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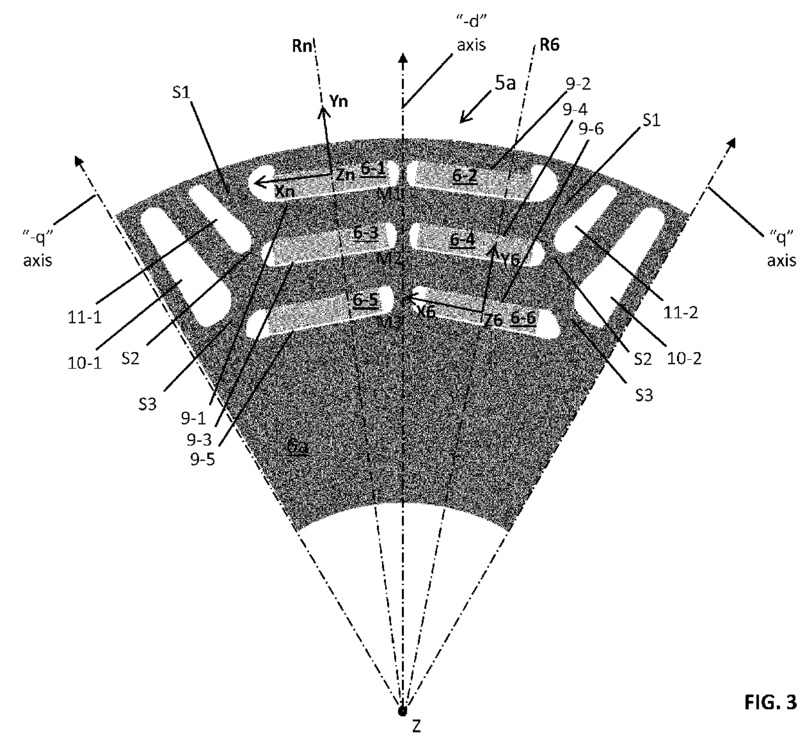

FIG. 3

(57) **Abstract:** The present disclosure relates to a rotor (3) for an electric machine (1). The rotor (3) has a plurality of permanent magnets (6-n) mounted in magnet apertures (9) formed in the rotor (3). The permanent magnets (6-n) each have a reference frame comprising a longitudinal central axis (Zn), a transverse major axis (Xn) and a transverse minor axis (Yn). The longitudinal central axis (Zn) of each permanent magnet (6-n) extends substantially parallel to a rotational axis (Z) of the rotor (3). The rotor (3) has a plurality of magnet poles (5a-f) each have a plurality of the permanent magnets (6-n) arranged in at least a first layer (L1). The first layer (L1) of each magnet pole (5a-f) includes a plurality of said permanent magnets (6-n), the permanent magnets (6-n) in said first layer (L1) being arranged such that the transverse minor axis (Yn) of each permanent magnet (6-n) extends along a radius (Rn) of the rotor (3).

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ELECTRIC MACHINE APPARATUS

TECHNICAL FIELD

The present disclosure relates to an electric machine apparatus. Particularly, but not exclusively, the present disclosure relates to a rotor for an electric machine; to an electric machine comprising a rotor; and to a vehicle comprising an electric machine.

BACKGROUND

A particular design challenge for electric machines is the positioning and arrangement of the permanent magnets within the rotor since the positioning and orientation affects the resulting magnetic flux path. The permanent magnets are mounted in magnet apertures formed in the rotor. The rotor may comprise flux barriers in the form of internal apertures for controlling the magnetic flux generated by the permanent magnets. The magnet apertures and flux barriers form a plurality of bridges (or ligaments) within the rotor. When the electric machine is operating, mechanical stresses are induced within the rotor as it rotates. The resulting mechanical stresses are particularly high at the corners of the magnet apertures. The bridges within the rotor must be sufficiently strong to withstand the resulting structural loads. However, in order to reduce magnetic flux leakage, the bridges should be as small and thin as possible.

At least in certain embodiments, the present invention seeks to provide an improved rotor for an electric machine.

SUMMARY OF THE INVENTION

Aspects of the present invention relate to a rotor for an electric machine; to an electric machine comprising a rotor; and to a vehicle as claimed in the appended claims.

According to a further aspect of the present invention there is provided a rotor for an electric machine, the rotor having:

a plurality of permanent magnets mounted in magnet apertures formed in the rotor, the permanent magnets each having a reference frame comprising a longitudinal central axis, a transverse major axis and a transverse minor axis; the longitudinal central axis of each permanent magnet extending substantially parallel to a rotational axis of the rotor;

a plurality of magnet poles each comprising a plurality of said permanent magnets arranged in at least a first layer;

wherein the first layer of each magnet pole comprises a plurality of said permanent magnets, the permanent magnets in said first layer being arranged such that the transverse minor axis of each permanent magnet extends at least substantially along a radius of the rotor. Thus, the transverse minor axis of each permanent magnet extends radially outwardly from the rotational axis of the rotor. The rotor may comprise one or more of said layers of permanent magnets. The rotor has a rotational axis about which the rotor is configured to rotate. The permanent magnets in at least said first layer are arranged such that the transverse minor axis of each permanent magnet extends at least substantially radially outwardly from the rotational axis of the rotor. At least in certain embodiments, the permanent magnets may help to reduce the mechanical stress within the rotor. In particular, the mechanical stress generated in the rotor at the corners of the permanent magnets may be reduced. The dimensions of bridges (ligaments) formed within the rotor may be reduced due to the lower mechanical stress. The magnetic flux leakage through these bridges may be reduced, thereby allowing an increase in the power of the electric machine.

The longitudinal central axis, the transverse major axis and the transverse minor axis are arranged perpendicular to each other. The transverse major axis and the transverse minor axis each define a central axis of the permanent magnet in a transverse section (i.e. a plane perpendicular to the longitudinal axis). The transverse major axis of each permanent magnet in said first layer extends substantially perpendicular to a radius of the rotor.

The permanent magnets are mounted in magnet apertures formed in the rotor. The magnet apertures are typically internal apertures. The internal apertures are formed by cut-outs in the rotor which are inset from an outer surface of the rotor. The magnet apertures extend substantially parallel to the rotational axis of the rotor.

One or more bridge may be formed between the permanent magnets in said first layer. For example, the first layer may consist of two permanent magnets and a first bridge may be formed between said permanent magnets in the first layer. It will be understood that the first layer may have three or more permanent magnets with a corresponding increase in the number of bridges formed in the rotor.

The first layer may comprise two or more of said permanent magnets. For example, the first layer may comprise three or four of said permanent magnets. The first layer may consist of two of said permanent magnets. In an alternate arrangement, the first layer may consist of three or four of said permanent magnets.

The magnet poles may each comprise a second layer of said permanent magnets. The second layer of each magnet pole may comprise a plurality of said permanent magnets. The permanent magnets in said second layer may be arranged such that the transverse minor axis of each permanent magnet extends at least substantially along a radius of the rotor. Thus, the permanent magnets may be arranged such that the transverse minor axis extends at least substantially radially outwardly from the rotational axis of the rotor. The transverse major axis of each permanent magnet in said second layer may extend substantially perpendicular to a radius of the rotor.

The second layer may consist of two of said permanent magnets. In an alternate arrangement, the second layer may consist of three or four of said permanent magnets.

One or more bridge may be formed between the permanent magnets in said second layer. For example, the second layer may consist of two permanent magnets and a second bridge may be formed between said permanent magnets in the second layer. It will be understood that the second layer may have three or more permanent magnets with a corresponding increase in the number of bridges formed in the rotor.

The magnet poles may each comprise a third layer of said permanent magnets. The third layer of each magnet pole may comprise a plurality of said permanent magnets. The permanent magnets in said third layer may be arranged such that the transverse minor axis of each permanent magnet extends at least substantially along a radius of the rotor. Thus, the permanent magnets may be arranged such that the transverse minor axis extends at least substantially radially outwardly from the rotational axis of the rotor. The transverse major axis of each permanent magnet in said third layer may extend substantially perpendicular to a radius of the rotor.

The first layer may be radially offset from said second layer and/or said third layer. The layers of permanent magnets may be radially offset from each other. The layers may be arranged substantially concentrically about the rotational axis of the rotor.

The rotor may comprise one or more flux barrier. The one or more flux barrier may comprise an aperture or cavity formed in the rotor. The one or more flux barrier may be disposed laterally of the permanent magnets in each layer. The first and second layers may be bounded laterally by respective outer and inner flux barriers. One or more bridge may be formed between the permanent magnets and said one or more flux barrier.

According to a further aspect of the present invention there is provided a rotor for an electric machine, the rotor having:

a plurality of permanent magnets mounted in magnet apertures formed in the rotor, the permanent magnets each having a reference frame comprising a longitudinal central axis (Zn), a transverse major axis (Xn) and a transverse minor axis (Yn); the longitudinal central axis (Zn) of each permanent magnet extending substantially parallel to a rotational axis of the rotor;

a plurality of magnet poles each comprising a plurality of said permanent magnets arranged in at least a first layer;

wherein the first layer of each magnet pole comprises a plurality of said permanent magnets, the permanent magnets in said first layer being arranged such that the transverse minor axis (Yn) of each permanent magnet extends at a first angle (α1) to a radius of the rotor. Thus, the transverse major axis (Xn) of each permanent magnet extends at the first angle (α1) to a tangent of the radius.

The first angle (α1) is non-zero. The first angle (α1) may be less than or equal to 5°, or less than or equal to 2°. The first angle (α1) may be zero (0) degrees plus or minus five (5) degrees (i.e. $\alpha1=0°\pm5°$), or zero (0) degrees plus or minus two (2) degrees (i.e. $\alpha1=0°\pm2°$). The first angle (α1) may be non-zero.

The magnet poles may each comprise a second layer. The second layer may comprise a plurality of said permanent magnets. The permanent magnets in said second layer may be arranged such that the transverse minor axis (Yn) of each permanent magnet extends at a second angle (α2) to a radius of the rotor. Thus, the transverse major axis (Xn) of each permanent magnet extends at a second angle (α2) to a tangent of the pole axis (d-axis) of the radius.

The second angle (α2) is non-zero. The second angle (α2) may be less than or equal to 5°, or less than or equal to 2°. The second angle (α2) may be zero (0) degrees plus or minus five (5) degrees (i.e. $\alpha2=0°\pm5°$), or zero (0) degrees plus or minus two (2) degrees (i.e. $\alpha2=0°\pm2°$). The second angle (α1) may be non-zero. The first angle (α1) and the second angle (α2) could be different from each other. Alternatively, the first angle (α1) and the second angle (α2) may be at least substantially equal to each other.

The magnet poles may each comprise a third layer. The third layer may comprise a plurality of said permanent magnets. The permanent magnets in said third layer may be arranged such that the transverse minor axis (Yn) of each permanent magnet extends at a third angle (α3) to a radius of the rotor. The transverse major axis (Xn) of each permanent magnet extends at a third angle (α3) to a tangent of the pole axis (d-axis) of the radius.

The third angle (α3) is non-zero. The third angle (α3) may be less than or equal to 5°, or less than or equal to 2°. The third angle (α3) may be zero (0) degrees plus or minus five (5) degrees (i.e. $\alpha3=0°\pm5°$), or zero (0) degrees plus or minus two (2) degrees (i.e. $\alpha3=0°\pm2°$). The third angle (α3) may be non-zero. The first angle (α1), the second angle (α2) and the third angle (α3) could be different from each other. Alternatively, the first angle (α1), the second angle (α2) and the third angle (α3) may be at least substantially equal to each other.

The first layer may be radially offset from said second layer and/or said third layer. The layers of permanent magnets may be radially offset from each other (i.e. offset from each other in a radial direction). The layers may be arranged substantially concentrically about the rotational axis of the rotor.

The permanent magnets in each layer may be angularly offset from the permanent magnets in the one or more other layers. For example, the permanent magnets in the first layer may be angularly offset from the permanent magnets in the second layer and/or the permanent magnets in the third layer.

According to a further aspect of the present invention there is provided an electric machine comprising a rotor as described herein. The electric machine may be a permanent magnet synchronous machine.

According to a still further aspect of the present invention there is provided a vehicle comprising an electric machine as described herein. The electric machine may be configured to generate a traction force for propelling the vehicle. The electric machine may be used as the sole means of propelling the vehicle or may be used in conjunction with another torque generating machine, such as an internal combustion engine.

Within the scope of this application it is expressly intended that the various aspects, embodiments, examples and alternatives set out in the preceding paragraphs, in the claims and/or in the following description and drawings, and in particular the individual features thereof, may be taken independently or in any combination. That is, all embodiments and/or features of any embodiment can be combined in any way and/or combination, unless such features are incompatible. The applicant reserves the right to change any originally filed claim or file any new claim accordingly, including the right to amend any originally filed claim to depend from and/or incorporate any feature of any other claim although not originally claimed in that manner.

BRIEF DESCRIPTION OF THE DRAWINGS

One or more embodiments of the present invention will now be described, by way of example only, with reference to the accompanying figures, in which:

Figure 1 shows a schematic illustration of a vehicle comprising an electric machine in accordance with an embodiment of the present invention;

Figure 2 shows a transverse section through the electric machine shown in Figure 1;

Figure 3 shows an enlarged view of a magnet pole of the electric machine shown in Figure 1;

Figure 4A is a graphical representation of the mechanical stress modelled in an initial magnet pole having permanent magnets orthogonal to a pole axis (d-axis) of the magnet pole;

Figure 4B is a graphical representation of the mechanical stress modelled in a modified magnet pole in accordance with an aspect of the present invention;

Figure 5 shows a first table showing the mechanical stress in the initial and modified magnet poles shown in Figures 4A and 4B;

Figure 6 shows a magnet pole of a rotor in accordance with a further embodiment of the present invention;

Figure 7 shows a magnet pole of a rotor in accordance with a further embodiment of the present invention; and

Figure 8 shows a magnet pole of a rotor in accordance with a further embodiment of the present invention.

DETAILED DESCRIPTION

An electric machine 1 in accordance with an embodiment of the present invention will now be described. The electric machine 1 in the present embodiment is configured for use as a traction drive in a motor vehicle 2, as shown in schematically in Figure 1.

With reference to Figure 2, the electric machine 1 is a permanent magnet synchronous motor comprising a rotor 3 and a stator 4. An air gap is maintained between the rotor 3 and the stator 4. The rotor 3 is made up of a plurality of laminations of a ferromagnetic material to form a rotor iron. The rotor 3 is configured to rotate about a rotational axis Z (extending perpendicular to the plane of the page in Figure 2). The rotor 3 comprises six (6) magnet poles 5a-f each comprising six (6) permanent magnets 6-n (where n represents the number of magnets in each of said magnet poles 5a-f). The magnet poles 5a-f each extend radially outwardly from the rotational axis Z of the rotor 3 and are angularly separated from each other. In alternate embodiments, the rotor 3 may comprise less than or more than six (6) magnet poles 5a-f. Moreover, each magnet pole 5a-f may comprise less than or more than six (6) magnets 6-n. The stator 4 comprises a plurality of stator teeth 7 extending radially inwardly to support coil windings 8. In the present arrangement, the stator 4 comprises fifty-four (54) stator teeth 7 such that there are nine (9) stator teeth 7 for each magnet pole 5a-f. The permanent magnets 6-n generate a magnetic flux and a torque is generated to drive the rotor 3 by energising the coil winding 8.

The magnet poles 5a-f all have the same general configuration and, for the sake of brevity, only a first magnet pole 5a will be described herein. An assumed reference frame for the first magnet pole 5a is shown in Figure 3. The reference frame comprises a pole axis (d-axis) aligned to the permanent magnet flux of the magnet poles 5a-f, and an inter-pole axis (q-axis) arranged transverse to the direction of the magnet poles 5a-f (i.e. transverse to the pole axis (d-axis)). The angular extent of each magnet pole 5a-f (i.e. the included angle between the positive inter-pole axis (+q-axis) and the negative inter-pole axis (–q-axis)) is referred to herein as the pole step. In the present embodiment the pole step of each magnet pole 5a-f is 60°. The angular separation of the pole axis (d-axis) of the first magnet pole 5a and the inter-pole axis (q-axis) is 30° in the present embodiment.

The permanent magnets 6-n are each mounted in a discrete magnet aperture 9 formed in the rotor 3. The magnet apertures 9 are internal apertures which extend substantially parallel to the rotational axis Z. The permanent magnets 6-n in the first magnet pole 5a are arranged in first, second and third layers L1-L3. As shown in Figure 2, the first, second and third layers L1-L3 are arranged concentrically about the rotational axis Z of the rotor 3 with a radial offset between each of the first, second and third layers L1-3. The first layer L1 is disposed in a radially outer position; and the third layer L3 is disposed in a radially inner position. The first, second and third layers L1-L3 within the first pole 5a each comprise a plurality of said permanent magnets 6-n arranged symmetrically about the pole axis (d-axis) of the first magnet pole 5a. In the present embodiment the first, second and third layers L1-L3 each consist of two (2) permanent magnets 6-n disposed on opposing sides of the pole axis (d-axis) in a symmetrical arrangement. In an alternative embodiment, the permanent magnets 6-n in the first magnet pole 5a may be arranged in one or two layers. Alternatively, or in addition, each layer may have three or more permanent magnets 6-n.

The first magnet pole 5a comprises two (2) outer flux barriers 10-1, 10-2 and two (2) inner flux barriers 11-1, 11-2 associated with the first and second layers L1, L2 respectively. The outer flux barriers 10-1, 10-2 and the inner flux barriers 11-1, 11-2 help to ensure the appropriate flux density distribution at the lateral boundaries of the poles (i.e. the “+q axis” and a “-q axis”). The outer flux barriers 10-1, 10-2 and the inner flux barriers 11-1, 11-2 are arranged symmetrically about the pole axis (d-axis) of the first magnet pole 5a. The outer flux barriers 10-1, 10-2 are disposed on opposing sides of the permanent magnets 6-n disposed in the first layer L1; and the inner flux barriers 11-1, 11-2 are disposed on opposing sides of the permanent magnets 6-n in the second layer L2. In the present embodiment the outer flux barriers 10-1, 10-2 and the inner flux barriers 11-1, 11-2 each comprise an air-filled cavity elongated in a radial direction from the centre of the rotor 3. The outer flux barriers 10-1, 10-2 and the inner flux barriers 11-1, 11-2 are internal apertures formed within the rotor 3 such that the outer surface of the rotor 3 is in the form of a continuous cylindrical surface.

The magnet apertures 9, the outer flux barriers 10-1, 10-2 and the inner flux barriers 11-1, 11-2 comprise internal apertures formed in the rotor 3. The internal apertures are formed by cut-outs in the laminations which are stacked to form the rotor 3. As shown in Figure 3, a plurality of bridges (or ligaments) is formed in the rotor 3. First, second and third central bridges M1-M3 are formed between the magnet apertures 9 in the first, second and third layers L1-L3 respectively. First, second and third lateral bridges S1-S3 are formed on each side of the first magnet pole 5a between the magnet apertures 9 in the first, second and third layers L1-L3 and the outer flux barriers 10-1, 10-2 and the inner flux barriers 11-1, 11-2. In use, the central bridges M1-M3 and the lateral bridges S1-S3 are subject to high mechanical stress due to the centripetal forces generated as the rotor 3 rotates. The mechanical stress in the central bridges M1-M3 and the lateral bridges S1-S3 is dependent at least in part on the size, position and profile of the magnet apertures 9 and the outer flux barriers 10-1, 10-2 and the inner flux barriers 11-1, 11-2. As described herein, the permanent magnets 6-n are mounted in the rotor 3 such that the mechanical stress within the first magnet pole 5a is reduced.

The permanent magnets 6-n are substantially rectangular in transverse section. With reference to Figure 3, the permanent magnets 6-n each have a reference frame comprising a longitudinal central axis Zn, a transverse major axis Xn and a transverse minor axis Yn. The longitudinal central axis Zn, the transverse major axis Xn and the transverse minor axis Yn are central axes of the permanent magnets 6-n and are arranged perpendicular to each other. The longitudinal central axis Zn extends substantially parallel to the longitudinal axis Z of the rotor 3. The transverse major axis Xn and the transverse minor axis Yn are disposed in a transverse section of the rotor 3 extending perpendicular to the rotational axis Z. With reference to Figure 3, the longitudinal central axis Zn extends perpendicular to the plane of the page; and the transverse major axis Xn and the transverse minor axis Yn are contained in the plane of the page. The orientation of the transverse minor axis Yn and the transverse major axis Xn are described herein with reference to a radius Rn of the rotor 3 which is coincident with the centre of that permanent magnet 6-n.

The permanent magnets 6-n in the first magnet pole 5a are mounted such that the longitudinal central axis Zn of each permanent magnet 6-n extends substantially parallel to the rotational axis Z of the rotor 3. The permanent magnets 6-n are arranged such that the transverse minor axis Yn of each permanent magnet 6-n extends at least substantially along the radius Rn of the rotor 3 coincident with the centre of that permanent magnet 6-n. Thus, the transverse minor axis Yn of each permanent magnet 6-n extends at least substantially radially outwardly. The permanent magnets 6-n are arranged such that the transverse major axis Xn of each permanent magnet 6-n extends substantially perpendicular to the radius Rn of the rotor 3 coincident with the centre of that permanent magnet 6-n. Thus, the transverse major axis Xn of each permanent magnet 6-n is disposed substantially orthogonal to the radius Rn . Within each of the first, second and third layers L1-L3, the permanent magnets 6-n are arranged such that the transverse major axes Xn are inclined at an angle relative to each other (i.e. a non-linear configuration). In the present arrangement in which each of the first, second and third layers L1-L3 consists of two (2) permanent magnets 6-n, the permanent magnets 6-n are arranged in an inverted V arrangement in which the radially outer faces of the permanent magnets 6-n are inclined away from each other. This mounting configuration may reduce the peak (maximum) mechanical stress within the rotor 3, particularly the mechanical stress generated at the corners of the magnet apertures 9. The dimensions of the central bridges M1-M3 and/or the lateral bridges S1-S3 may be reduced due to the lower mechanical stress. The magnetic flux leakage through the central bridges M1-M3 and/or the lateral bridges S1-S3 may be reduced and this may allow an increase in the power of the electric machine 1.

The results of a computational analysis to model the mechanical stress in the first magnet pole 5a when the electric machine 1 is rotating at 21600RPM will now be described with reference to Figures 4A and 4B. The mechanical stress modelled in an initial first magnet pole having permanent magnets arranged orthogonal to the pole axis (d-axis) of the magnet pole is illustrated in Figure 4A. The results of this analysis identified a maximum mechanical stress of approximately 391MPa in the first magnet pole in the first central bridge M1 formed between the magnet apertures in the first layer. The mechanical stress modelled in a modified first magnet pole having permanent magnets arranged orthogonal to the radius Rn of the rotor 3 in accordance with an embodiment of the present invention is illustrated in Figure 4B. The results of this analysis identified a maximum mechanical stress of approximately 309MPa in the first magnet pole 5a in the first central bridge M1 disposed between the magnet apertures 9 in the first layer L1. The width of each of the central bridges M1-M3 and the lateral bridges S1-S3 in the initial and modified models is shown in a first table T1 shown in Figure 5. The first table T1 also shows the peak mechanical stress (MPa) modelled in each of the central bridges M1-M3 and the lateral bridges S1-S3 in the initial and modified first magnet poles 5a. It will be understood that the arrangement of the permanent magnets 6-n in accordance with the present invention thereby reduces the mechanical stress within the rotor 3. Moreover, the width of at least some of the central bridges M1-M3 may be reduced in the modified first magnet pole 5a.

A first magnet pole 5a of a rotor 3 in accordance with a further embodiment of the present invention is shown in Figure 6. The rotor 3 is a development of the embodiment described herein with reference to Figure 3. It will be understood that all of magnet poles 5-n of the rotor 3 have substantially the same configuration. The description herein focuses on the orientation of the permanent magnets 6-n within the first magnet pole 5a. Like reference numerals are used for like components.

An assumed reference frame for the first magnet pole 5a is shown in Figure 6. The reference frame comprises a pole axis (d-axis) aligned to the permanent magnet flux of the magnet poles 5a-f, and an inter-pole axis (q-axis) arranged transverse to the direction of the magnet poles 5a-f (i.e. transverse to the pole axis (d-axis)). The angular extent of each magnet pole 5a-f (i.e. the included angle between the positive inter-pole axis (+q-axis) and the negative inter-pole axis (–q-axis)) is referred to herein as the pole step. In the present embodiment the pole step of each magnet pole 5a-f is 60°. The angular separation of the pole axis (d-axis) of the first magnet pole 5a and the inter-pole axis (q-axis) is 30° in the present embodiment.

The permanent magnets 6-n are each mounted in a discrete magnet aperture 9 formed in the rotor 3. The magnet apertures 9 are internal apertures which extend substantially parallel to the rotational axis Z. The permanent magnets 6-n in the first magnet pole 5a are arranged in first, second and third layers L1-L3. The first, second and third layers L1-3 have the arrangement illustrated in Figure 2. The first, second and third layers L1-L3 each consist of two (2) permanent magnets 6-n disposed on opposing sides of the pole axis (d-axis) in a symmetrical arrangement. In an alternative embodiment, the permanent magnets 6-n in the first magnet pole 5a may be arranged in one or two layers. Alternatively, or in addition, each layer may have three or more permanent magnets 6-n.

The first magnet pole 5a may optionally include flux barriers (not shown) of the type described herein with reference to Figure 3. The magnet apertures 9 and any such flux barriers may comprise apertures formed in the rotor 3. The apertures form a plurality of bridges (or ligaments) in the rotor 3. The bridges formed in the rotor 3 according to the present embodiment are not described herein for the sake of brevity. However, it will be understood that the rotor 3 may comprise bridges corresponding to the central bridges M1-M3 and the lateral bridges S1-S3 described herein with reference to Figure 3.

The permanent magnets 6-n are substantially rectangular in transverse section. The permanent magnets 6-n each have a reference frame comprising a longitudinal central axis Zn, a transverse major axis Xn and a transverse minor axis Yn. The longitudinal central axis Zn, the transverse major axis Xn and the transverse minor axis Yn are central axes of the permanent magnets 6-n and are arranged perpendicular to each other. The longitudinal central axis Zn extends substantially parallel to the longitudinal axis Z of the rotor 3. The transverse major axis Xn and the transverse minor axis Yn are disposed in a transverse section of the rotor 3 extending perpendicular to the rotational axis Z. With reference to Figure 6, the longitudinal central axis Zn extends perpendicular to the plane of the page; and the transverse major axis Xn and the transverse minor axis Yn are contained in the plane of the page. The orientation of the transverse minor axis Yn and the transverse major axis Xn are described herein with reference to a radius Rn of the rotor 3 which is coincident with the centre of that permanent magnet 6-n.

The permanent magnets 6-n in the first magnet pole 5a are mounted such that the longitudinal central axis Zn of each permanent magnet 6-n extends substantially parallel to the rotational axis Z of the rotor 3. The permanent magnets 6-n are arranged such that the transverse minor axis Yn of each permanent magnet 6-n extends at an angle (α) relative to the radius Rn of the rotor 3 coincident with the centre of that permanent magnet 6-n. Thus, the transverse minor axis Yn of each permanent magnet 6-n extends at an angle (α) to the radius of the rotor 3. The permanent magnets 6-n are arranged such that the transverse major axis Xn of each permanent magnet 6-n extends at the angle (α) to an axis perpendicular (i.e. tangential) to the radius Rn of the rotor 3 coincident with the centre of that permanent magnet 6-n.

With reference to Figure 6, the permanent magnets 6-1, 6-2 disposed in the first layer of the magnet pole 5a are arranged such that the transverse minor axis (Y1) of each permanent magnet 6-1, 6-2 extends at a first angle ($\alpha 1$) to a radius R1 of the rotor 3 coincident with the centre of that permanent magnet 6-1, 6-2. The permanent magnets 6-3, 6-4 disposed in the second layer of the magnet pole 5a are arranged such that the transverse minor axis (Y2) of each permanent magnet 6-3, 6-4 extends at a second angle (α2) to a radius R2 of the rotor 3 coincident with the centre of that permanent magnet 6-3, 6-4. The permanent magnets 6-5, 6-6 disposed in the second layer of the magnet pole 5a are arranged such that the transverse minor axis (Y3) of each permanent magnet 6-5, 6-6 extends at a third angle (α3) to a radius R3 of the rotor 3 coincident with the centre of that permanent magnet 6-5, 6-6.

In the present embodiment, the first angle (α1), the second angle (α2) and the third angle (α3) are at least substantially equal to each other. In the embodiment illustrated in Figure 6, each of the first angle (α1), the second angle (α2) and the third angle (α3) is +5° (i.e. α1=α2=α3=+5°). As illustrated herein, the reference frame of each permanent magnet 6-n is defined such that the transverse minor axis Yn extends outwardly. When the first angle (α1), the second angle (α2) and the third angle (α3) are positive variables (+ve), the transverse minor axis Yn of the respective permanent magnets 6-n are rotated inwardly towards the d-axis of the magnet pole 6a. The included angle between the transverse major axis Xn of the respective permanent magnets 6-n and the d-axis of the magnet pole 6a is thereby reduced. In the present embodiment, the layers L1, L2, L3 each comprise two (2) permanent magnets 6-n disposed on opposite sides of the d-axis. By increasing the first angle (α1), the second angle (α2) and the third angle (α3), which are positive variables, the angular offset between the transverse major axes Xn of the opposing permanent magnets 6-n is reduced. At least in the present embodiment, the angle formed between the transverse major axes Xn of the opposing permanent magnets 6-n is non-zero.

Within each of the first, second and third layers L1-L3, the permanent magnets 6-n are arranged such that the transverse major axes Xn are inclined at an angle relative to each other (i.e. a non-linear configuration). In the present arrangement in which each of the first, second and third layers L1-L3 consists of two (2) permanent magnets 6-n, the permanent magnets 6-n are arranged in an inverted V arrangement in which the radially outer faces of the permanent magnets 6-n are inclined away from each other. In the present embodiment, the permanent magnets 6-n in each layer L1-3 is angularly offset from the permanent magnets 6-n in the other layers. Consequently, the radii Rn coincident with the centres of the permanent magnets 6-n are angularly separated from each other. The angle defined between the transverse major axes Xn of the permanent magnets 6-n in each layer L1-L3 is different.

A variant of the embodiment of the rotor 3 described herein with reference to Figure 6 is shown in Figure 7. Like reference numerals are used for like components. As in the previous embodiment, the first angle (α1), the second angle (α2) and the third angle (α3) are at least substantially equal to each other. However, in the present variant, each of the first angle (α1), the second angle (α2) and the third angle (α3) is -5° (i.e. α1=α2=α3=-5°). As illustrated herein, the reference frame of each permanent magnet 6-n is defined such that the transverse minor axis Yn extends outwardly. When the first angle (α1), the second angle (α2) and the third angle (α3) are negative variables (-ve), the transverse minor axis Yn of the respective permanent magnets 6-n are rotated away from the d-axis of the magnet pole 6a. The included angle between the transverse major axis Xn of the respective permanent magnets 6-n and the d-axis of the magnet pole 6a is thereby increased. In the present embodiment, the layers L1, L2, L3 each comprise two (2) permanent magnets 6-n disposed on opposite sides of the d-axis. By increasing the first angle (α1), the second angle (α2) and the third angle (α3), which are negative angles, the angular offset between the transverse major axes Xn of the opposing permanent magnets 6-n is increased. At least in the present embodiment, the angular offset between the transverse major axes Xn of the opposing permanent magnets 6-n is non-zero. It will be understood that the permanent magnets 6-n may usefully be inclined at other angles.

A variant of the embodiment of the rotor 3 described herein with reference to Figure 6 is shown in Figure 8. Like reference numerals are used for like components. In the present variant, the first angle (α1), the second angle (α2) and the third angle (α3) are different from each other. In the present embodiment the first angle (α1) is less than the second angle (α2) which is less than the third angle (α3) (i.e. α1<α2<α3). In the illustrated example, the first angle (α1) is -5° (i.e. α1 =-5°), the second angle (α2) is 0° (i.e. α2 =0°) and the third angle (α3) is +5° (i.e. α3=+5°). In the present embodiment, the permanent magnets in each of the layers L1, L2, L3 are non-parallel (i.e. inclined at an angle relative to each other). The angular orientation of the transverse major axis X1 of the first permanent magnet 6-1 relative to the d-axis is greater than the angular orientation of the transverse major axis X3 of the third permanent magnet 6-3 relative to the d-axis. Furthermore, the angular orientation of the transverse major axis X3 of the third permanent magnet 6-3 relative to the d-axis is greater than the angular orientation of the transverse major axis X5 of the fifth permanent magnet 6-5 relative to the d-axis.

It will be appreciated that various modifications may be made to the embodiment(s) described herein without departing from the scope of the appended claims. The present invention has been described with reference to a permanent magnet synchronous machine. The configuration of the permanent magnets 6-n in the rotor 3 may be applied to other types of electric machine, such as a switched reluctance electric motor.

CLAIMS:

1. A rotor for an electric machine, the rotor having:

a plurality of permanent magnets mounted in magnet apertures formed in the rotor, the permanent magnets each having a reference frame comprising a longitudinal central axis (Zn), a transverse major axis (Xn) and a transverse minor axis (Yn); the longitudinal central axis (Zn) of each permanent magnet extending substantially parallel to a rotational axis of the rotor;

a plurality of magnet poles each comprising a plurality of said permanent magnets arranged in at least a first layer;

wherein the first layer of each magnet pole comprises a plurality of said permanent magnets, the permanent magnets in said first layer being arranged such that the transverse minor axis (Yn) of each permanent magnet extends at least substantially along a radius of the rotor.

2. A rotor as claimed in claim 1, wherein at least said first layer consists of two of said permanent magnets

3. A rotor as claimed in claim 1 or claim 2 comprising one or more bridge formed between the permanent magnets in said first layer.

4. A rotor as claimed in claim 1 or claim 2, wherein the magnet poles each comprise a second layer of said permanent magnets.

5. A rotor as claimed in claim 4 comprising one or more bridge formed between the permanent magnets in said second layer.

6. A rotor as claimed in claim 4 or claim 5, wherein the second layer of each magnet pole comprises a plurality of said permanent magnets, the permanent magnets in said second layer being arranged such that the transverse minor axis of each permanent magnet extends along at least substantially a radius of the rotor.

7. A rotor as claimed in any one of claims 4, 5 or 6, wherein the magnet poles each comprise a third layer of said permanent magnets.

8. A rotor as claimed in claim 7 comprising one or more bridge formed between the permanent magnets in said third layer.

9. A rotor as claimed in claim 7 or claim 8, wherein the third layer of each magnet pole comprises a plurality of said permanent magnets, the permanent magnets in said third layer being arranged such that the transverse minor axis of each permanent magnet extends at least substantially along a radius of the rotor.

10. A rotor as claimed in any one of claims 4 to 9, wherein the first layer is radially offset from said second layer and/or said third layer.

11. A rotor for an electric machine, the rotor having:

a plurality of permanent magnets mounted in magnet apertures formed in the rotor, the permanent magnets each having a reference frame comprising a longitudinal central axis (Zn), a transverse major axis (Xn) and a transverse minor axis (Yn); the longitudinal central axis (Zn) of each permanent magnet extending substantially parallel to a rotational axis of the rotor;

a plurality of magnet poles each comprising a plurality of said permanent magnets arranged in at least a first layer;

wherein the first layer of each magnet pole comprises a plurality of said permanent magnets, the permanent magnets in said first layer being arranged such that the transverse minor axis (Yn) of each permanent magnet extends at a first angle (α1) to a radius of the rotor.

12. A rotor as claimed in claim 11, wherein the first angle (α1) is less than or equal to 5°, or less than or equal to 2°.

13. A rotor as claimed in claim 11 or claim 12, wherein the magnet poles each comprise a second layer comprising a plurality of said permanent magnets, the permanent magnets in said second layer being arranged such that the transverse minor axis (Yn) of each permanent magnet extends at a second angle (α2) to a radius of the rotor.

14. A rotor as claimed in claim 13, wherein the second angle (α2) is less than or equal to 5°, or less than or equal to 2°.

15. A rotor as claimed in any one of claims 11 to 14, wherein the magnet poles each comprise a third layer comprising a plurality of said permanent magnets, the permanent

magnets in said third layer being arranged such that the transverse minor axis (Yn) of each permanent magnet extends at a third angle (α3) to a radius of the rotor.

16. A rotor as claimed in claim 15, wherein the third angle (α3) is less than or equal to 5°, or less than or equal to 2°.

17. A rotor as claimed in claim 15 or claim 16 when dependent directly or indirectly on dependent claim 13, wherein the first angle (α1), the second angle (α2) and the third angle (α3) are at least substantially equal to each other.

18. A rotor as claimed in any one of claims 11 to 17, wherein the permanent magnets in each layer of each magnet pole are angularly offset from the permanent magnets in one or more other layers of the same magnet pole.

19. A rotor as claimed in any one of the preceding claims comprising one or more flux barrier disposed laterally of the permanent magnets.

20. A rotor as claimed in claim 19 comprising one or more bridge formed between the permanent magnets and said one or more flux barrier.

21. An electric machine comprising a rotor as claimed in any one of the preceding claims.

22. An electric machine as claimed in claim 19, wherein the electric machine is a permanent magnet synchronous machine.

23. A vehicle comprising an electric machine as claimed in claim 21 or claim 22.

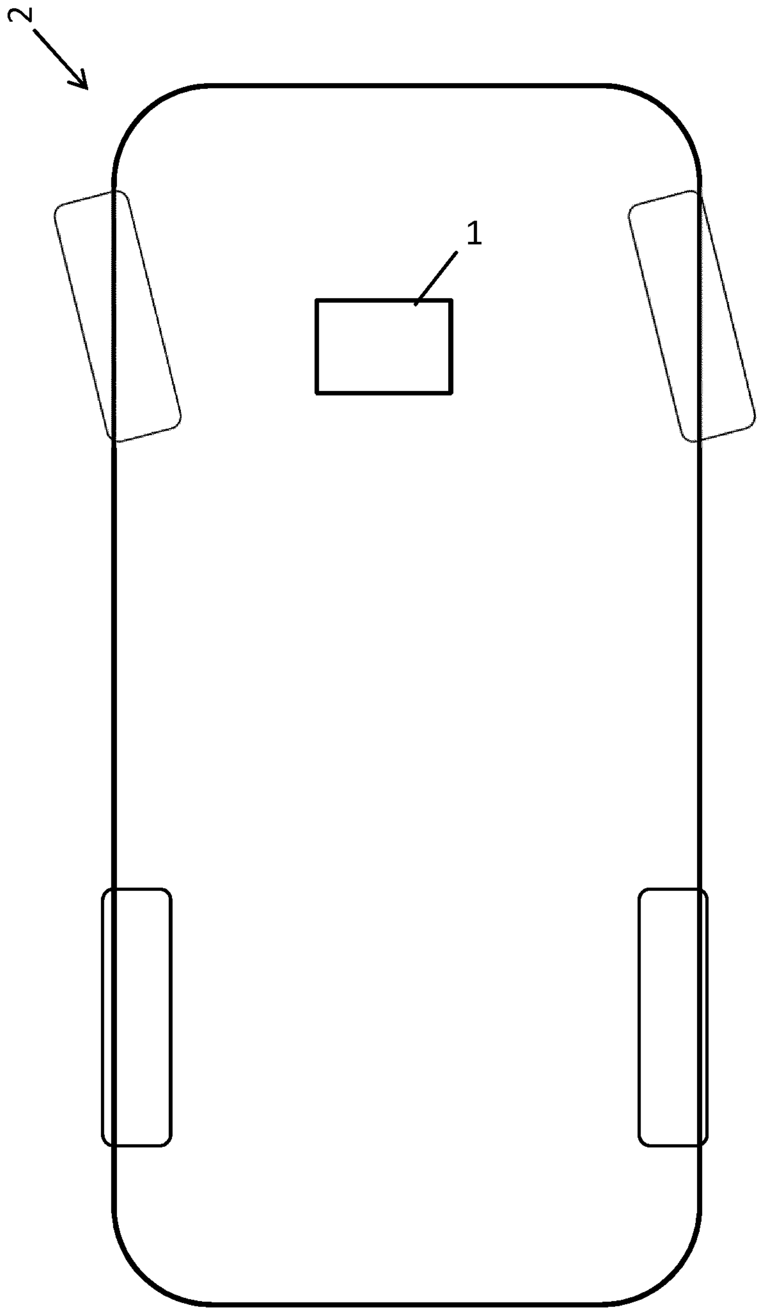


FIG. 1

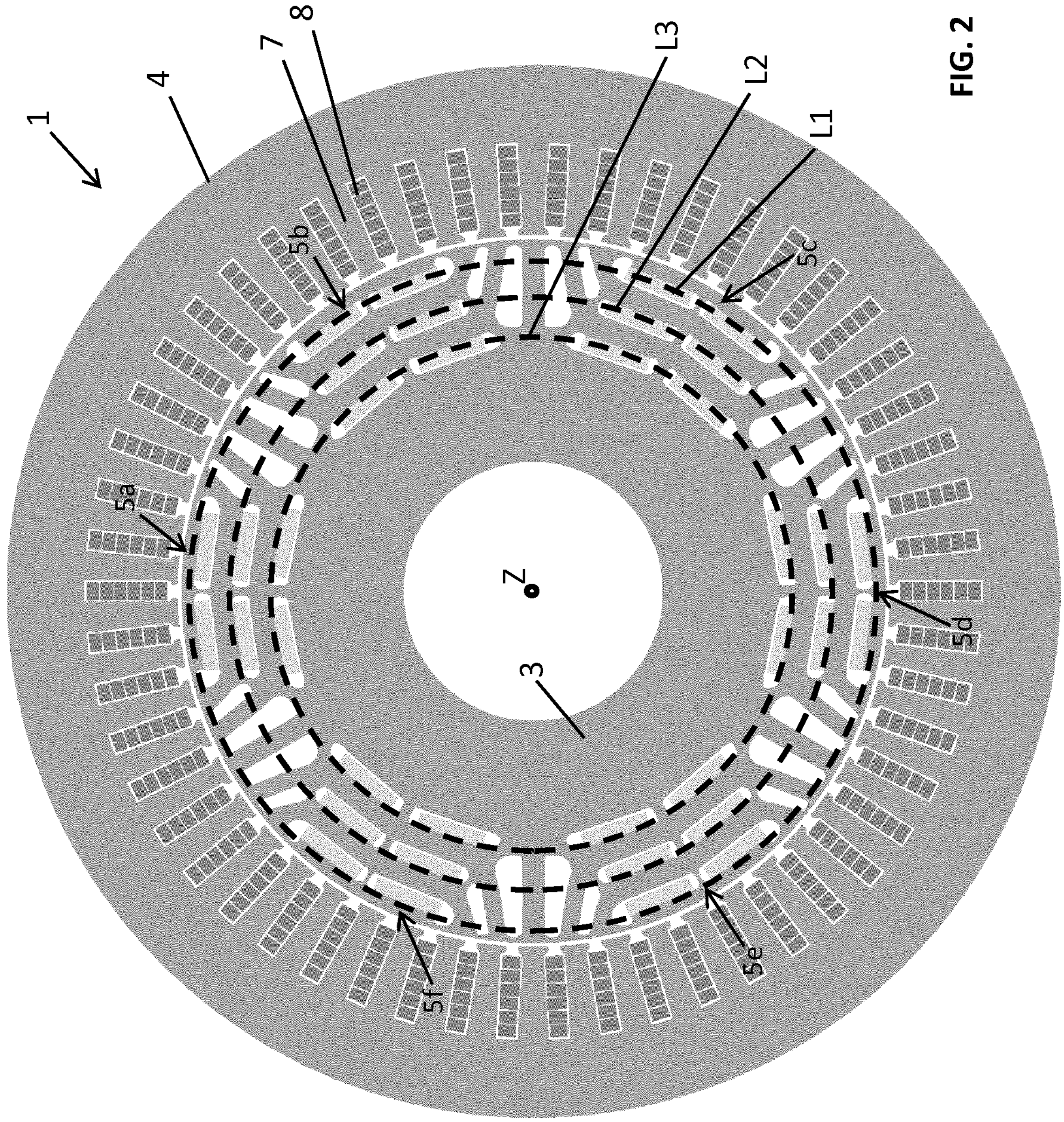
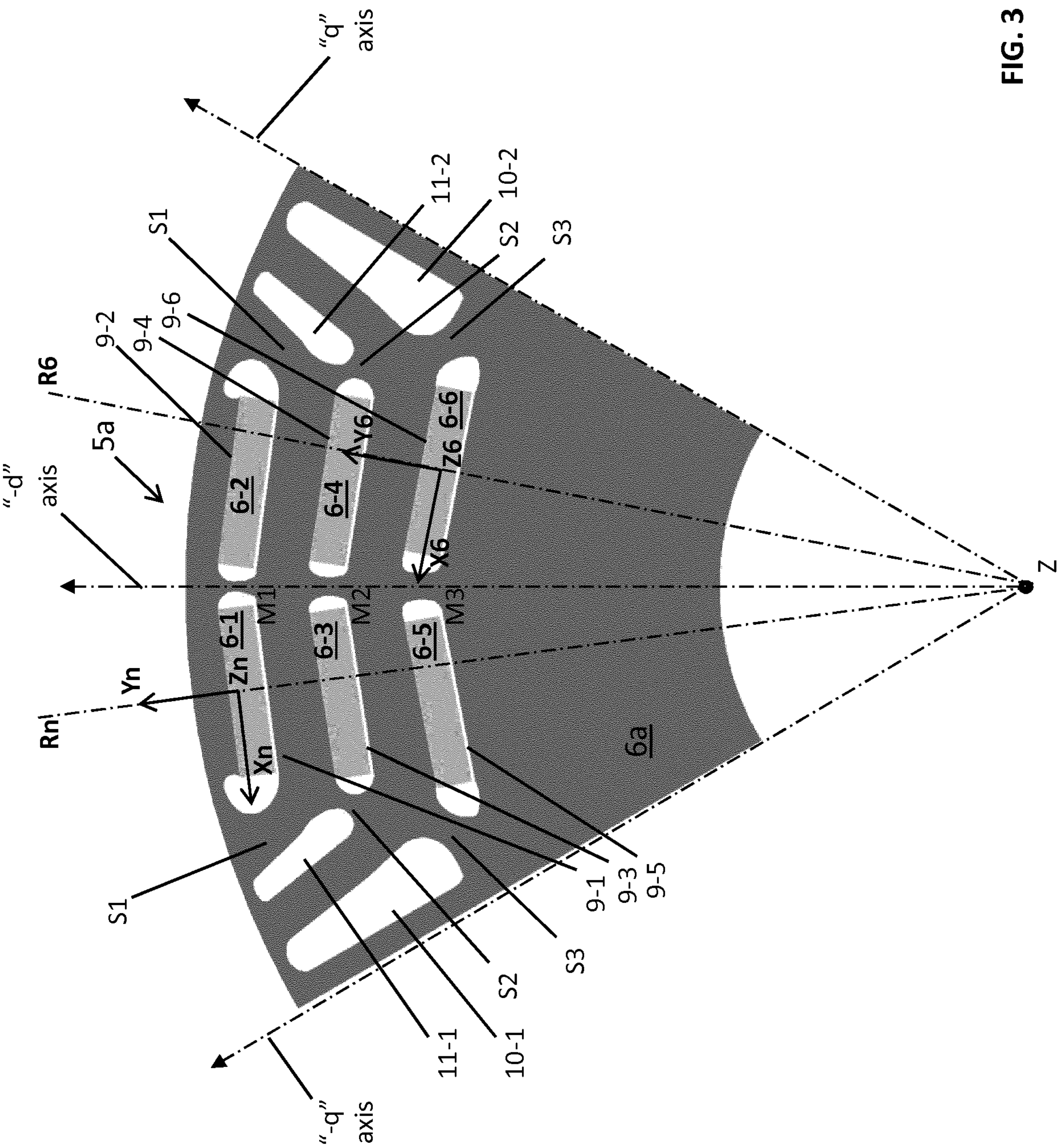


FIG. 2



"q" axis
"-d" axis
"-q" axis
S1
S2
S3
11-2
10-2
9-2
9-4
9-6
R6
5a
6-2
6-4
6-6
Y6
Z6
X6
M1
M2
M3
Z
6-1
6-3
6-5
Zn
Yn
Rn
Xn
6a
9-1
9-3
9-5
S1
S2
S3
11-1
10-1

FIG. 3

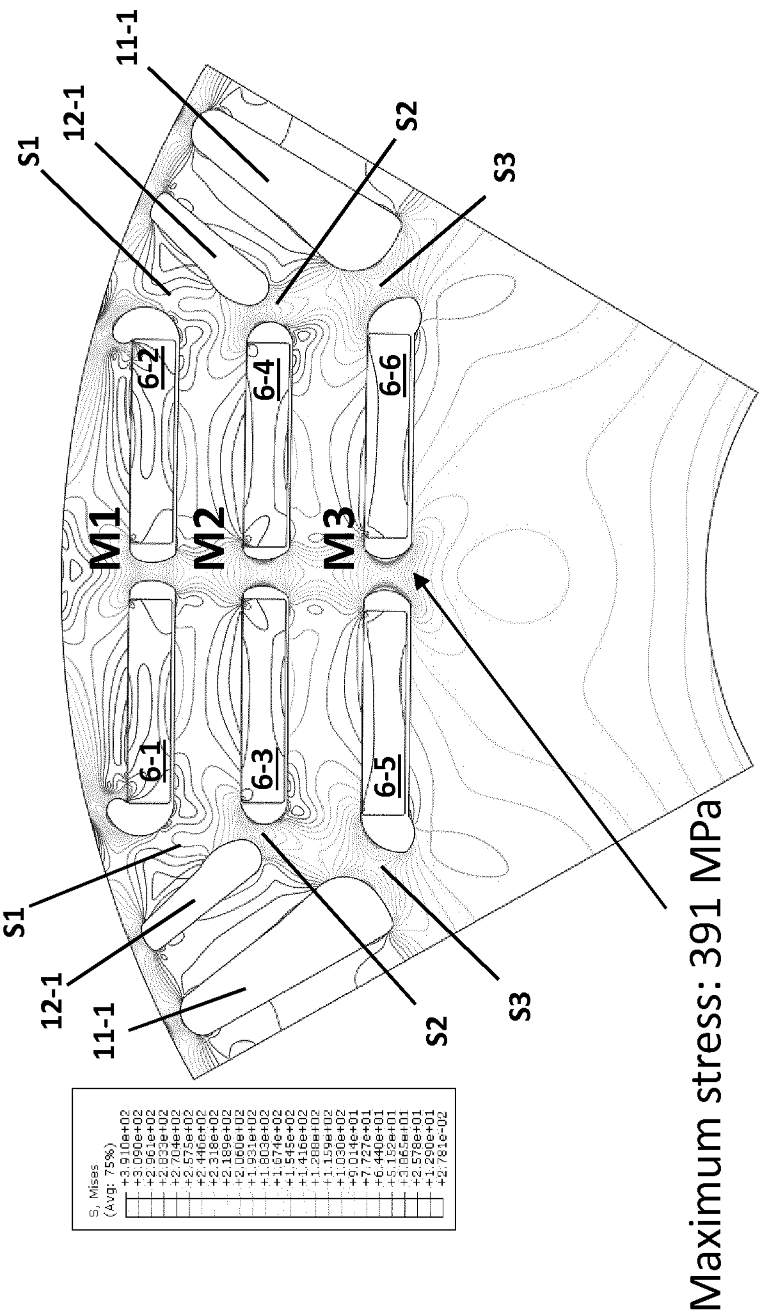

11-1
12-1
S1
S2
S3
6-1
6-2
6-3
6-4
6-5
6-6
M1
M2
M3
S1
S2
S3
12-1
11-1
Maximum stress: 391 MPa

FIG. 4A

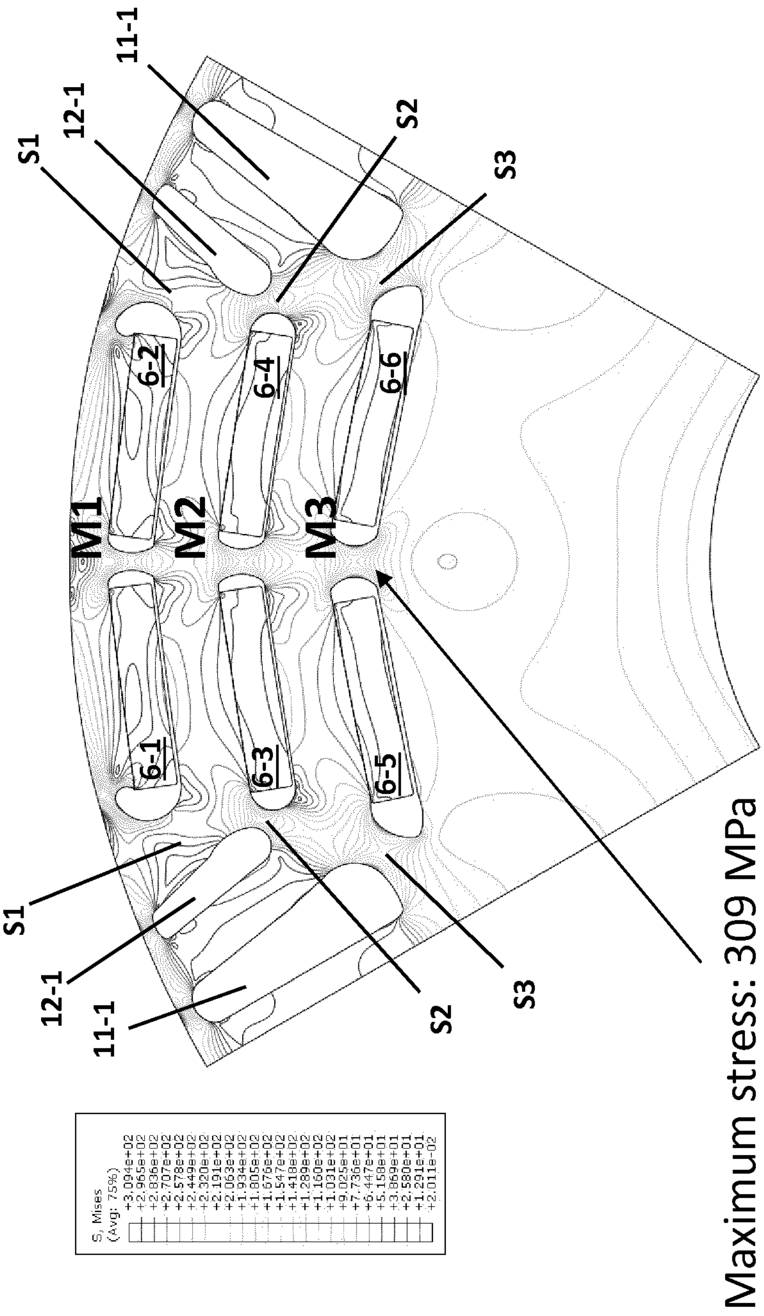

11-1
12-1
S1
S2
S3
6-1
6-2
6-3
6-4
6-5
6-6
M1
M2
M3
S1
12-1
11-1
S2
S3
Maximum stress: 309 MPa
S, Mises
(Avg: 75%)

FIG. 4B

Bridge	Thickness (mm)		Stress (Mpa)	
	Initial	Modified	Initial	Modified
S1	1.2	1.17	480	340
S2	1.25	1.42	430	324
S3	2.36	2.62	440	340
M1	1.13	0.93	406	320
M2	1.58	1.58	552	302
M3	2.51	2.18	610	347

TABLE (T1)

FIG. 5

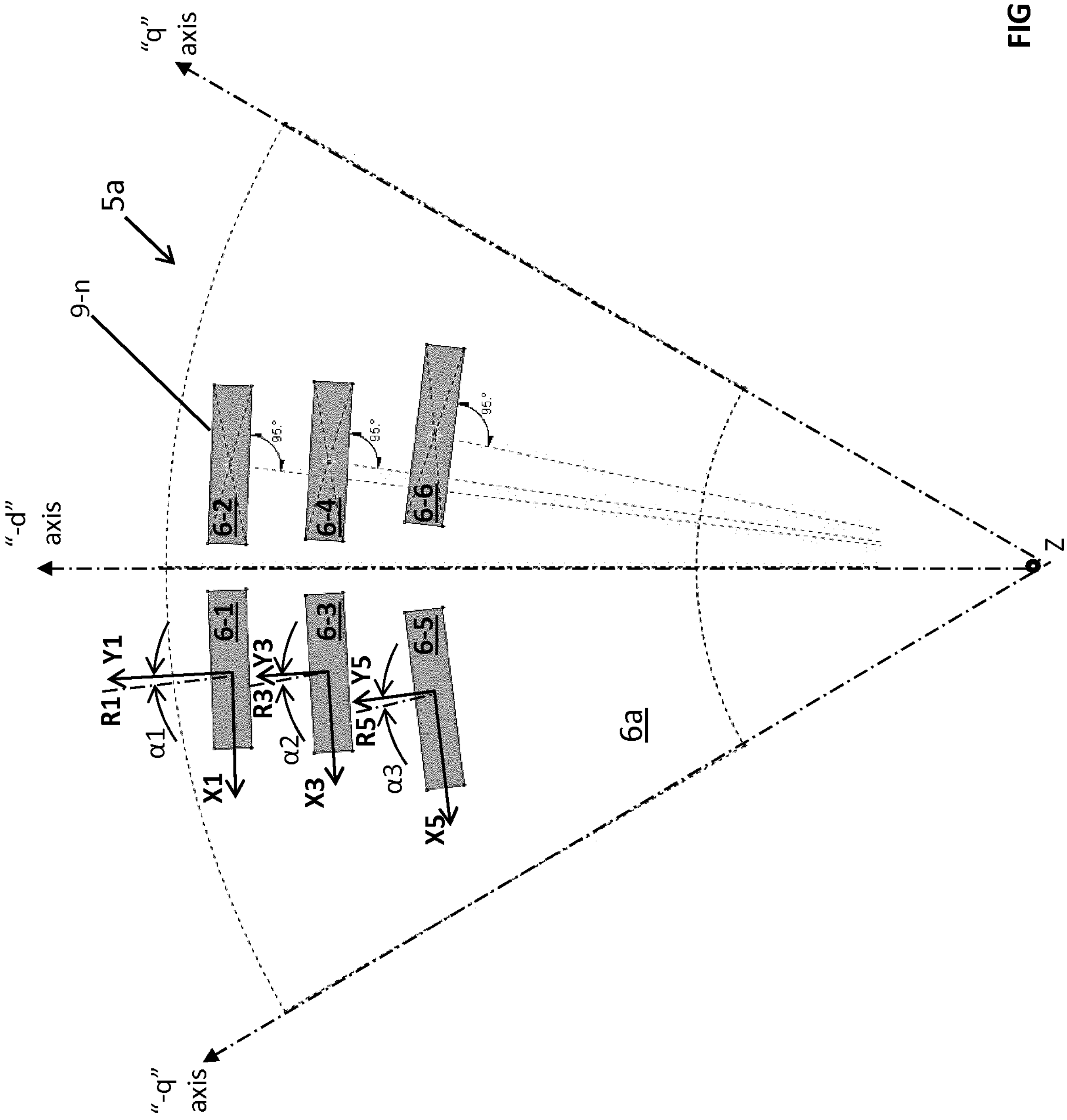

"q" axis
5a
9-n
"-d" axis
6-2
6-4
6-6
95.°
95.°
95.°
Z
6-1
6-3
6-5
Y1
R1
α1
X1
Y3
R3
α2
X3
Y5
R5
α3
X5
6a
"-q" axis

FIG. 6

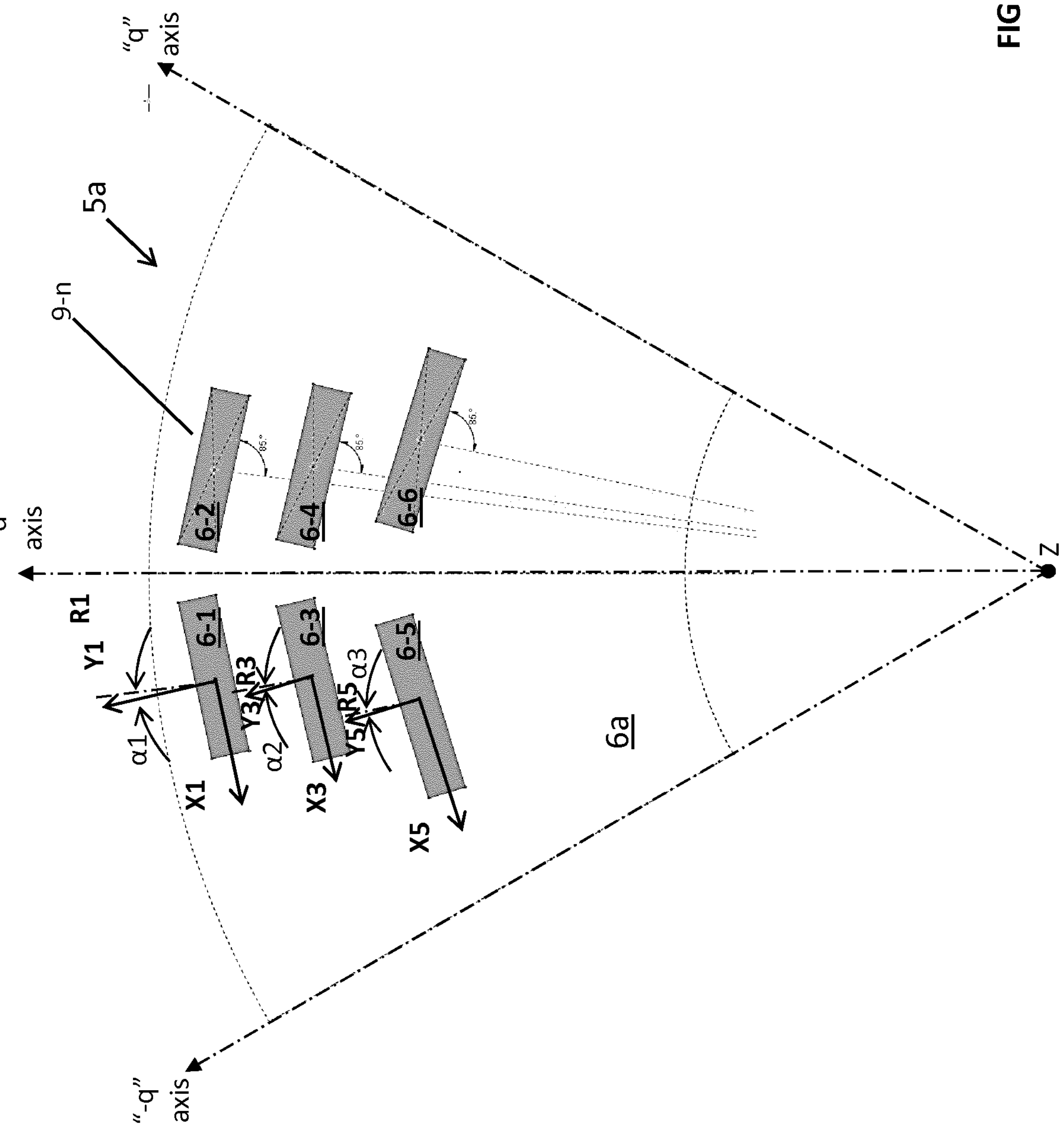

"q" axis
"-d" axis
"-q" axis
5a
9-n
6-1
6-2
6-3
6-4
6-5
6-6
6a
Z
R1
Y1
X1
α1
R3
Y3
X3
α2
R5
Y5
X5
α3

FIG. 7

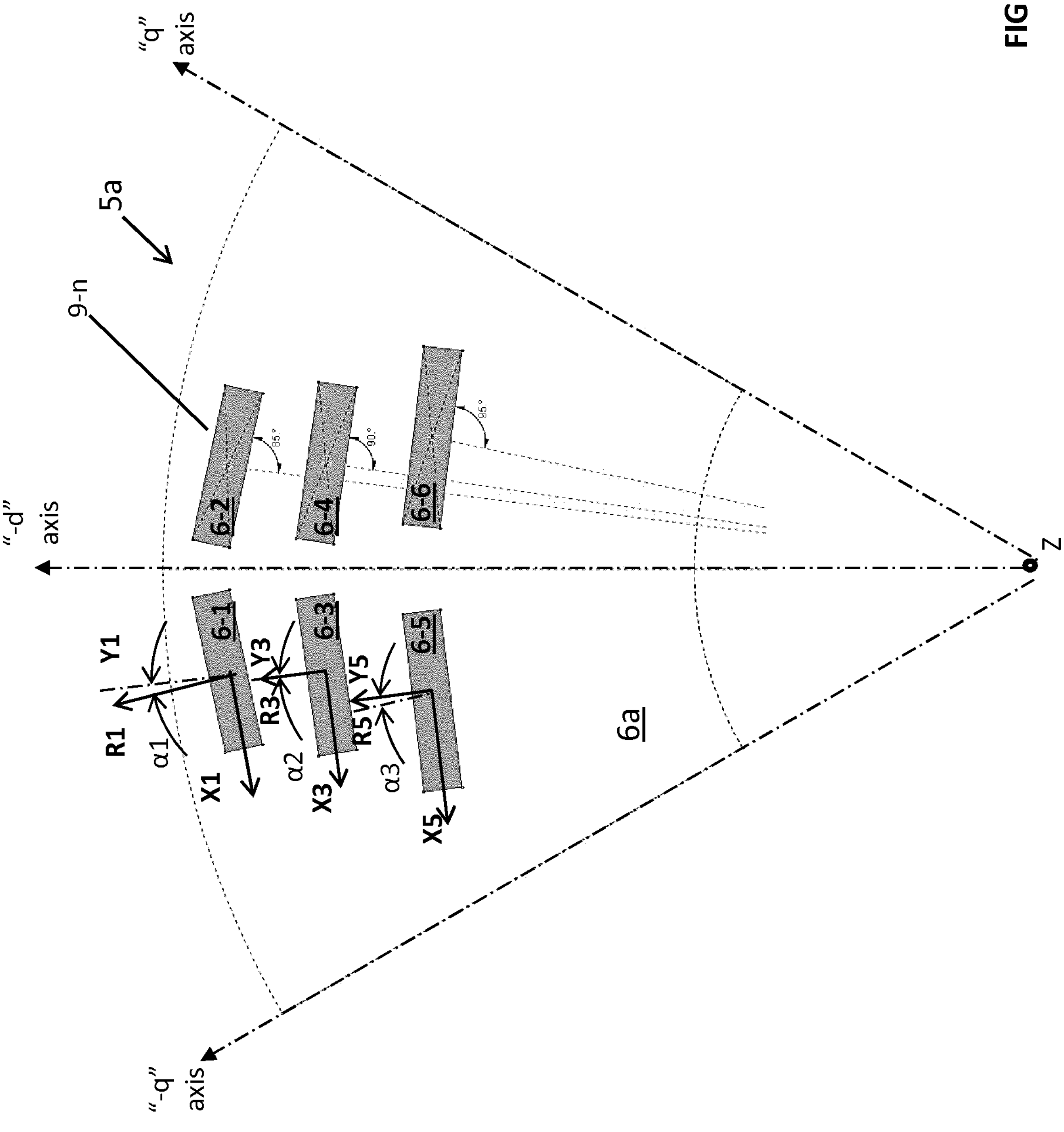

"q" axis
5a
9-n
"-d" axis
6-2
6-4
6-6
85°
90°
95°
6-1
6-3
6-5
Y1
Y3
Y5
R1
R3
R5
α1
α2
α3
X1
X3
X5
6a
Z
"-q" axis

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/080038

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02K1/27
ADD.

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	US 8 766 468 B1 (RILLA MARKO [US] ET AL) 1 July 2014 (2014-07-01) figures 1a, 1b column 1, line 25 - line 39 column 5, line 21 - line 66 -----	1-3, 19-23 4-10
X A	EP 2 207 253 A2 (HITACHI LTD [JP]) 14 July 2010 (2010-07-14) paragraphs [0005], [0007], [0040]; figures 7, 10, 15 -----	1,3, 19-23 4-10
X A	DE 102 17 977 A1 (OSWALD ELEKTROMOTOREN GMBH [DE]) 27 November 2003 (2003-11-27) paragraphs [0002], [0009]; figure 1 -----	1,3, 21-23 4-10
	-/--	

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

[X] See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
1 February 2018	12/02/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Georgopoulos, P

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2013/133474 A1 (ILJIN ELECTRIC [KR]; KIM SEONG HOON [KR]; CHOI WOONG CHUL [KR]; KIM WO) 12 September 2013 (2013-09-12) paragraph [0003]; figures 1-3	11,13, 15,17, 19,21-23

X	CN 204 906 031 U (SHANGHAI GIE EM CO LTD) 23 December 2015 (2015-12-23)	11,13, 15,18, 19,21-23
Y	paragraph [0001]; figure 1	4-10,14, 16

X	JP 2006 333656 A (TOSHIBA IND PRODUCTS MFG CORP) 7 December 2006 (2006-12-07)	11,12, 21-23
Y	paragraphs [0001], [0014], [0028]; figures 1, 2	14,16

X	EP 3 073 614 A1 (HITACHI AUTOMOTIVE SYSTEMS LTD [JP]) 28 September 2016 (2016-09-28)	11-13, 18-23
A	paragraph [0004]; figures 4, 8	14,16

X	JP 2007 068357 A (TOSHIBA IND PRODUCTS MFG CORP; TOSHIBA CORP) 15 March 2007 (2007-03-15)	11,19-23
A	paragraphs [0028] - [0030]; figures 2, 4	14,16

1

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 8766468	B1	01-07-2014	NONE		
EP 2207253	A2	14-07-2010	EP 2207253	A2	14-07-2010
			JP 5308832	B2	09-10-2013
			JP 2010161883	A	22-07-2010
			US 2010176682	A1	15-07-2010
DE 10217977	A1	27-11-2003	NONE		
WO 2013133474	A1	12-09-2013	KR 20130103643	A	24-09-2013
			WO 2013133474	A1	12-09-2013
CN 204906031	U	23-12-2015	NONE		
JP 2006333656	A	07-12-2006	NONE		
EP 3073614	A1	28-09-2016	CN 105745820	A	06-07-2016
			EP 3073614	A1	28-09-2016
			JP 6263551	B2	17-01-2018
			JP WO2015076045	A1	16-03-2017
			US 2016301271	A1	13-10-2016
			WO 2015076045	A1	28-05-2015
JP 2007068357	A	15-03-2007	NONE		