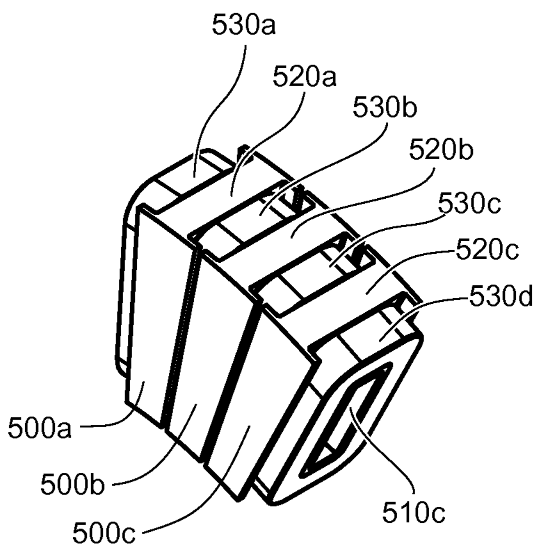
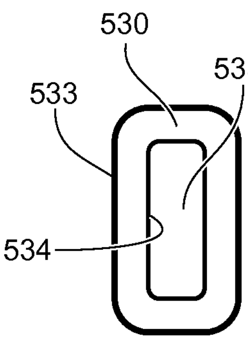


Fig. 19

Fig. 20





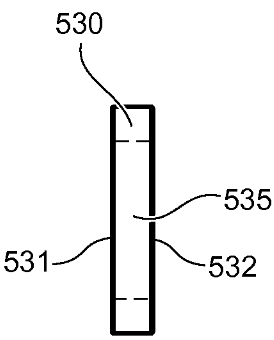


Fig. 21

Fig. 22

Fig. 23

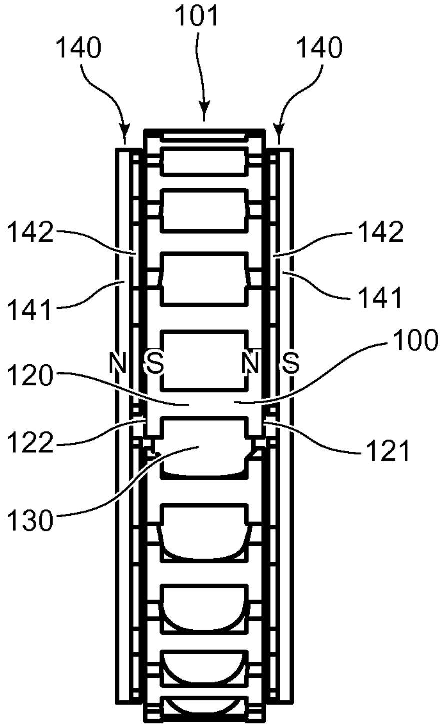


Fig. 24

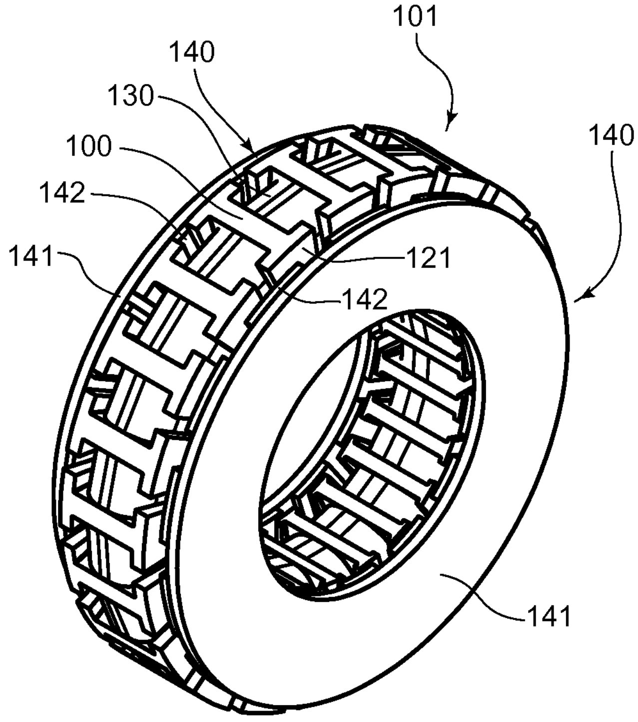


Fig. 25

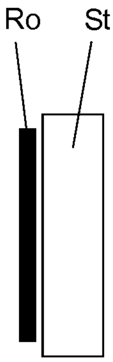


Fig. 26

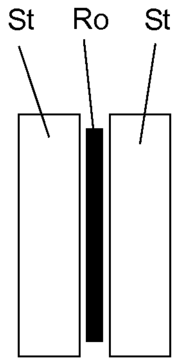


Fig. 27

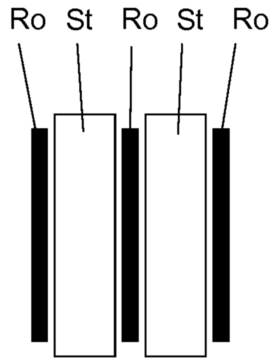


Fig. 28

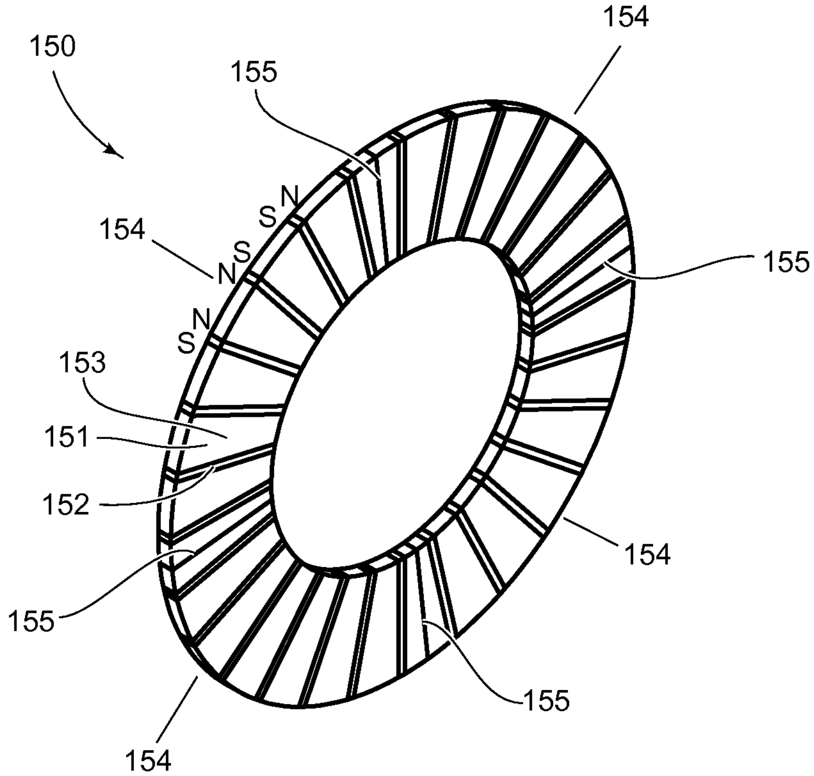


Fig. 29

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/069921

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02K1/14
ADD. H02K1/12 H02K1/16

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02K

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

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

EPO-Internal , WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y A	JP 2010 226937 A (TDK CORP) 7 October 2010 (2010-10-07) Paragraphs 1 5, 10, 28; figures 2,3,4a,4b,5,6 -----	1-8, 12-14 9,11,15 10
Y	KR 101 276 633 BI (KOREA IND TECH INST [KR]) 18 June 2013 (2013-06-18) paragraph [0033] - paragraph [0034] ; figures 5,6 -----	11
A	FR 2 946 811 AI (CHEVALLIER PATRICK [FR] ; AZZI LH0UCINE [FR]) 17 December 2010 (2010-12-17) abstract; figures 1,2,5 -----	1-8, 12-14
	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" documentwhich may throw doubts on priority claim(s) orwhich is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

25 September 2015

Date of mailing of the international search report

13/10/2015

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Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Jabri , Tarak

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Information on patent family members

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