(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
9 February 2012 (09.02.2012)

PCT

(10) International Publication Number
WO 2012/017303 A2

(51) International Patent Classification:
H02K 1/27 (2006.01)

(21) International Application Number:
PCT/IB2011/001814

(22) International Filing Date:
4 August 2011 (04.08.2011)

(25) Filing Language: Italian

(26) Publication Language: English

(30) Priority Data:
VI2010A000220 4 August 2010 (04.08.2010) IT

(71) Applicant *(for all designated States except US)*: **NUOVA SACCARDO MOTORI S.R.L.** [IT/IT]; Via Lazio, 5/B, I-36015 SCHIO (VI) (IT).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: **BATTISTELLA, Francesco** [IT/IT]; Via Nori, 41, I-36078 Valdagno (VI) (IT).

(74) Agent: **BONINI, Ercole**; Studio Bonini SRL, Corso Fogazzaro, 8, I-36100 Vicenza (IT).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) **Title**: PERMANENT MAGNET GENERATOR WITH REDUCED COGGING EFFECT AND RELATED MAGNETS

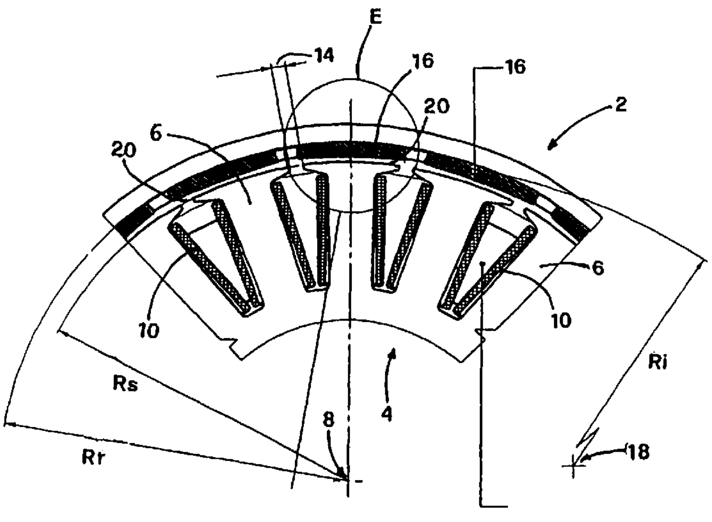


FIG. 2

(57) **Abstract**: The invention concerns a permanent magnet generator with reduced cogging effect, comprising a stator (4) provided with a plurality of stacks of tooth- shaped magnetic laminations (6; 306) having respective electric windings (10) arranged radially around the rotation axis (8) of the generator, which alternate with a plurality of slots (12; 312) having a correspondent opening (14; 314), and a rotor (2) provided with a plurality of permanent magnets (16; 116; 216) arranged radially spaced from the rotation axis (8) of the generator, in which the permanent magnets (16; 116; 216) have skew edges. The air gap (20) between the stacks of tooth-shaped magnetic laminations (6; 306) and the permanent magnets (16; 116; 216) is variable; the magnets are variable air gap magnets in which the top and bottom sides of the magnets define an internal curved surface and an external curved surface having the same curvature direction and defining, in cross section, with respect to the height of the magnet in the direction of the rotation axis, non-concentric circle arcs with different radiuses (R1, R2, R11, R12), so that the distance between the two surfaces that represents the thickness of the magnets varies in its cross section; the rotor (2) is outside the stator (4) and the circle arc defined by the radius (Ri; R1; R11) of the internal curved surface in cross section, located in front of the stacks of tooth-shaped magnetic laminations (6), is not concentric with the circle arc defined by the radius (Rs) corresponding to the cylindrical surface defined by the stacks of tooth-shaped magnetic laminations (6).

WO 2012/017303 A2

PERMANENT MAGNET GENERATOR WITH REDUCED COGGING EFFECT AND RELATED MAGNETS.

DESCRIPTION

Technical field of the invention

The invention concerns a permanent magnet generator with reduced cogging effect comprising a stator with a plurality of stacks of tooth-shaped magnetic laminations having electric windings located radially around the rotation axis of the generator which alternate with a plurality of slots having a correspondent opening and a rotor having a plurality of permanent magnets arranged radially spaced from the rotation axis of the generator, in which said permanent magnets have skew edges. The invention also relates to corresponding magnets.

State of the art

Permanent magnet generators of the known type are disadvantageously subject to the cogging effect. The cogging torque (stick-slip phenomenon) is the typical braking torque which opposes the rotation of the rotors of electric permanent magnet motors (PMM) even with no load.

It is very important to reduce this cogging torque in wind turbines because it tends to significantly limit the start up of the blades at wind speeds below the nominal wind speed (with significant loss of energy production) and also because it causes mechanical vibrations and noise.

For example, with a nominal wind speed of 10 m/s and a cogging torque of 10%, the blades begin to move with a rather high wind speed: about 4 m/s, while with a cogging torque of 1% a wind speed of 2 m/s is sufficient (the usable power varies with the cube of the wind speed).

A significant reduction of the cogging effect would result in a major reduction of the wind speed needed to make the wind turbine start.

Figure 1 schematically illustrates how the cogging effect works.

The cogging torque is caused by the interaction between the magnets mounted on the rotor **R** and the anisotropy of the stator due to the opening of the slots **A** (change in the magnetic reluctance). In fact, the highest value is found during the rotation when the magnet edge **B** and the slot **A** are facing each other, while when the magnet edge **B** is in the middle of the tooth **D** or in the middle of the slot **A** the cogging torque is equal to zero, as can be seen in the representation of the cogging torque **C** in the diagram below. The arrow **M** shows the movement direction of the rotor **R**.

A smaller variation of the magnetic reluctance during the rotation process, as well as the lack of correspondence between the edges **B** of the different magnets and the opening **A** of the different slots of the stator, will result in a lower contribution to the cogging torque.

In essence, the cogging torque is due to the variation of the magnetic energy of the field generated by the magnets with the angular position of the rotor **R**: formally, the cogging torque is equal to the partial derivative of the coenergy with respect to the angular position.

Clearly, an acceptable cogging torque value depends on the application. For example, the cogging torque is not particularly important for electric generator units equipped with PMG (permanent magnet generators), therefore values close to 20% of the rated torque are acceptable.

The cogging torque is an important parameter of PMGs when used in wind generation technology: the typical reference values may range from 3% to 5% of the rated value, a value of 1% is considered extremely low for mass production wind generators.

The wind generators available on the market today feature a rather high cogging effect.

Documents JP 2006 304407 A, US 2006/038457 A1, US 2004/070300 A1 and US 2009/224622 A1 describe permanent magnet motors or generators and methods to reduce the cogging effect.

<u>Description of the invention</u>

The object of the present invention is to construct a permanent magnet generator with a low cogging effect, and in particular a low power wind generator (microwind generator) with a lower cogging effect compared to generators of the known art.

A further object of the invention is to propose a generator in which the lower cogging effect does not result in a high power loss.

Another object of the invention is to construct a permanent magnet that helps to reduce the cogging effect with a limited loss of power.

The objects of the invention are achieved by a permanent magnet generator of the type mentioned above, where the air gap between said stacks of tooth-shaped magnetic laminations and said permanent magnets is variable, and the magnets are suited to create a variable air gap, wherein the upper side and the lower side of said magnets define an internal curved surface and an external curved surface having the same curvature direction and defining, in cross section, with respect to the height of the magnet in the direction of the rotation axis, non concentric circle arcs with different radiuses, so that the distance between the two surfaces that represents the magnet thickness is variable in said cross section, and wherein the rotor is outside the stator and the circle arc defined by the radius of the internal curved surface in said cross section, located in front of the stacks of tooth-shaped magnetic laminations, is not concentric with the circle arc defined by the radius corresponding to the cylindrical surface described by the stacks of tooth-shaped magnetic laminations.

In the specific sector, the term “variable air gap magnets” means magnets that due to their specific design (size, thickness, arc configuration, ...) are suited to create a variable air gap, that is, an air gap that is not uniform during the rotation of the rotor.

Preferably, the height coincides with the height of the magnet in the longitudinal direction.

The skew of the edges means, as is known in the state of the art, an inclination with respect to the vertical axis of the magnet that is parallel to the rotation axis of the generator.

To achieve a reduction of the cogging torque without sacrificing the output voltage too much, the skew of the magnets is chosen with an angle value (in a radial direction) which ranges between a minimum corresponding to the cogging period and half of the slot pitch of the rotor. The combination of variable air gap and skew magnets has significantly reduced the cogging effect.

The skew of the magnets makes it a little more challenging to produce the rotor, but this disadvantage is largely compensated by the significantly reduced cogging torque. The bigger the inclination angle, the smaller the cogging effect. This design enables the attainment of cogging torques less than 1% of the maximum torque.

Advantageously, the optimization of one or more parameters is added to the variable air gap and the skew magnets, including: the ratio between the number of slots and pairs of poles, the pole expansion of the magnets with respect to the pole pitch in relation to the slots/poles ratio, the value of the air gap as a function of the slot opening, as well as the stack length to reduce the cogging effect.

The adjustment must be a good compromise between the construction needs and the performance (power) of the generator.

The slots/poles (c/2p) ratio is an important parameter that enables the value of the fundamental cogging frequency to be raised as much as possible. This value corresponds to the lowest common multiple between slots and poles. A combination of 18 slots and 16 poles, and more preferably 18 slots and 22 poles, has proved particularly suitable with 144 and 198 cogging peaks per revolution.

The pole expansion of the magnets with respect to the pole pitch can be optimally adjusted to the slots/poles ratio.

The value of the air gap is a parameter that can be varied depending on the opening of the slot in order to obtain a smaller variation of the magnetic reluctance when the magnet passes underneath the slot opening.

The choice of the opening of the slot and the width of the tooth is preferably a compromise between the cogging torque, magnetic saturation, the Carter factor, leakage inductance and an acceptable geometric dimension suited to allow the automatic winding of the stator.

The variability of the air gap is achieved thanks to the fact that the top and bottom sides of the magnets define a curved internal surface and a curved external surface having the same curvature direction and defining, in cross section, non concentric circle arcs with different radiuses, such that the distance between the two surfaces, representing the magnet thickness, is variable in said cross section, and thanks to the fact that the arc of a circle determined by the radius of the curved internal surface in cross section, located in front of the stacks of tooth-shaped magnetic laminations, is not concentric with the arc of a circle determined by the radius corresponding to the cylindrical surface described by the stacks of tooth-shaped magnetic laminations themselves. In this way, a variable air gap that is effective from the stand point of the reduction of the cogging effect can be easily obtained.

Therefore, the thickness of the magnet is variable in the radial direction.

These are magnets that in cross section are midway between a "bread loaf" shape that is, "D-shaped", and a radial shape, that is, "C-shaped".

Advantageously, the ratio between the maximum air gap **Δ2** at the edges of the magnet and the minimum air gap **Δ1** at the centre of the magnet is 3 to 1.1. A very advantageous embodiment of the generator according to the invention, which enables the reduction of the cogging torque to values below 1%, is a generator having the following dimensions and size ratios:

Table 1

Parameter	***Rated size***	***Minimum value***	***Maximum value***
Slot opening	3.2 mm	3.0 mm	3.5 mm
Central air-gap	1.1 mm	0.8 mm	1.6 mm
Ratio between side air gap Δ2 and central air gap Δ1	1.5	1.1	3
Magnet internal radius	145 mm	88 mm	500 mm
Magnet central thickness	3.5 mm	3.00 mm	3.6 mm
16 p magnet width	25.3 mm	24.6 mm	26 mm
22 p magnet width	18.5 mm	17.8 mm	19.2 mm
Stator external radius	75 mm		

In a very advantageous embodiment of the invention, the magnet thickness is constant in the middle direction of the magnet, so that the cross section follows a helicoidal path where the middle direction is defined, in a top view of the magnets, as a bisecting line parallel to the skew sides of the magnets.
Advantageously the magnet, in top view, has substantially the shape of a parallelogram. In this case, the middle direction of the magnet can be defined as a segment joining the midpoints of two opposite sides and parallel to the skew sides.
Preferably, the external curved surface is a part of a cylindrical surface and is concentric with the radius of the cylindrical surface described by the stacks of magnetic laminations, while the internal curved surface of the magnet is not cylindrical.
A constant thickness in the middle direction ZZ (skew with respect to the axis of the generator) ensures a smaller cogging effect and a reduced loss of power compared to a magnet with variable thickness in its middle direction Z.
Preferably, the magnets are defined by the fact that the maximum thickness is constant along the midline ZZ which follows a helicoidal path and decreases symmetrically towards the edges of the magnet. The fact that the cross section

follows a helicoidal path also means that the individual cross sectional areas which follow one another at different heights of the magnet in the helicoidal path are essentially congruent.

In an embodiment of the invention, the internal curved surface and the external curved surface are parts of cylindrical surfaces and the magnet thickness varies in the middle direction of the magnet (Z), where the middle direction is defined as above.

In a very advantageous embodiment of the invention, the stacks of tooth-shaped magnetic laminations have shaped clefts that are opposite each other at the height of the opening of the slot extending along the full height of the tooth-shaped magnetic laminations, wherein magnetic keys, suitably shaped to close said opening of the slot, can be or are inserted in said clefts.

This closure system is more feasible and more effective with regard to the reduction of the cogging torque than the known method in which ferrite plates are placed directly on the windings inside the slots.

The shaped clefts in the stacks of magnetic laminations are not tied to generators with variable air gap and/or skew magnets. Obviously, they can also be applied to generators with straight magnets and constant air gap or generators with variable air gap and straight magnets or even generators with skew magnets and constant air gap etc.

Advantageously, the keys are made from a composite of insulating resin and iron powder. Preferably, the iron content is above 50%.

The use of the keys is possible in generators in which the rotor is located outside the stator but the inverse system, in which the rotor turns inside the stator, is also conceivable.

In an advantageous embodiment of the generator according to the invention, the length of the stack of magnetic laminations is variable. The cogging torque, like the power, varies as a function of the stack length and thus as regards the desired power there is a certain amount of cogging torque which increases as the power increases.

A stack length of 42 mm gives an output of 700 W in continuous service at 415 rpm with a rated torque of 16.1 Nm, and a maximum output power of about 1000W (415 rpm) with a torque of 23 Nm. The cogging torque is 0.20 Nm.

With a stack length of 20 mm, an output of 450 W in continuous service at

520 rpm with a rated torque of 8.26 Nm and a maximum output power of 520 W with a torque of 9.55 Nm, the cogging torque is 0.12 Nm. Longer stacks are also conceivable.

A very important aspect of the invention is illustrated by the embodiment in which the generator according to the invention is a wind generator, preferably with an output power between 400 W and 5 kW and a torque between 9 and 120 Nm.

Given powers and torques are characteristics of the generator that can be easily attained by selecting suitable construction parameters and sizes that are well known to the experts.

As stated above, wind turbines are particularly sensitive to the cogging effect at low wind speeds.

Particularly satisfactory as a material for the permanent magnets is NdFeB (neodymium iron boron) with a residual induction value equal to Br = 1.2 ÷ 1:35 T, Hc (KA/m) > 850 and BH_{max} (KJ/m^3) > 240.

Double-layer concentrated stator windings, non-overlapping with a fractional number of slots per pole and per phase q = 3/8 or q = 3/11, with a winding factor K = 0.945 or K = 0.902, have been found to be particularly suitable for a generator according to the invention.

Combining all the advantages described above and selecting the dimensions in the field as indicated, a low-power (1000 W), permanent magnet mini-wind turbine is obtained: at 415 rpm (with a corresponding torque of 23 Nm), with dimensions of the active parts not exceeding 170 mm in diameter and 42 mm in length, the cogging torque does not exceed 0.20 Nm (about 1% of the rated torque).

Another aspect of the invention also relates to a permanent magnet suited to create a variable air gap in a permanent magnet generator in which the top and the bottom sides of said magnet define a curved internal surface and a curved external surface having the same curvature direction and defining in cross section, with respect to the longitudinal height of the magnet, non-concentric circle arcs with different radiuses, so that the distance between the two surfaces that represents the thickness of the magnet varies in said cross section where said magnet has skew edges, wherein the distance between the two curved surfaces is constant along the middle direction of the magnet, so that the cross section follows a helicoidal path, or wherein the internal curved surface and the external curved surface are parts of cylindrical surfaces, and wherein the thickness of the magnet varies in the middle direction of the magnet, where the middle direction is defined, from time to time, in a top view of the magnet, as a bisecting line parallel to the skew sides of the magnet.

A magnet in which the internal curved surface and the external curved surface are parts of cylindrical surfaces and in which the thickness of the magnet varies in the middle direction of the magnet can be obtained by cutting a starting permanent magnet that seen from above is substantially rectangular and that is suited to create a variable air gap in a permanent magnet generator, more precisely having an internal cylindrical curved surface and an external cylindrical curved surface with the same curvature direction and different radiuses (115), so that the cut-out seen from above has substantially the shape of a parallelogram in which two parallel sides form a given angle with respect to the central axis of the starting magnet that defines its greatest thickness.

Brief description of the drawings

The invention is now illustrated with the aid of the attached drawings, wherein:

- Figure 1 shows a schematic representation of the cogging effect according to the state of the art;
- Figure 2 shows a cross section of a detail of the stator and the rotor of a wind generator according to the invention;
- Figure 3 shows an enlarged view of a detail of Figure 2;
- Figures 4a-4f show various views of a skew magnet with variable air gap and variable thickness along the midline according to the invention, and in particular: Figure 4a is an axonometric view of the magnet, Figure 4b is a top view of the magnet, Figures 4c and 4d are side views of the magnet, Figure 4e shows a cross section of the magnet along line A1-A1 of Figure 4c, while Figure 4f shows a cross section of the magnet along line B1-B1 of Figure 4b;
- Figures 5a and 5b illustrate the cutting of an essentially rectangular magnet to produce the skew magnet with variable air gap according to Figures 4a-4f (Figure 5a in a top view and Figure 5b in a side view), while Figures 5c and 5d show cross sections of the magnet along the lines C1-C1 (Figure 5c) and D1-D1 (Figure 5d) of Figure 5a;

- Figures 6a-6g show various views of a skew magnet with variable air gap and constant thickness along the midline according to the invention, and in particular: Figure 6a is a top view of the magnet, Figures 6b and 6e are side views of the magnet, Figure 6c shows a cross section of the magnet along line A2-A2 of Figure 6b, and Figures 6d, 6f and 6g show cross sections of the magnet along the lines C2-C2 (Figure 6d), D2-D2 (Figure 6f) and B2-B2 (Figure 6g) of Figure 6a;
- Figure 7a shows the helicoidal cut made to obtain the magnet according to Figures 6a-6g, while Figure 7b shows an enlarged view of the detail circled in Figure 7a;
- Figure 8 schematically shows the position of the skew magnet with variable thickness along the midline with respect to the starting magnet with variable air gap as seen from above;
- Figure 9a shows a cross section of a detail of a rotor according to the invention, in which the stacks of magnetic laminations have shaped clefts suited to house correspondingly shaped magnetic keys, and Figure 9b shows an enlarged view of a detail of Figure 9a with a magnetic key inserted in a cleft;
- Figures 10a and 10b show the inclination of a magnet according to the invention.

Description of the preferred embodiments

Figure 2 shows a cross section of a detail of a wind generator. It is possible to observe the external rotor **2** and the internal stator **4**. The stator **4** is provided with a plurality of stacks of tooth-shaped magnetic laminations **6** arranged radially around the axis of rotation **8** of the rotor **2**. The external radius of the stator corresponding to the external surface of the stacks of tooth-shaped magnetic laminations **6** is indicated by **Rs**.

Each stack of tooth-shaped magnetic laminations **6** has an electrical winding **10**. The stacks of tooth-shaped magnetic laminations **6** alternate with an equally large number of slots **12**.

The part of the stacks of tooth-shaped magnetic laminations **6** which is opposite the permanent magnet poles **16** is anvil-shaped ("T" section) with the sides extending each on a neighbouring slot **12**. In this way a rather narrow opening **14** of the slot is obtained. The permanent magnet poles **16** are located on the internal side of the rotor and are arranged radially around the axis of rotation **8**.

The internal radius of the rotor casing which coincides with the external radius of the magnets is indicated by **Rr**. Each individual magnet **16** has an internal side that is opposite the stator and is curved following the shape of an arc of a circle whose centre **18** is not concentric with the centre **8** of the stator **4**. The corresponding radius is indicated by **Ri**. The radius **Rr** is shorter than the radius **Ri**; furthermore **Rr** and **Ri** do not have the same centre. This eccentricity is responsible for ensuring that the air gap **20** is not constant, that is, that the air gap is variable, as shown best in Figure 3.

Figure 3 shows an enlarged view of the detail indicated by **E** in Figure 2. The air gap **20** which is located between a magnet **16** and a stack of tooth-shaped magnetic laminations **6** is not constant along the entire width **l** of the magnet **16**. Due to the eccentricity of the radius **Ri**, the central air gap **20** located between the centre of the magnet **16** and the centre of the stack of tooth-shaped magnetic laminations **6** corresponds to a distance **Δ1** which is shorter than the respective lateral distances **Δ2** (side air gaps) that are at the edges of the magnet **16**.

The cross section geometry of the magnet **16** suggests a "D" which at the centre has a thickness **b1** and on the sides a smaller thickness **b2**.

Figure 4a shows an axonometric view of a skew magnet **116** with variable air gap in which the thickness of the magnet in the middle direction is not constant. The recesses **117c** are useful to fasten the magnet in the rotor **116**.

The magnet seen from above is shown in Figure 4b. The width of the magnet is defined by the lengths **l1**. Compared to the length (height) **l2** of the magnet, the magnet is inclined by an angle **α1**.

Figures 4c and 4d show the magnet **116** in side views, seen respectively from one side **117a** or **117b** (Figure 4a).

The magnet **116** is substantially a curved parallelepiped where the curvatures follow different non-concentric radiuses **R1** and **R2**, thus determining a variable cross section thickness of the magnet **116**; in fact, the thicknesses **s1** and **s2** are different from each other.

Figure 4e shows a cross section of the magnet **116** along line **A1-A1** of Figure 4d. The thickness along line **A1-A1** is constant. Figure 4f shows the cross section of the magnet **116** along line **B1-B1** of Figure 4b. The width **l1** is constant in the axial direction of the magnet. The thicknesses of the edges **s3** and **s4** are different from the central thickness **s5**.

Figure 5a shows the production of the skew magnet with variable air gap **116** starting from a magnet with an essentially rectangular base surface, seen from above, indicated by the dotted line **115** with a starting width **l100**.

Along the width the thickness of the rectangle varies symmetrically with respect to the central line **X**, as seen for example in the side view of the magnet shown in Figure 5b, while the thickness is constant along the line **X** and along each line parallel to the line **X**.

The cutting lines **113** indicate where the "rectangle" **115** is cut in order to obtain the skew magnet **116**. It is obvious that a cut along the lines **113** results in a magnet **116** in which the thickness varies in the middle direction **Z**, and therefore also along the skew edges **119** of the magnet. This fact is highlighted in Figures 5c and 5d which show cross sections through the magnet **116** respectively following the lines **C1-C1** (Figure 5c) and **D1-D1** (Figure 5d) shown in Figure 5a. The thicknesses **s6** and **s8**, as well as the thickness **s7** and **s9**, are differentiated from each other.

Differently from the figures described above, Figure 6a shows, in a view from above, a skew magnet with variable air gap **216** in which the thickness is constant along the middle direction **ZZ** and along the skew edges. Figures 6b and 6e show side views of the magnet related to sides **217a** and **217b**. The width of the magnet **216** is indicated by **l201** (Figures 6d-6g).

The radiuses **R11** and **R12** are different and non-concentric thus creating a variable cross section thickness of the magnet. Figure 6c shows a cross section of the magnet along line **A2-A2** of Figure 6b. The length of the magnet is indicated by **l202**. Figures 6d, 6f and 6g show different cross sections of the magnet **216**, Figure 6d shows the section along line **C2-C2** of Figure 6a, Figure 6f shows the section along line **D2-D2** of Figure 6a and Figure 6g shows the section along line **B2-B2** of Figure 6a. The thicknesses of the magnet edges are all equal and are indicated by **s10**, and the central thicknesses **s11** are also all the same.

Figure 7a shows how a magnet with constant thickness in its middle direction **ZZ** can be constructed. Figure 7b shows an enlargement of the relevant part of Figure 7a. The external surface of the magnet **216** is cylindrical with a given radius **R12**. The section follows a helicoidal path **E**. The individual sections determine areas with equal size and shape.

Figure 8 illustrates in another way how the magnet, with variable thickness in its middle direction, can be constructed starting from a "bread-loaf" kind of magnet with a rectangular base seen from above, that is, starting from a magnet whose thickness varies symmetrically with respect to the axis **X**.
In the case of a magnet with variable thickness in the middle direction, the magnet **116** (solid line in bold) takes a position within the "starting rectangle" in which the axis **Z** defining the middle direction is skew with respect to the central axis **X**.
In the case of the magnet with constant thickness in the middle direction **ZZ**, the cross section (Figure 6g) describes a helicoidal path **E** (Figures 7a and 7b) in which the axis of the helix **Y** is coincident with the axis of the external cylindrical surface of the magnet with radius **R12**.
Figure 9 shows another applicable measure to lower the cogging effect in a wind generator. At the top of the stacks of tooth-shaped magnetic laminations **306** around the slot opening there are shaped clefts **307** which extend along the entire height of the stacks. Correspondingly shaped magnetic keys **309** can be inserted in these clefts **307** between two stacks of magnetic laminations (Figure 9b shows an enlarged view of a detail of Figure 9a). These keys magnetically close the openings of the slots **314** and thus significantly contribute to lowering the cogging effect.
Figures 10a and 10b describe the concept of the inclination of the magnets in a general manner (that is, independently of the choice of the other magnet parameters).
Figure 10b illustrates the inclination angle **α** of a magnet with skew edges according to the invention. The inclination angle is the angle between a skew edge (parallel to the midline **M**) and the height of the magnet.
Figure 10a shows the magnet of Figure 10b viewed from the direction **V**. The inclination of the magnet is selected with an angle (in radial direction) which varies between a minimum corresponding to the period of cogging and half of the slot pitch of the rotor. In other words, the circle arc **AC** with radius **RC** obtained by projecting the ends **P1** and **P2** of the same edge of a magnet on a radial surface (the dashed line represents the limits of the radial plane of a radial surface) is equal to a value included between the cogging pitch and half of the value of the circumference with radius **RC** divided by the number of slots of the stator. The cogging pitch with 18 slots and 22 poles corresponds to

1/11 of the slot pitch, while it corresponds to 1/8 with 18 slots and 16 poles. This inclination angle **α** of the magnets seen from an axial standpoint results in inclination values that vary with the stack length: the shorter the stack length the more the axial inclination increases given the same inclination percentage of the slot pitch.

This can be seen in Table 2 below where, by way of example, the values of the angle **α** as a function of the length **L** of the stack and of some slot pitch inclination fractions expressed as a percentage were included:

Table 2

Stator length mm	α		
	20% slot pitch	33% slot pitch	50% slot pitch
42	~ 7°	~ 12°	~ 18°
25	~ 12°	~ 20°	~ 28°

Table 3 below compares the characteristics of the two different skew magnets with variable air gap:

Table 3

Specifications		Magnet type		
	Figure 2	Figures 4a-f, Figures 5a-d		Figures 6a-g, Figures 7a, 7b
		116		**216**
Variable air gap	Ri-Rs	yes		yes
skew magnets		yes		yes
magnet external surface	Rr	R2 cylindrical		R12 cylindrical
magnet internal surface	Ri	R1 cylindrical		R11 non-cylindrical
magnet thickness along the midline		variable axis Z		constant axis ZZ
concentricity of internal (Ri) and external (Rr) surfaces of the magnet	Rr-Ri	R2-R1 non_concentric		R12-R11 non_concentric

concentricity of magnet internal surface (Ri) and external surface (Rs) of the stator teeth	Ri-Rs	Rs-R1 non_concentric		Rs-R11 non_concentric
concentricity of magnet external surface (Rr) and external surface (Rs) of the stator teeth	Rr-Rs	R2-Rs concentric		R12-Rs concentric

The invention has achieved its object of creating a permanent magnet generator with low cogging effect (<1%).

In particular, a low power wind generator was proposed that has a reduced cogging effect compared to generators of the known art.

The proposed skew magnet achieves the reduction of the cogging effect without reducing the power excessively.

During the construction phase, the permanent magnet generator and the magnet of the invention may be subjected to additional modifications or result in new embodiments not described in this document. Such modifications or embodiments must all be considered protected by this patent, provided that they fall within the scope of the claims that follow.

Where technical features mentioned in any claim are followed by reference signs, those reference sings have been included for the sole purpose of increasing the intelligibility of the claims and accordingly such reference signs do not have any limiting effect on the protection of each element identified by way of example by such reference signs.

CLAIMS

1) Permanent magnet generator with reduced cogging effect, comprising a stator (4) provided with a plurality of stacks of tooth-shaped magnetic laminations (6; 306) having respective electric windings (10), arranged radially around the rotation axis (8) of the generator, which alternate with a plurality of slots (12; 312) having a correspondent opening (14; 314), and a rotor (2) having a plurality of permanent magnets (16; 116; 216) arranged radially spaced from the rotation axis (8) of the generator, in which said permanent magnets (16; 116; 216) have skew edges, **characterized in that** the air gap (20) between said stacks of tooth-shaped magnetic laminations (6; 306) and said permanent magnets (16; 116; 216) is variable, that the magnets are variable air gap magnets in which the top and bottom sides of said magnets define an internal curved surface and an external curved surface having the same curvature direction and defining, in cross section, with respect to the height of the magnet in the direction of the rotation axis, non-concentric circle arcs with different radiuses (R1, R2; R11, R12), so that the distance between the two surfaces that represents the magnet thickness is variable in said cross section, **and in that** the rotor (2) is located outside the stator (4), **and in that** the circle arc defined by the radius (Ri; R1; R11) of the internal curved surface in cross section, located in front of the stacks of tooth-shaped magnetic laminations (6), is not concentric with the circle arc defined by the radius (Rs) corresponding to the cylindrical surface defined by the stacks of tooth-shaped magnetic laminations (6).

2) Generator according to claim 1), **characterized in that** the thickness (s10, s11) of the magnets is constant in the magnet middle direction (ZZ), so that the cross section follows a helicoidal path, wherein the middle direction is defined, in a top view of the magnets, as a bisecting line parallel to the skew sides of the magnets.

3) Generator according to claim 2), **characterized in that** said magnets (216) are defined by the fact that the maximum thickness (s11) remains constant in the middle direction (ZZ) which follows a helicoidal path and decreases symmetrically towards the magnet edges, wherein the middle direction is defined, in a top view of the magnets, as a bisecting line parallel to the skew sides of the magnets.

4) Generator according to claim 2) or 3), **characterized in that** the

external curved surface is a part of a cylindrical surface and is concentric with the radius of the cylindrical surface defined by the stacks of magnetic laminations, while the internal curved surface of the magnet is not cylindrical.

5) Generator according to claim 1), **characterized in that** the internal curved surface and the external curved surface are parts of cylindrical surfaces and in that the thickness (s1-s9) of the magnets varies in the middle direction of the magnets (Z), wherein the middle direction is defined, in a top view of the magnets, as a bisecting line parallel to the skew sides of the magnets.

6) Permanent magnet generator according to any of the preceding claims, **characterized in that** said stacks of tooth-shaped magnetic laminations (306) have shaped clefts (307) which are one in front of the other at the level of the opening of the slot (314), extending along the whole height of the stack of tooth-shaped magnetic laminations, and wherein magnetic keys (309), accordingly shaped in order to close said opening of the slot (314), are inserted in said clefts.

7) Permanent magnet generator according to claim 6), **characterized in that** the ratio between the maximum air gap (Δ2) at the magnet edges and the minimum air gap (Δ1) at the centre of the magnet is 3 to 1.1.

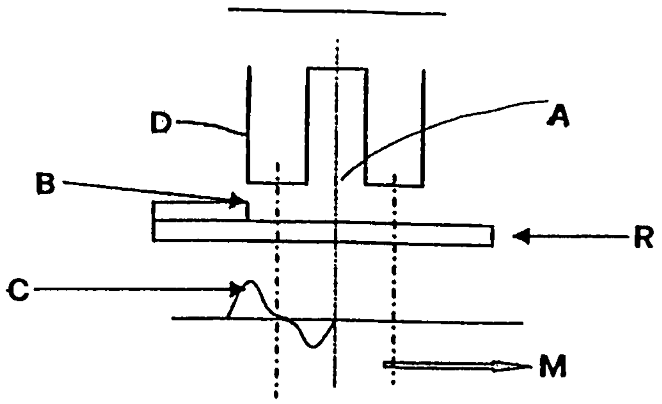
8) Generator according to any of the preceding claims, **characterized in that** said generator is a wind turbine preferably having a power between 400 W and 5kW and a torque between 9 Nm and 120 Nm.

9) Permanent magnet suited to create a variable air gap (116, 216) in a permanent magnet generator where the top and bottom sides of said magnet define an internal curved surface and an external curved surface having the same curvature direction and defining, in cross section, with respect to the longitudinal height of the magnet, non-concentric circle arcs with different radiuses (R1, R2; R11, R12), so that the distance between the two surfaces that represents the magnet thickness is variable in cross section, and where said magnet has skew edges, **characterized in that** the distance between the two curved surfaces is constant along the middle direction (ZZ) of the magnet, so that the cross section follows a helicoidal path, **or in that** the internal curved surface and the external curved surface are parts of cylindrical surfaces **and in that** the thickness (s1-s9) of the magnet changes along the middle direction of the magnet (Z), where the middle direction is defined from time to time, in a top view of the magnet, as a bisecting line parallel to the skew edges of the

magnet.

10) Magnet according to claim 9), in which the internal curved surface and the external curved surface are parts of cylindrical surfaces and the magnet thickness varies in the middle direction of the magnet, **characterized in that** said magnet can be obtained by cutting a starting permanent magnet that seen from above is substantially rectangular and suited to create a variable air gap in a permanent magnet generator, said magnet having an internal cylindrical curved surface and an external cylindrical curved surface with the same curvature direction and different radiuses (115), so that the cut-out, in a top view, is substantially in the shape of a parallelogram in which two parallel sides form a given angle with respect to the central axis of the starting magnet that defines its greatest thickness.

11) Permanent magnet generator with reduced cogging effect, comprising a stator (4) provided with a plurality of stacks of tooth-shaped magnetic laminations (6; 306) with respective electric windings (10) arranged radially around the rotation axis (8) of the generator that alternate with a plurality of slots (12; 312) having a correspondent opening (14; 314), and a rotor (2) provided with a plurality of permanent magnets (16; 116; 216) arranged radially spaced from the rotation axis (8) of the generator, **characterized in that** said stacks of tooth-shaped magnetic laminations (306) have shaped clefts (307) located in front of each other at the height of the opening of the slot (314) extending along the entire height of the stack of tooth-shaped magnetic laminations and in which correspondingly shaped magnetic keys (309) are inserted to close said opening of the slot (314).



PRIOR ART

FIG. 1

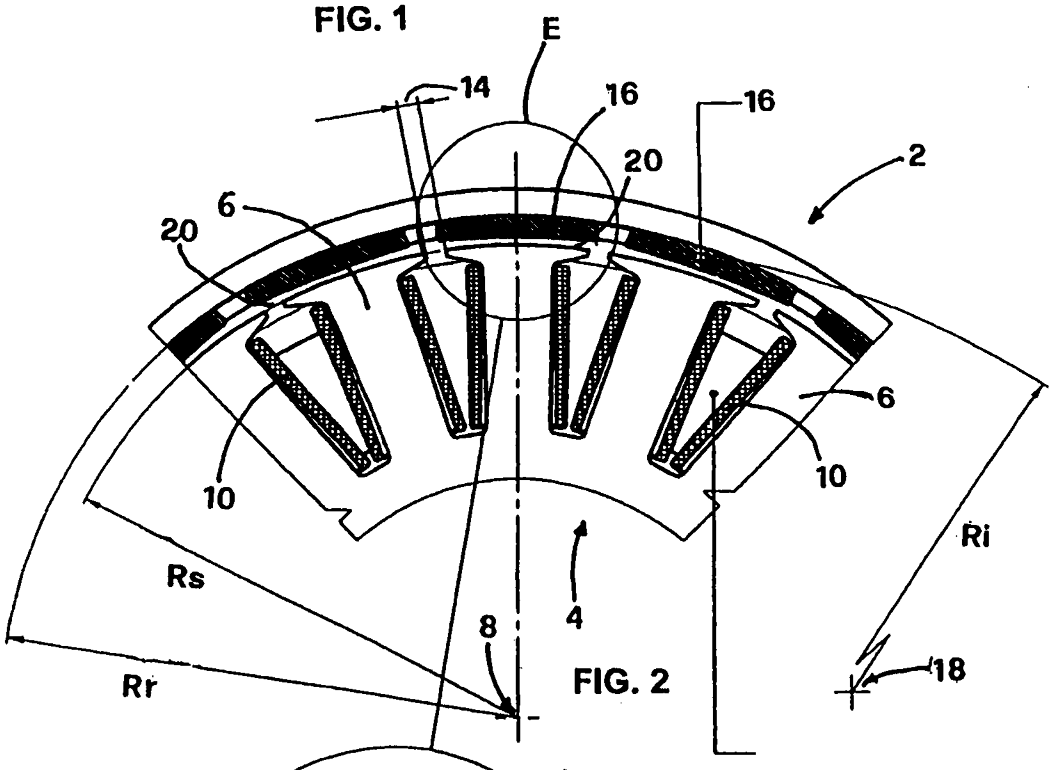


FIG. 2

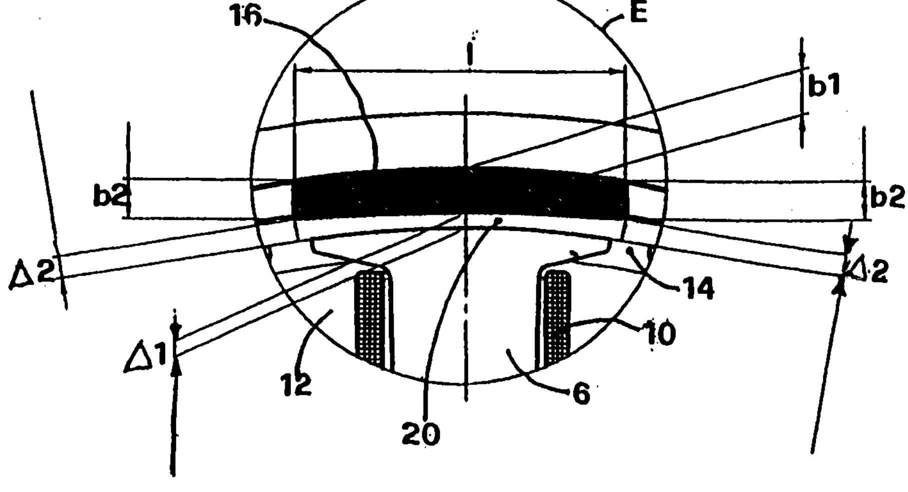


FIG. 3

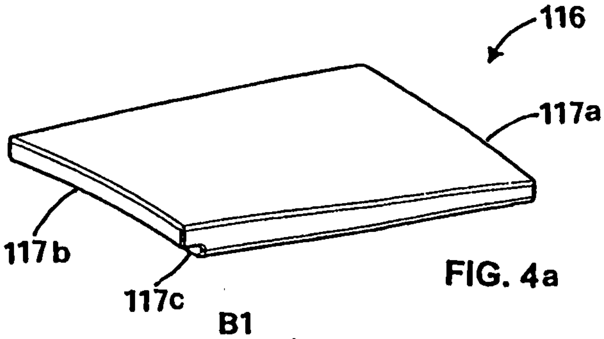


FIG. 4a

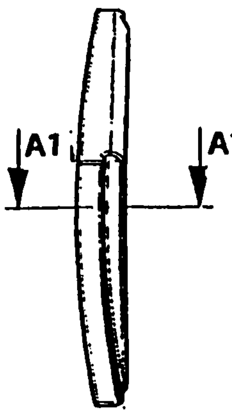


FIG. 4c

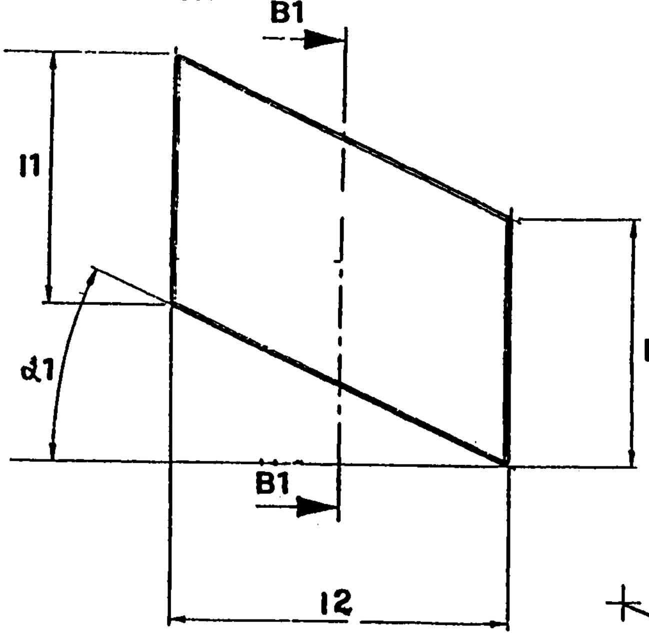


FIG. 4b

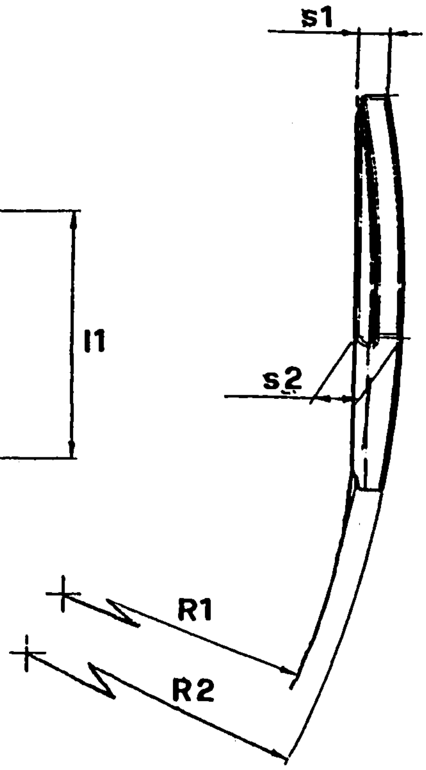


FIG. 4d

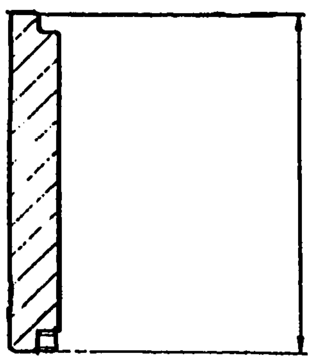


FIG. 4e

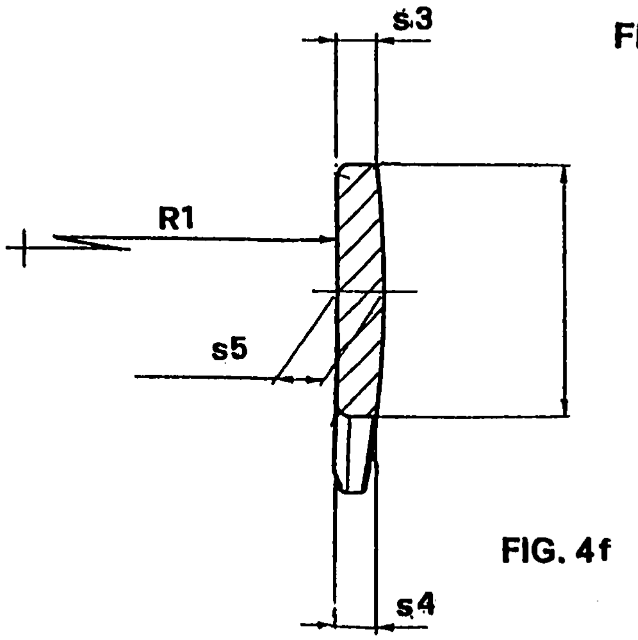


FIG. 4f

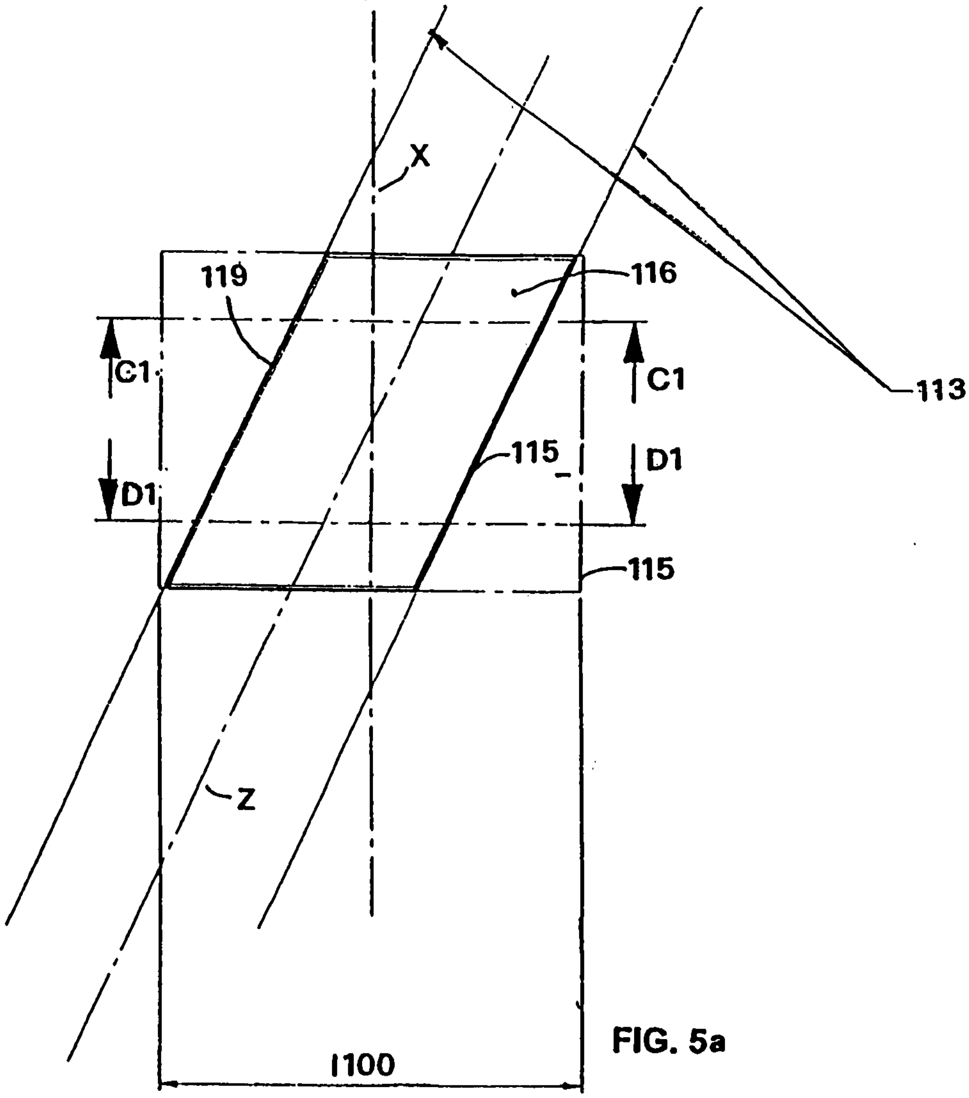


FIG. 5a

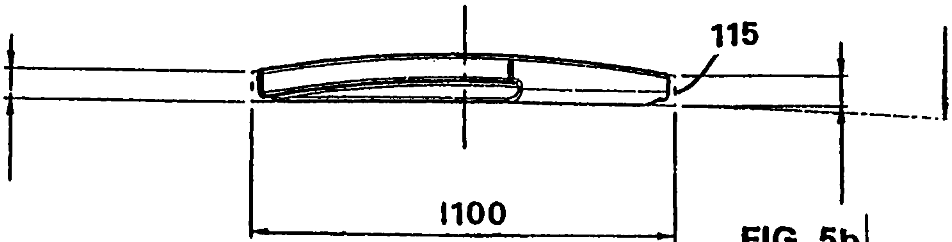


FIG. 5b

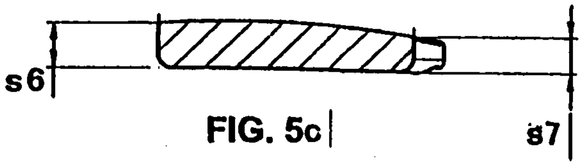


FIG. 5c

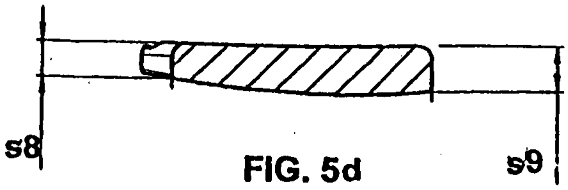


FIG. 5d

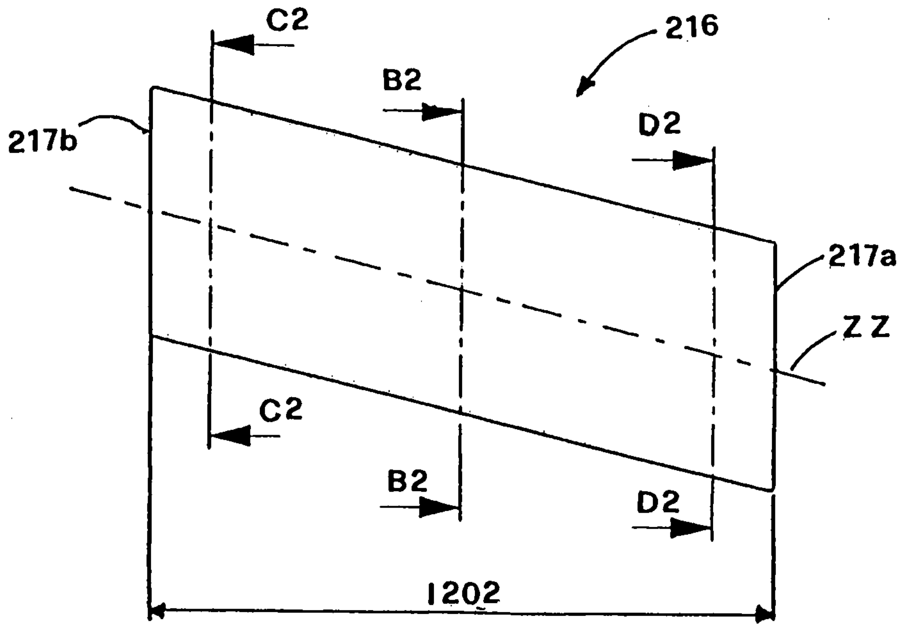


FIG. 6a

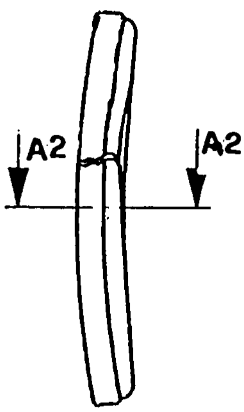


FIG. 6b

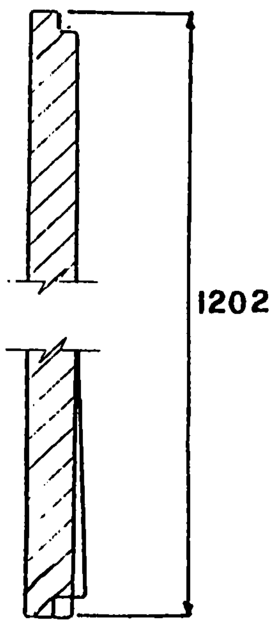


FIG. 6c

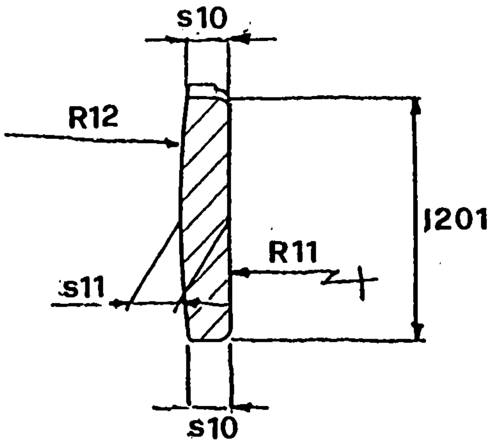


FIG. 6d

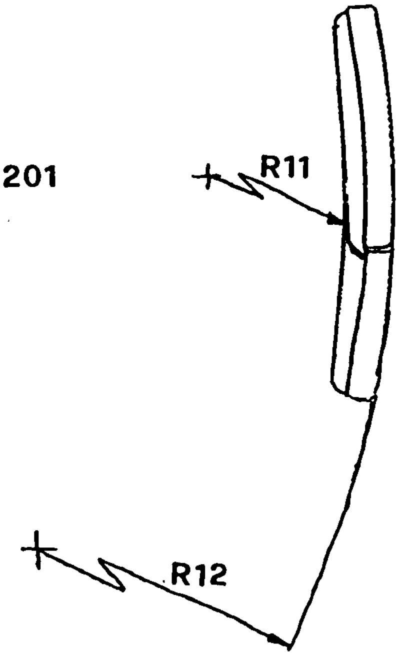


FIG. 6e

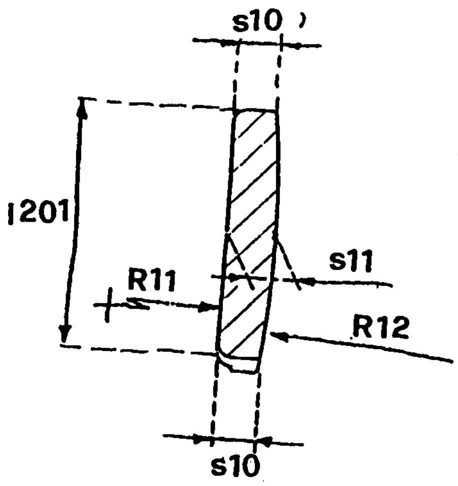


FIG. 6f

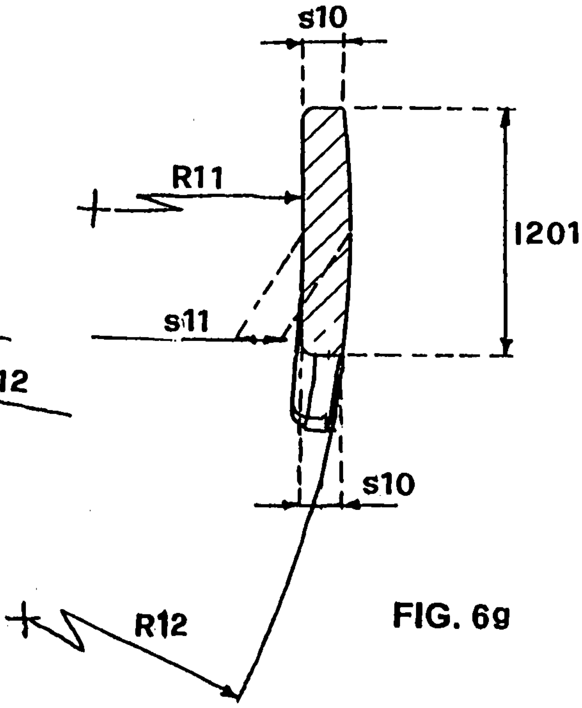


FIG. 6g

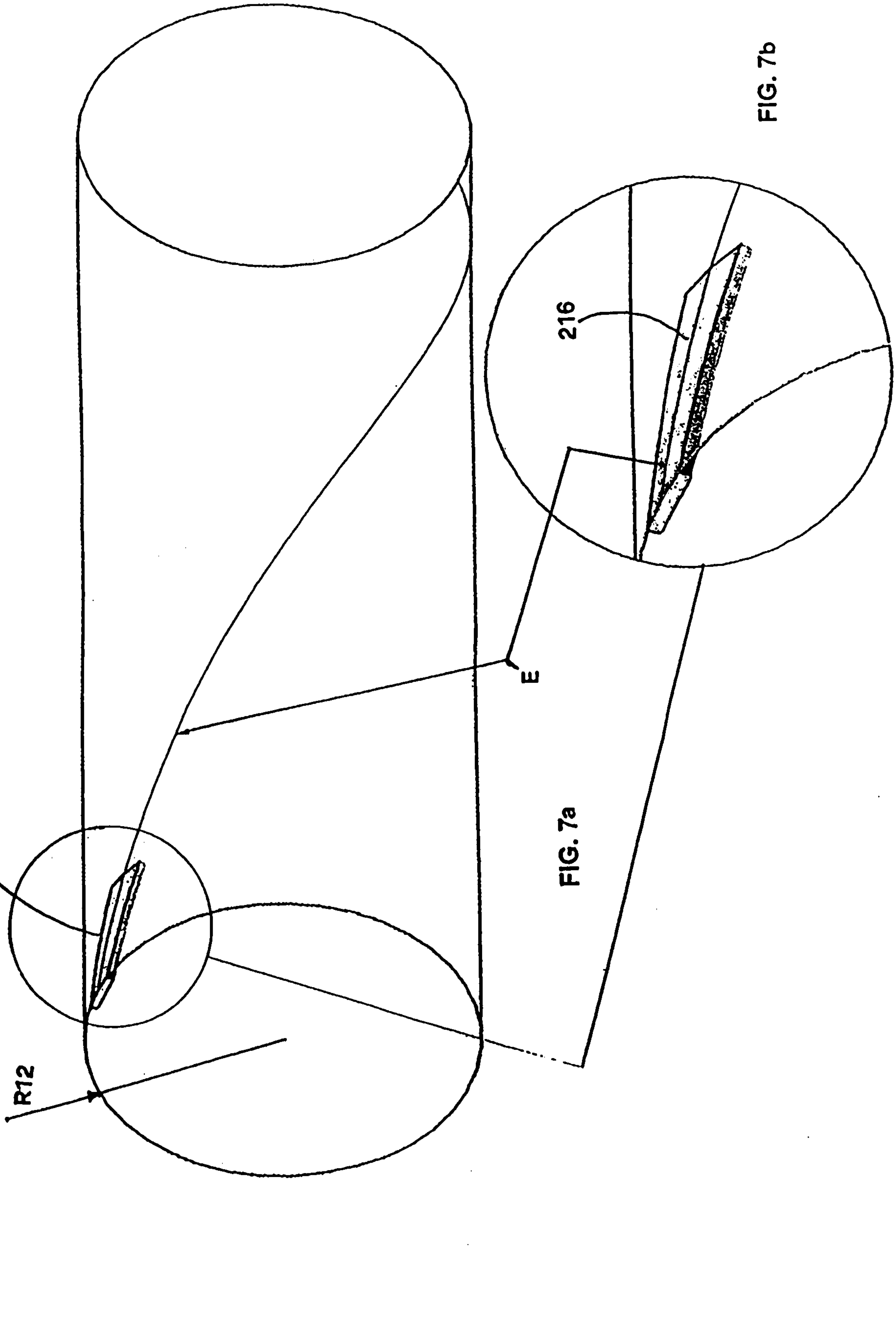


FIG. 7a

FIG. 7b

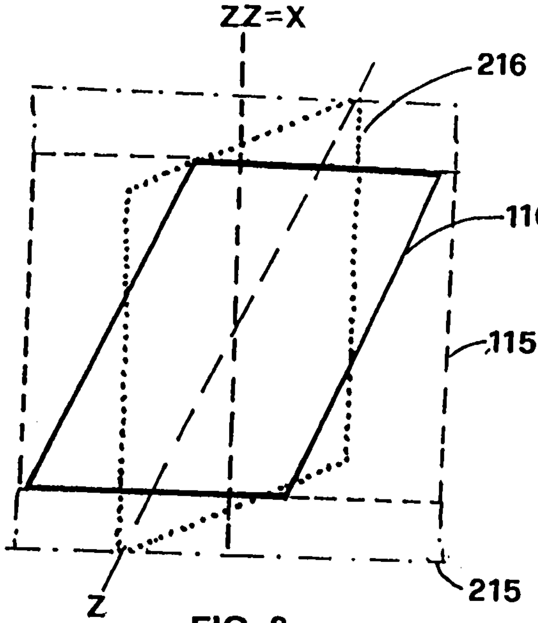


FIG. 8

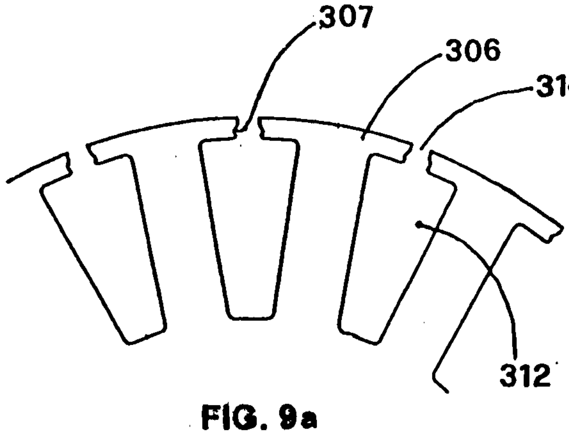


FIG. 9a

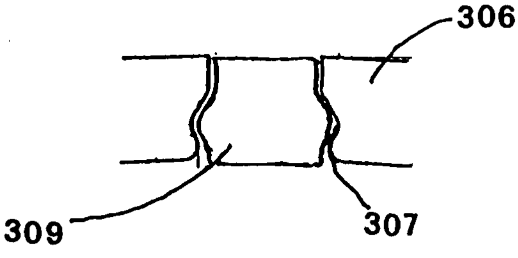


FIG. 9b

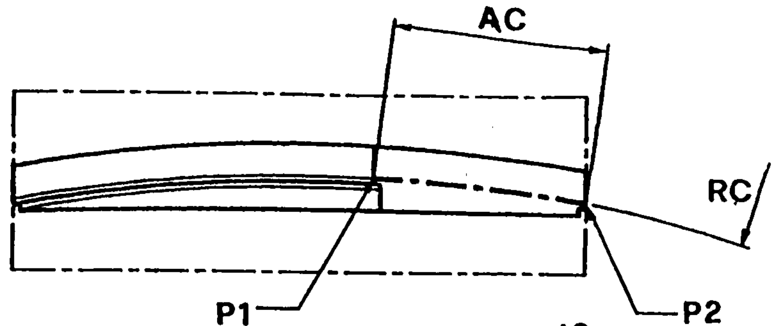


FIG. 10a

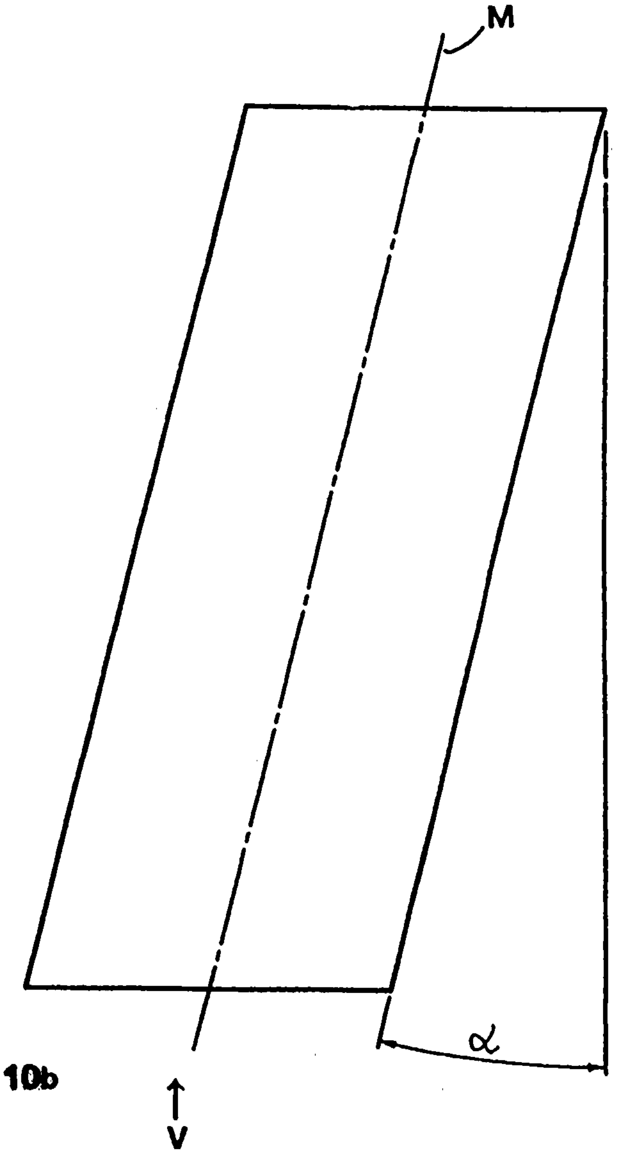


FIG. 10b