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(54) **Title**: MAGNETIC GEAR

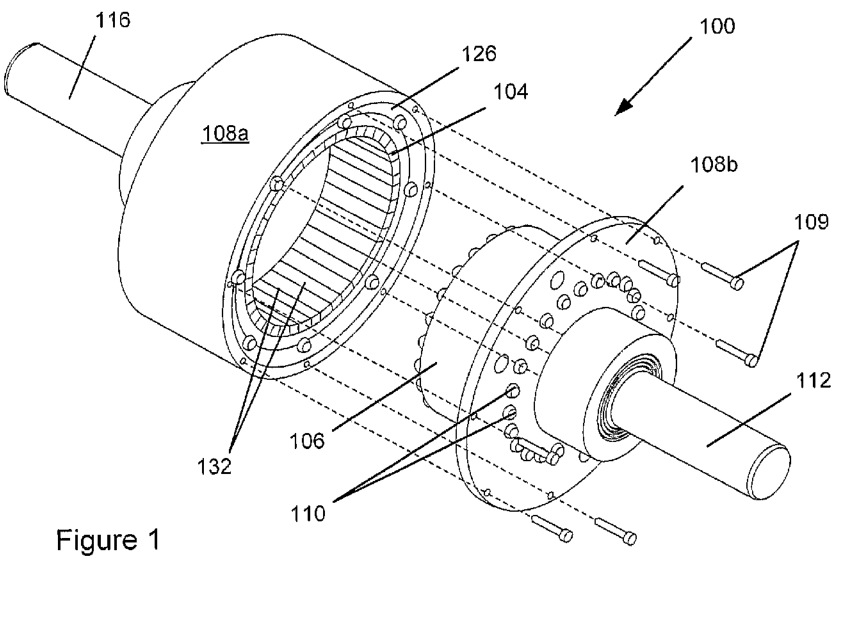

Figure 1

(57) **Abstract**: A magnetic gear (100) is provided that includes three coaxially mounted members: a high speed inner rotor (102), a low speed outer rotor (104) and a modulator (106) interposed between the inner rotor and the outer rotor. The modulator is constructed from a series of stacked ferromagnetic laminations (200) each of generally annular shape and having a number of regularly spaced and integrally formed projections (202) joined by narrow bridging portions (204), the projections aligning when the laminations are stacked together to form ridges (212) that extend across the axial length of the modulator to form a number of spaced ferromagnetic poles. The inner rotor is made from a solid ferromagnetic material such as mild steel.

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MAGNETIC GEAR

FIELD OF THE INVENTION

This invention relates to magnetic gears of the type where sets of permanent magnets are carried on inner and outer rotors and ferromagnetic poles are provided on a modulator interposed between the inner and outer rotor, the poles modulating the magnetic field acting between the sets of permanent magnets to produce a gearing ratio between the inner and outer rotors.

BACKGROUND TO THE INVENTION

Gears are used in many applications in which the rotational speed of an input source must be matched to the required rotational speed of an output load. In some cases, the output load must be rotated faster than the input source (e.g. in wind turbine applications) while in other applications the input source must rotate much faster than the output (e.g. ship propellers or industrial machinery). Mechanical gears are often employed for this purpose but suffer from the disadvantage that they are subject to wear, can overheat, are often damaged in an over-torque situation and require periodic lubrication and maintenance.

Recently, magnetic gear arrangements have been developed that overcome some of the disadvantages associated with mechanical gears. Typically, magnetic gear arrangements include axially concentric inner and outer rotors that carry sets of permanent magnets. A set of ferromagnetic pole pieces is provided on a modulator which is interposed between the inner and outer rotor. The pole pieces modulate the magnetic field acting between the sets of permanent magnets to produce a gearing between the inner and outer rotors.

In one variation, the pole pieces may be placed on one of the rotors and a set of permanent magnets carried on a stator.

Magnetic gears offer the advantage that the coupling between high speed and low speed rotors is essentially frictionless with the resultant saving in lubrication and maintenance needs. These gears cannot be damaged in over-torque situations as they merely slip once the maximum torque transmission has been overcome.

One problem associated with the manufacture of magnetic gears is that the separately formed pole pieces must be embedded in the modulator in such a way that they permit high magnetic flux transmission but are also held securely in place so as to resist the radial, as well as tangential forces, acting on them due to the magnetic coupling with the pole pieces. Existing arrangements for mounting the pole pieces include moulding them into the modulator. This is an expensive and difficult manufacturing process and the pole pieces have been known to break free from their setting.

OBJECT OF THE INVENTION

It is an object of this invention to provide a magnetic gear which, at least to some extent, alleviates some of the difficulties mentioned above.

SUMMARY OF THE INVENTION

In accordance with the invention there is provided a magnetic gear comprising three coaxially mounted members: namely, a first high speed drive member, a second low speed drive member and a third member, wherein the high speed drive member and the low speed drive member are arranged to rotate relative to the third member, and wherein two of the members include sets of permanent magnets and the other member is a modulator, the modulator being formed from a series of stacked ferromagnetic laminations of generally annular shape and having a number of regularly spaced and integrally formed projections joined by narrow bridging portions, the projections aligning when the laminations are stacked together to form ridges that extend across the axial length of the modulator to form a number of spaced ferromagnetic poles.

Further features of the invention provide for the first high speed drive member to be an inner rotor; for the second low speed drive member to be an outer rotor; and for the third member to be a modulator interposed between the inner rotor and the outer rotor.

Still further features of the invention provide for the inner rotor to be made from a solid ferromagnetic material such as mild steel.

Yet further features of the invention provide for the bridging portions to extend along the radially inner surface of the modulator and for the ridges to extend along the radially outer surface of the modulator.

Further features of the invention provide for the modulator to include non-ferromagnetic bars that are held in place in the gaps between the ridges by end plates fixed to each axial end of the modulator; for the non-ferromagnetic bars to be stainless steel rods, and for the radially outer surface of the modulator to be covered by an epoxy resin to form a smooth outer surface.

The invention extends to a modulator for modulating the magnetic field acting between two sets of permanent magnets carried on coaxially mounted drive members in a magnetic gear, the modulator comprising a series of stacked ferromagnetic laminations each of generally annular shape and having a number of regularly spaced and integrally formed projections joined by narrow bridging portions, the projections aligning when the laminations are stacked together to form ridges that extend across the axial length of the modulator to form a number of spaced ferromagnetic poles.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:-

Figure 1 is an exploded perspective view of a magnetic gear in accordance with the invention;

Figure 2 is an end view of the magnetic gear of Figure 1;

Figure 3 is a sectional elevation along line "A – A" in Figure 2;

Figure 4 is a sectional not-to-scale illustration of the main components of the magnetic gear;

Figure 5 is a perspective view of the high speed inner rotor;

Figure 6 is an end view of the inner rotor;

Figure 7 is a perspective view of the modulator of the magnetic gear;

Figure 8 is a sectional elevation through the modulator of Figure 7;

Figure 9 is a perspective view of the stack of laminations of the modulator;

Figure 10 is a side elevation of one lamination of the modulator;

Figure 11 is an expanded view of a portion "A" of the lamination shown in Figure 10;

Figure 12 is a flux density waveform (12a) and its space harmonic distribution (12b) due to only the outer magnets in the air gap between the inner rotor and the modulator, for a modulator constructed in accordance with the prior art with separate pole pieces embedded in the modulator;

Figure 13 is the same as Figure 12 but where the modulator is constructed according to the invention;

Figure 14a is a graph of the torque profile of the outer rotor of the magnetic gear for a modulator constructed in accordance with the prior art with separate pole pieces embedded in the modulator;

Figure 14b is the same as Figure 14a but where the modulator is constructed according to the invention;

Figures 15a and 15 b are the same as Figures 14a and 14b except that they show the torque profile of the inner rotor;

Figure 16 is a flux plot of the magnetic gear of the invention under load;

Figure 17 is similar to Figure 16 but with the magnetic gear in a different position; and

Figure 18a is a plot of the losses in the solid inner rotor (including magnets) for a modulator constructed in accordance with the prior art with separate pole pieces embedded in the modulator; and

Figure 18b is the same as Figure 18a but where the modulator is constructed according to the invention.

DETAILED DESCRIPTION WITH REFERENCE TO THE DRAWINGS

Figures 1 to 3 show a magnetic gear (100) in accordance with the invention. As shown most clearly in the sectional view of Figure 3, the gear includes a first high speed drive member, in this embodiment an inner rotor (102), a second low speed drive member, in this embodiment the outer rotor (104) and a third member, namely a modulator (106) interposed between the inner rotor and the outer rotor. The inner rotor, outer rotor and modulator are coaxially mounted within a gear housing which is formed of two parts (108a, 108b) that are mounted together with bolts (109). The inner rotor and outer rotor are mounted for rotation in the housing by means of a first set of bearings (114) and a second set of bearings (118) respectively, while the modulator is fixed to the housing by means of bolts (110).

The inner rotor (102) is integrally formed with an elongate shaft (112) that extends from one end of the housing, and the outer rotor (104) also includes an elongate shaft (116) that extends from the other end of the housing. The shaft of the inner rotor may be driven by a high speed power source like an electric motor with the shaft of the outer rotor coupled to a low speed load source. Alternatively, the shaft of the outer rotor may be driven by a low speed power source like a wind turbine and the shaft of the inner rotor coupled to a high speed load like an electric generator. The magnetic gear can, in other words, be driven in either direction.

The shaft of the outer rotor is joined to an integrally formed radially widened plate (124) onto which a cylindrical yoke (126) is mounted using bolts (128). The yoke (126) can be seen in Figures 1 and 3, and is also illustrated schematically and not to scale in Figure 4. The cylindrical yoke has a smooth radially outer surface (130) and a radially inner surface on which a set of permanent magnets (132) is arranged. The magnets (132) are arranged with their north and south poles at their radially inner and outer ends and with alternating polarity so that each magnet is oppositely oriented from the magnet on either side of it. Typically, the magnets are set in place by a moulding process, such as moulding them in epoxy resin that substantially fills the gaps (133) between the magnets (132) to form a smooth inner surface (134) for the cylindrical support. The outer rotor yoke (126) is made of silicon laminated steel so as to minimize iron losses therein.

Figures 5 and 6 show the inner rotor (102) in more detail. The inner rotor (102) includes a shaft (112) extending from a radially wider yoke (120). A set of permanent magnets (122) are mounted in a spaced configuration on the rotor yoke (120). In this embodiment, four permanent magnets (122) are spaced apart around the rotor yoke. The magnets (122) are arranged with their north and south poles at their radially inner and outer ends and with alternating polarity so that each magnet is oppositely oriented from the magnet on either side of it, as illustrated in Figure 6. An even number of permanent magnets is therefore required. In this embodiment, the inner rotor yoke (120) is made from solid ferromagnetic material, such as mild steel. As with the outer rotor, the magnets can be set in place by an epoxy resin that substantially fills the gaps (123) between the magnets (122) to form a smooth outer surface for the rotor yoke.

The ratio of the number of permanent magnets on the inner rotor and the number of permanent magnets on the outer rotor determine the gearing between the inner rotor and the outer rotor. In this embodiment, the high speed inner rotor includes four permanent magnets (two pole pairs) and the low speed outer rotor includes forty-two permanent magnets (twenty-one pole pairs). There are therefore a total of twenty-three pole pieces. The gearing between the outer and inner rotor is therefore 10.5:1. Of course, other desired gearing ratios can be used.

It is also possible to make the inner rotor the low speed rotor and the outer rotor the high speed rotor by putting fewer magnets on the outer rotor than on the inner rotor. However, it is preferable to have the high speed rotor be the one of smaller radial diameter to limit mechanical stresses, and it is easier to place the greater number of permanent magnets on the rotor with the greatest circumference. Therefore, the illustrated embodiment, where the inner rotor is the high speed rotor, is preferred.

The modulator (106) and components thereof are illustrated in more detail in Figures 7 to 11. As explained previously with reference to Figure 2, the modulator (106) is bolted to the housing (108b) by means of bolts (110) that extend through holes in the housing to hold the modulator in a fixed position relative to the housing. The purpose of the modulator is to modulate the magnetic field acting between the permanent magnets of the inner and outer rotors (122 and 132, respectively). It does this by having a number of poles of ferromagnetic material spaced about its circumference. As the inner and outer rotors rotate relative to the modulator, the poles modulate the magnetic field between the inner and outer rotor to provide flux harmonics corresponding to the magnet pole pairs on each side of the air-gap, thereby producing the gearing between the inner and outer rotor. The selection of the number of poles required for the modulator is based on the number of magnets of the inner and outer rotor. The theory behind the selection is known in the art and will not be repeated herein.

Importantly, the modulator of this invention is formed from a series of stacked ferromagnetic laminations (200) of generally annular shape. The stacked laminations are shown most clearly in Figure 9 and a single lamination is shown in Figure 10. Each lamination is made from a sheet of M19 electrical steel, also referred to as silicon steel. As shown most clearly in Figure 11, the laminations have a number of regularly spaced and integrally formed projections (202) joined by narrow bridging portions (204). In this embodiment, the projections have radially extending sides (206) with arcuate outer edges (208) that have the same centre of radius as the centre of the modulator.

When stacked together as shown in Figure 9, the projections (202) overlap to form ridges (212) that extend across the axial length of the modulator. These ridges form the poles of the modulator.

The bolts (110) are non-ferromagnetic bars that are held in place in the gaps (214) between the ridges (212) by means of end plates (216) that are mounted at each axial end of the modulator, as shown in Figure 7. A suitable non-ferromagnetic material for making the bolts is stainless steel. The outer surface (218) of the modulator is covered in an epoxy resin so as to form a smooth outer surface which helps diminish turbulence in the gap between modulator and outer rotor. The sides of the projections (206) – shown in Figure 11 – may also include recesses (219) to assist with the bonding of the epoxy resin to the stacked laminations.

Having poles formed by the integral ridges (212) of the laminations greatly strengthens the modulator as compared to existing modulators in which separately manufactured pole pieces must be embedded into a support structure. The pole pieces on modulators are subjected to substantial radial as well as tangential forces and it should be appreciated that an even very slight twist, in mechanical degrees, of a pole piece may result in a significant skew in terms of electrical degrees. The modulator of the current invention provides greater torsional stiffness than existing modulators in which separately manufactured pole pieces are used.

The performance of the modulator of the invention will now be illustrated with reference to the simulation plots shown in Figures 12 to 18, in which comparisons are made between the modulator of the invention and a modulator constructed in accordance with the prior art with separate pole pieces. The air gaps referred to are illustrated most clearly in Figure 4.

Figure 12a is a simulation graph of flux density in the air-gap (300) between the inner rotor (102) and the modulator (106) due to only the outer permanent magnets (132) (assuming the inner permanent magnets (122) have been removed) and assuming that the pole pieces do not include the ferromagnetic bridges (204) – i.e. that the modulator is constructed in accordance with the prior art with separate pole pieces embedded in the modulator. The vertical axis of Figure 12a is the flux density in Tesla, and the horizontal axis is the displacement around the air gap.

Figure 12b is the Fourier transform of Figure 12a, illustrating the space harmonic distribution of the flux density waveform in Figure 12a. The primary harmonic corresponds with the number of the high speed rotor pole pairs and the secondary harmonic with the number of low speed rotor pole pairs. In this embodiment, the high speed rotor has two pole pairs and the low speed rotor has 21 pole pairs.

Figures 13a and 13b show the same as Figures 12a and 12b, except that the modulator now includes laminations according to the invention with the pole pieces linked by the narrow bridging portions (204). As can be seen by comparing Figures 12 and 13, the bridges (204) of the modulator of the invention effectively suppress higher order harmonic components of the flux density waveform at a cost of reducing the amplitude of the working harmonic. The suppression of the higher order harmonics is due to some of the high-frequency flux harmonics being shunted sideways through the bridging portions, also accounting for the loss of flux amplitude. A significant result of the present invention is that as long as the bridges are formed on the high speed side (i.e. inner side), the fundamental harmonic remains strong. Once the modulated magnetic field shown in Figure 13b is superimposed with the inner rotor magnets fields, the magnetic coupling between the inner and outer rotors of the invention is only marginally less than the magnetic coupling with separate pole pieces.

Figures 14 and 15 illustrate the influence of the modulator of the invention on the transmission torque of the magnetic gear.

Figure 14a shows the outer rotor rated torque profile for the magnetic gear with the modulator constructed with separate pole pieces according to the prior art, while Figure 14b shows the same as Figure 14a except that the modulator includes laminations according to the invention with the pole pieces linked by the narrow bridging portions. The vertical axes of Figures 14a and 14b are the torque of the outer rotor in Newton-metres, while the horizontal axes shows time in milliseconds. Figure 15a and 15b are similar to Figures 14a and 14b, except that they show the rated torque profile for the inner rotor of the magnetic gear. As can be seen, the lower values in the torque ripple for rated torque for both the inner and outer rotors are somewhat lower as a result of using the laminated modulator of the invention, although the average torque suffers only a small reduction.

Another important feature of the present invention is that the inner rotor is solid. It is much cheaper to manufacture a solid inner rotor than a laminated one. Figure 16 shows a magnetic flux distribution plot of the magnetic gear of the invention under rated load, and Figure 17 shows the same as Figure 16 but with the magnetic gear at another operating position. As can be seen, the flux plots are similar and there is relatively little flux variation in the solid yoke of the inner rotor. The bridging portions in the modulator suppress higher order harmonics from reaching the inner rotor, making it even more viable to use a solid inner rotor without resulting in significant eddy losses.

Figure 18a shows a graph of the losses in the solid inner rotor (including magnets) in Watts over time at a rotation speed of 1000 rev/min, for a magnetic gear with the modulator constructed in accordance with the prior art with separate pole pieces. Figure 18b is the same as Figure 18a, except the laminated modulator of the invention is used. As can be seen, the losses in the inner rotor when using the modulator of the invention is almost half of the losses when using a prior art modulator. The suppression of higher order harmonics by the modulator of the invention makes it possible, for the same losses in the solid inner rotor, to operate the magnetic gear of the invention faster than a magnetic gear that has separate pole pieces in the modulator. It should be noted, however, that a solid inner rotor may not be well suited for very high speed operation as the core losses will increase significantly at higher frequency, lowering the efficiency markedly.

The invention therefore provides a magnetic gear of more robust construction having poles integrally formed in the modulator and a solid inner rotor. Although the integrally formed poles result in a small reduction in maximum torque and flux density, the magnetic gear of the invention offers significant advantages in that the modulator can be manufactured more cheaply and made more robust, and a solid inner rotor can be used with its attendant advantages.

It will be appreciated that the invention is not limited to the described embodiment and that variations may be made without departing from the scope of the invention. For example, the modulator could be placed on one of the rotors in which case a fixed stator would carry a set of permanent magnets. The magnetic gear could be manufactured from any suitable material and made to any appropriate size or specification. Any appropriate gearing ratio could be used and a laminated inner rotor instead of a solid inner rotor could be used. Many other design changes could be made to the manner of assembly and operation of the magnetic gear.

CLAIMS:

1. A magnetic gear (100) comprising three coaxially mounted members: namely, a first high speed drive member, a second low speed drive member and a third member, wherein the high speed drive member and the low speed drive member are arranged to rotate relative to the third member, and wherein two of the members include sets of permanent magnets (122, 132) and the other member is a modulator (106), characterized in that the modulator is formed from a series of stacked ferromagnetic laminations (200) each of generally annular shape and having a number of regularly spaced and integrally formed projections (202) joined by narrow bridging portions (204), the projections aligning when the laminations are stacked together to form ridges (212) that extend across the axial length of the modulator to form a number of spaced ferromagnetic poles.

2. A magnetic gear as claimed in claim 1 in which the first high speed drive member is an inner rotor (102), the second low speed drive member is an outer rotor (104) and the third member is a modulator (106) interposed between the inner rotor and the outer rotor.

3. A magnetic gear as claimed in claim 2 in which the inner rotor is made from a solid ferromagnetic material.

4. A magnetic gear as claimed in claim 3 in which the inner rotor is made from mild steel.

5. A magnetic gear as claimed in any one of claims 2 to 4 in which the bridging portions (204) extend along a radially inner surface of the modulator and the ridges extend along a radially outer surface of the modulator.

6. A magnetic gear as claimed in any one of the preceding claims in which the modulator includes non-ferromagnetic bars (110) that are held in place in the gaps (214) between the ridges by means of end plates (216) that are fixed to each axial end of the modulator.

7. A magnetic gear as claimed in claim 6 in which the non-ferromagnetic bars are stainless steel rods.

8. A magnetic gear as claimed in any one of claims 5 to 7 in which the radially outer surface of the modulator is covered by an epoxy resin to form a smooth outer surface.

9. A modulator for modulating the magnetic field acting between two sets of permanent magnets carried on coaxially mounted drive members in a magnetic gear, characterized in that the modulator comprises a series of stacked ferromagnetic laminations (200) each of generally annular shape and having a number of regularly spaced and integrally formed projections (202) joined by narrow bridging portions (204), the projections aligning when the laminations are stacked together to form ridges (212) that extend across the axial length of the modulator to form a number of spaced ferromagnetic poles.

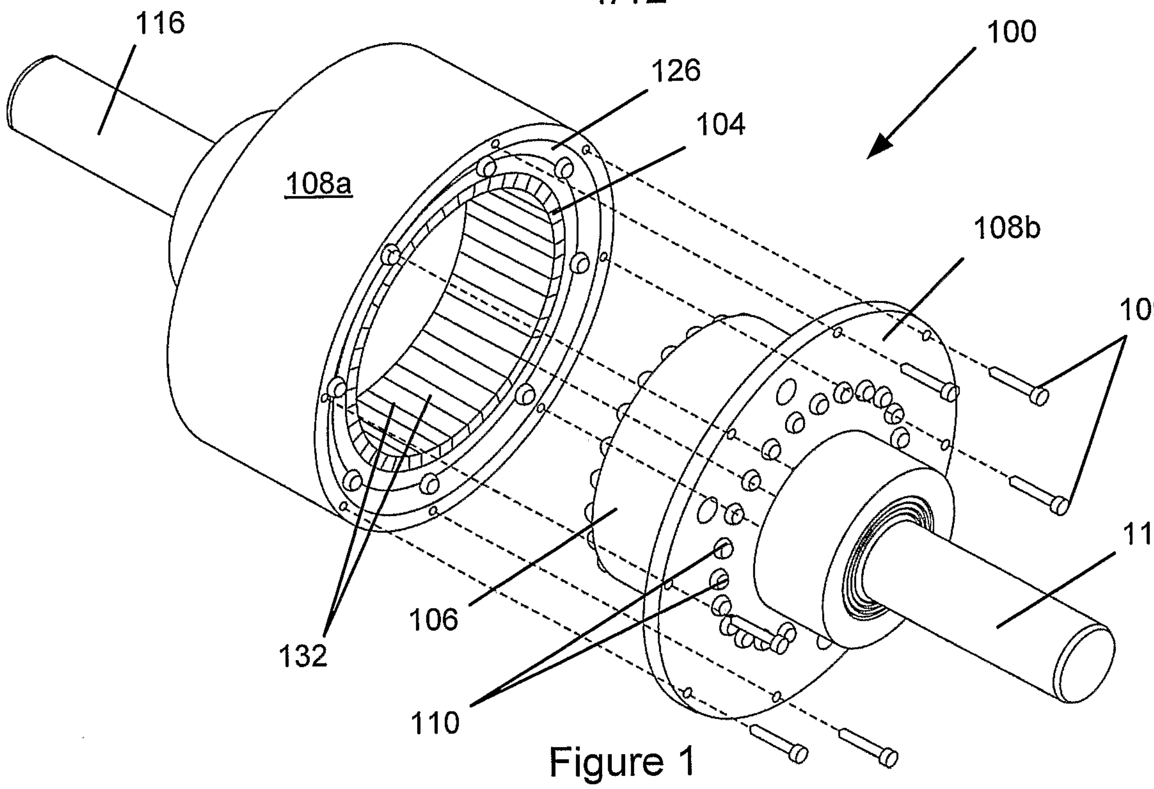

Figure 1

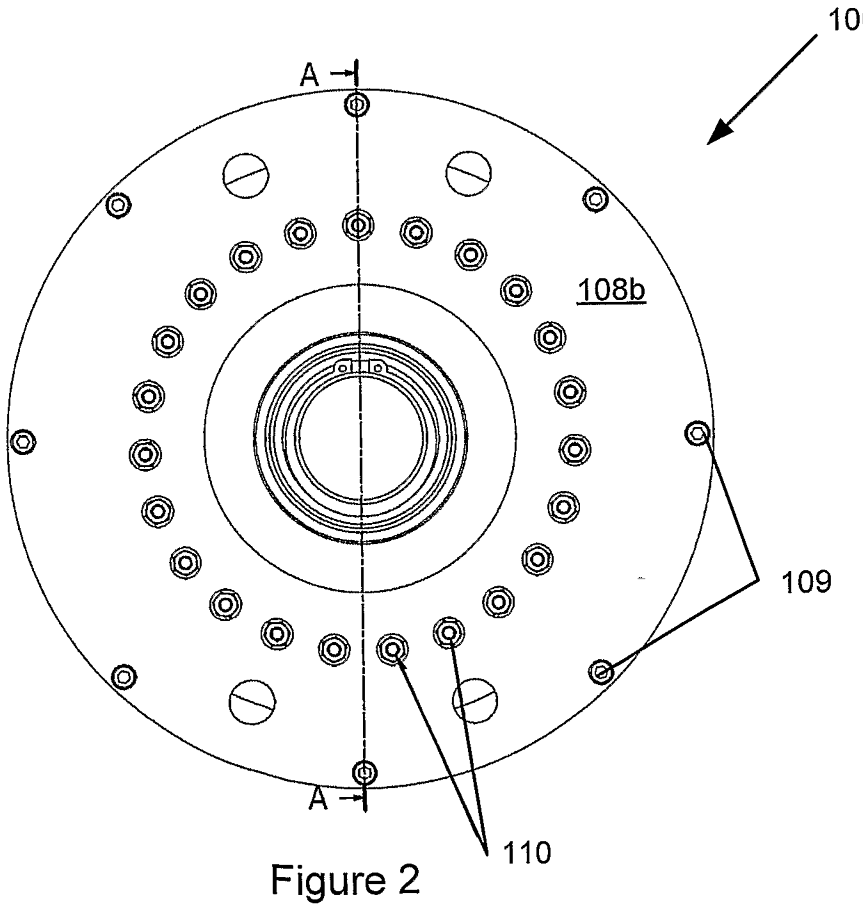

Figure 2

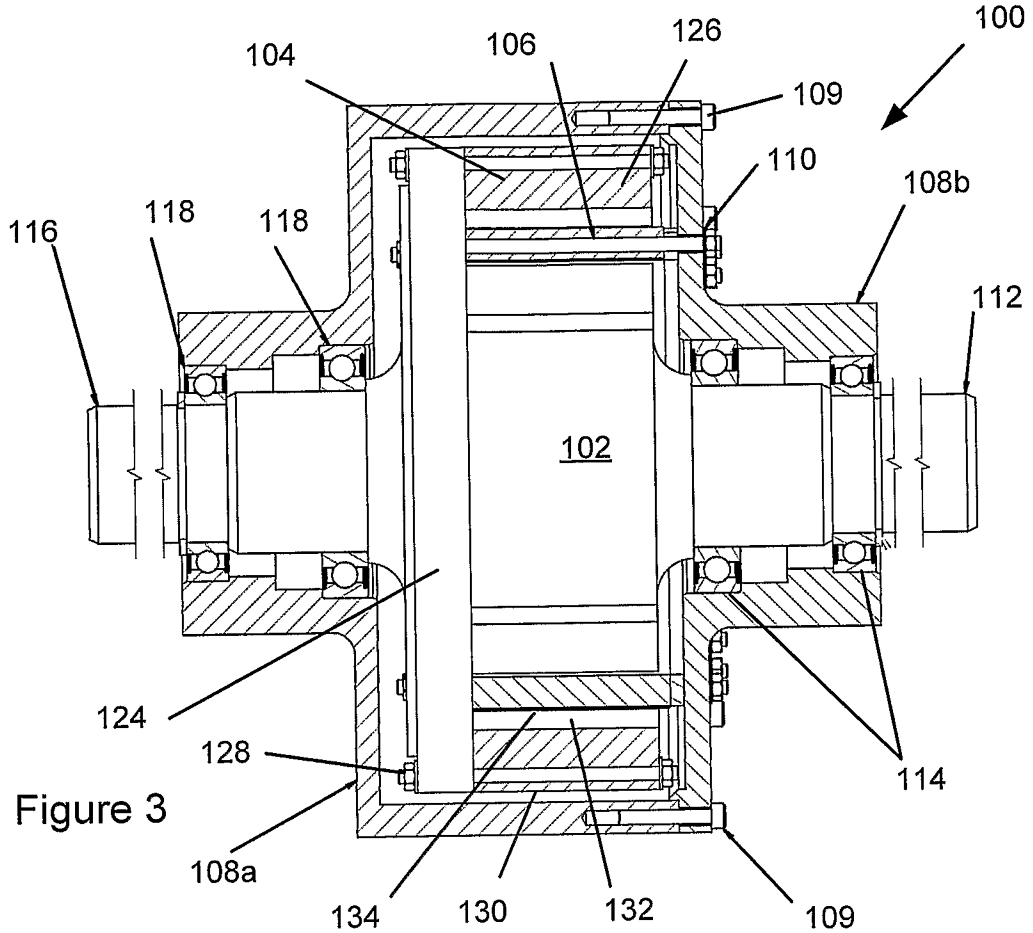

Figure 3

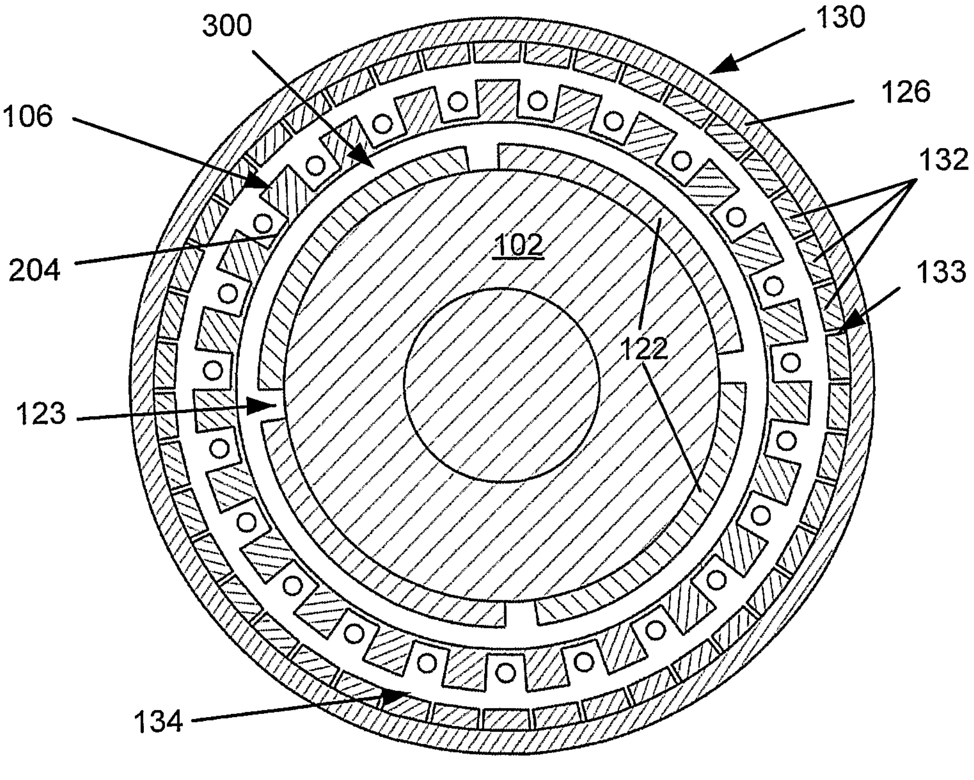

Figure 4

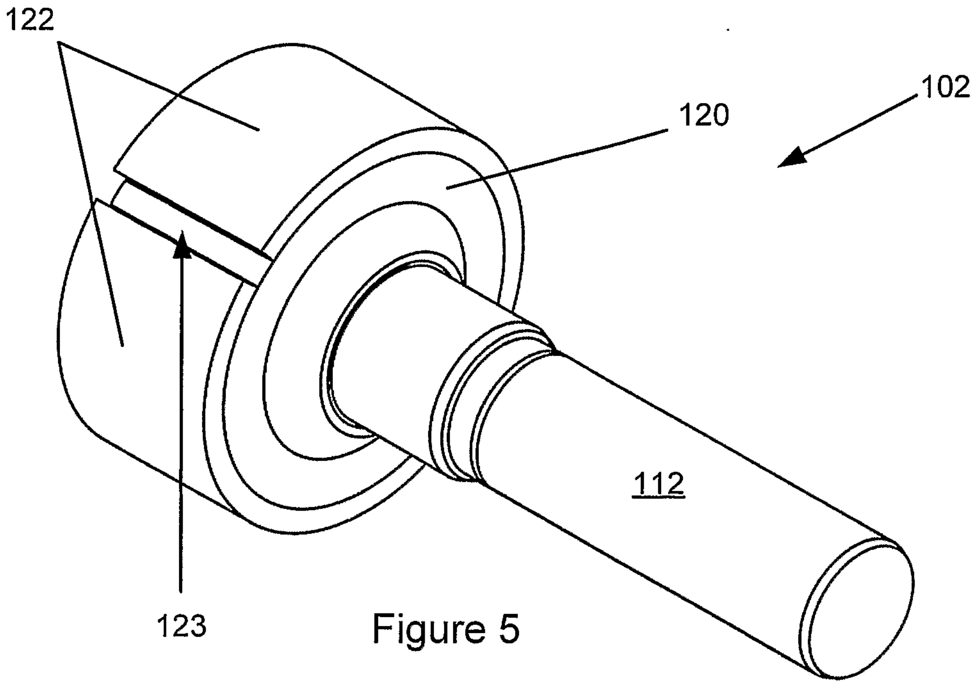

Figure 5

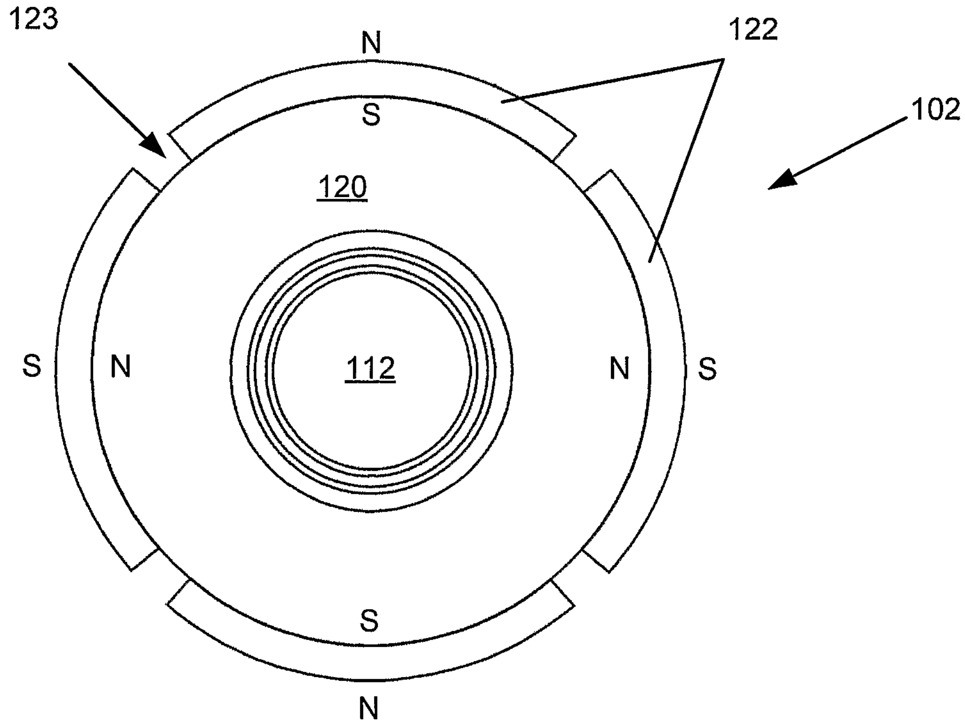

Figure 6

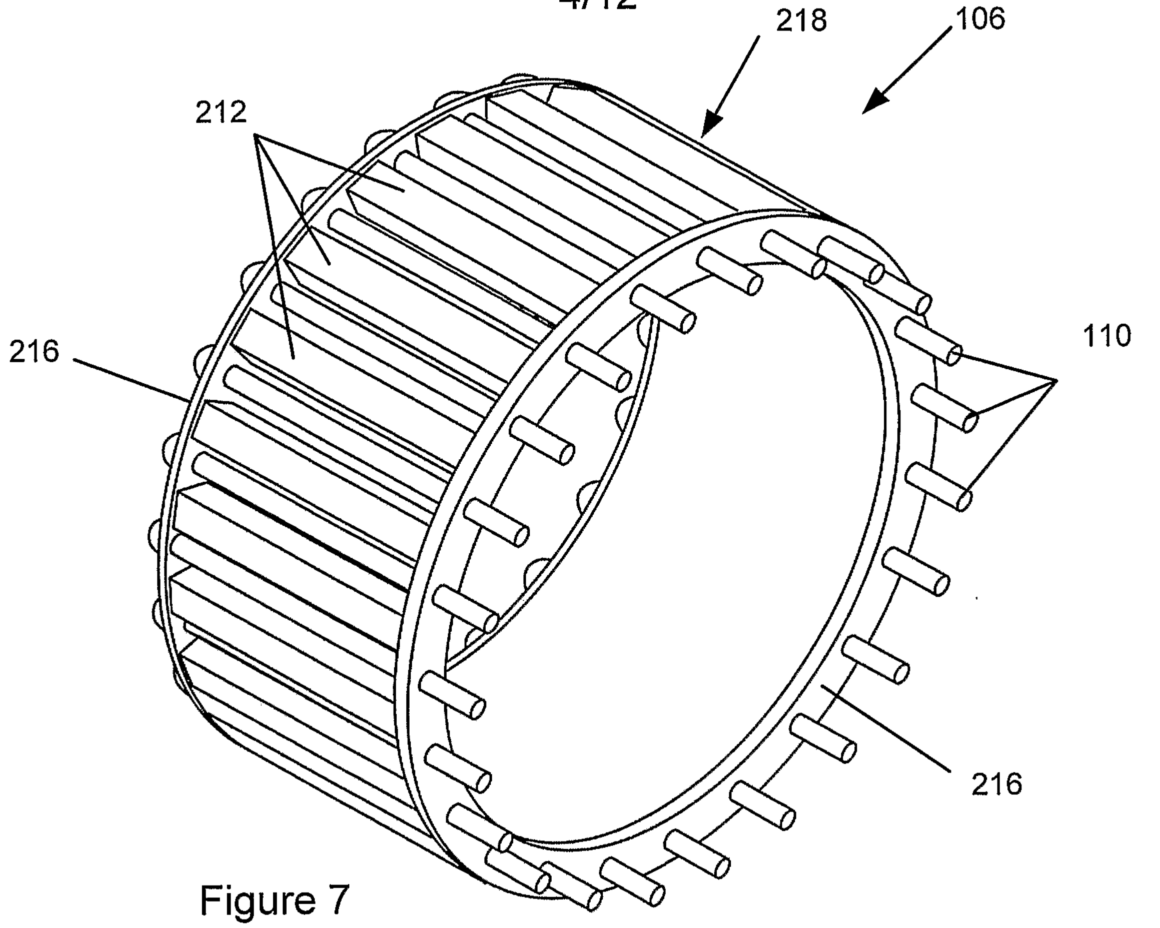

Figure 7

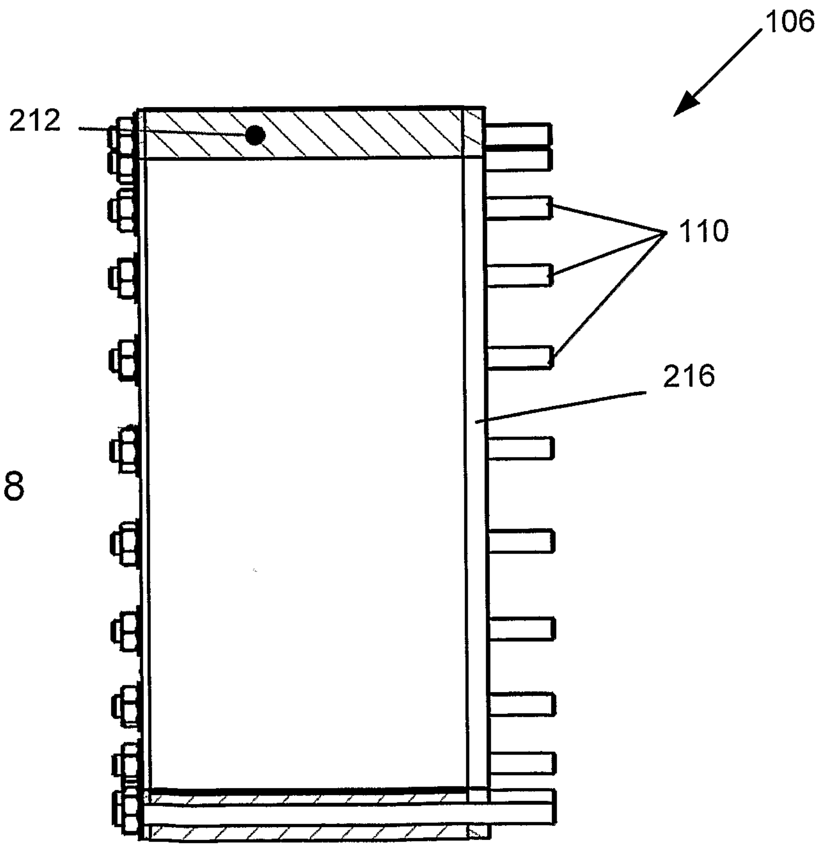

Figure 8

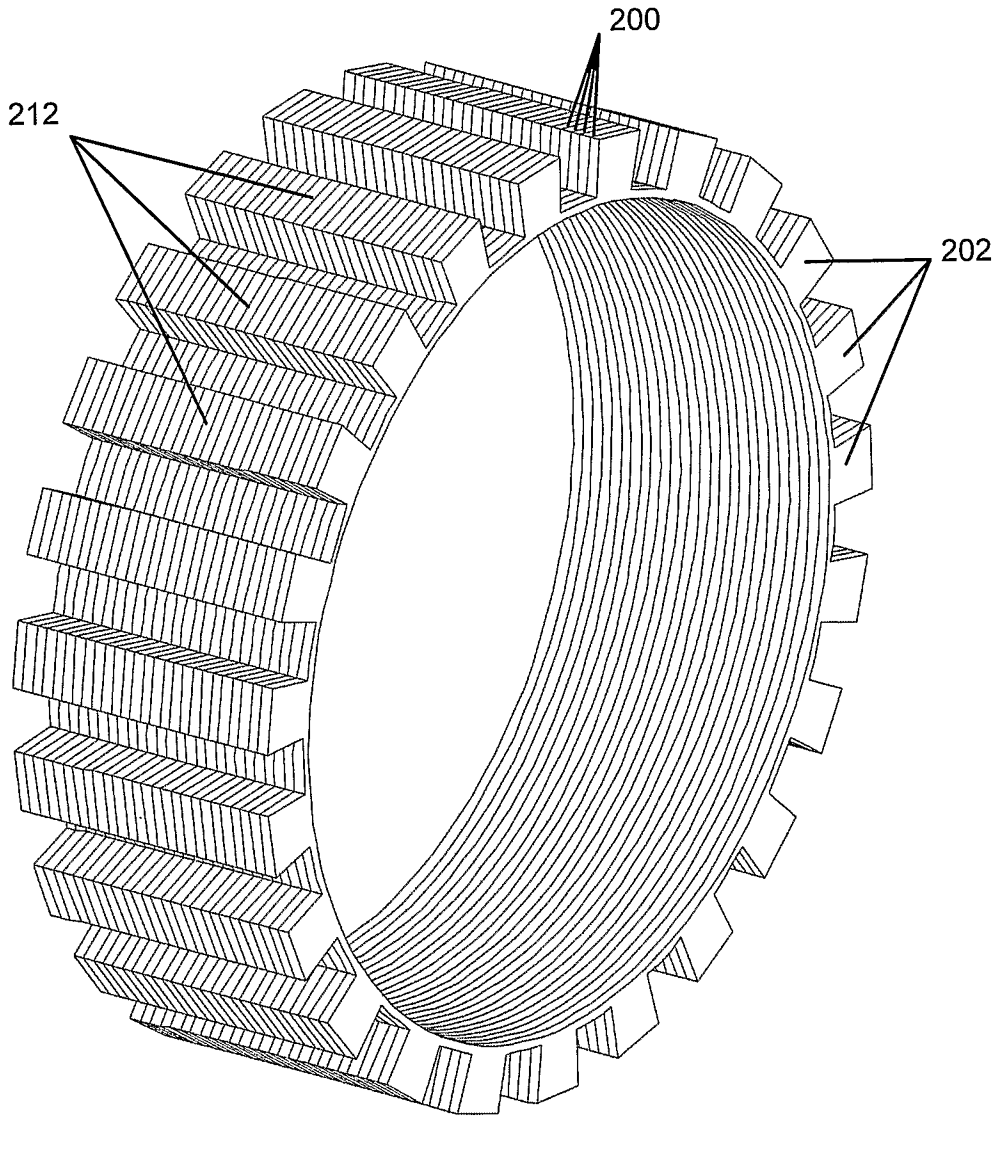

Figure 9

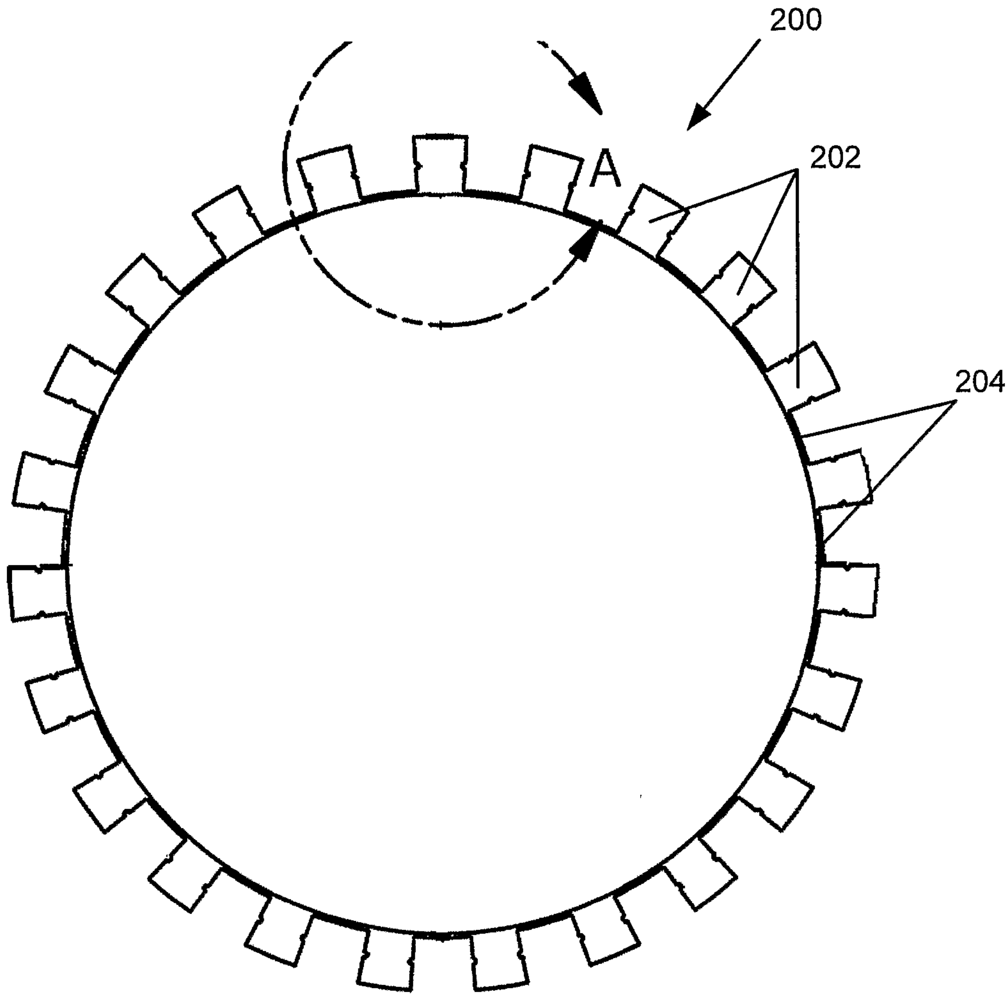

Figure 10

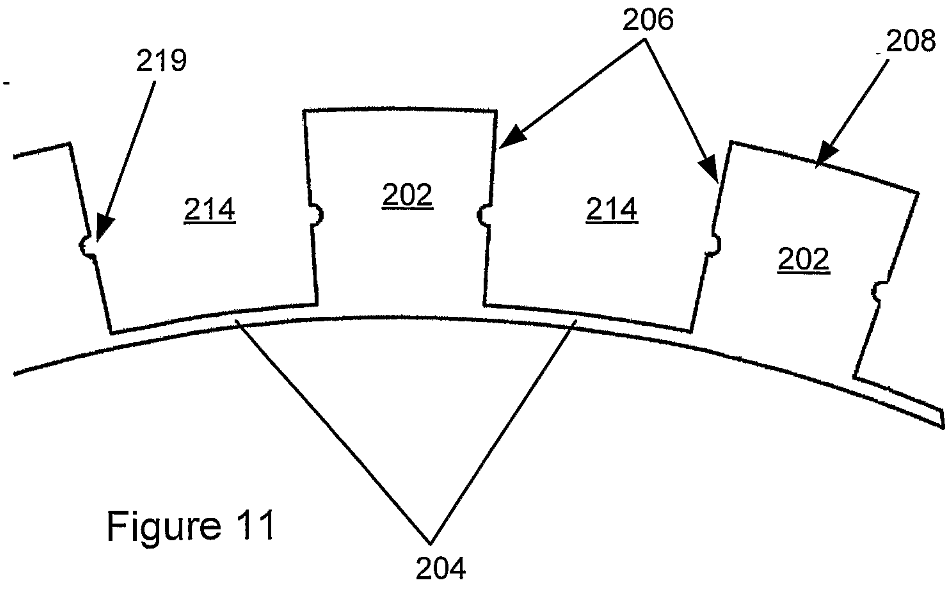

Figure 11

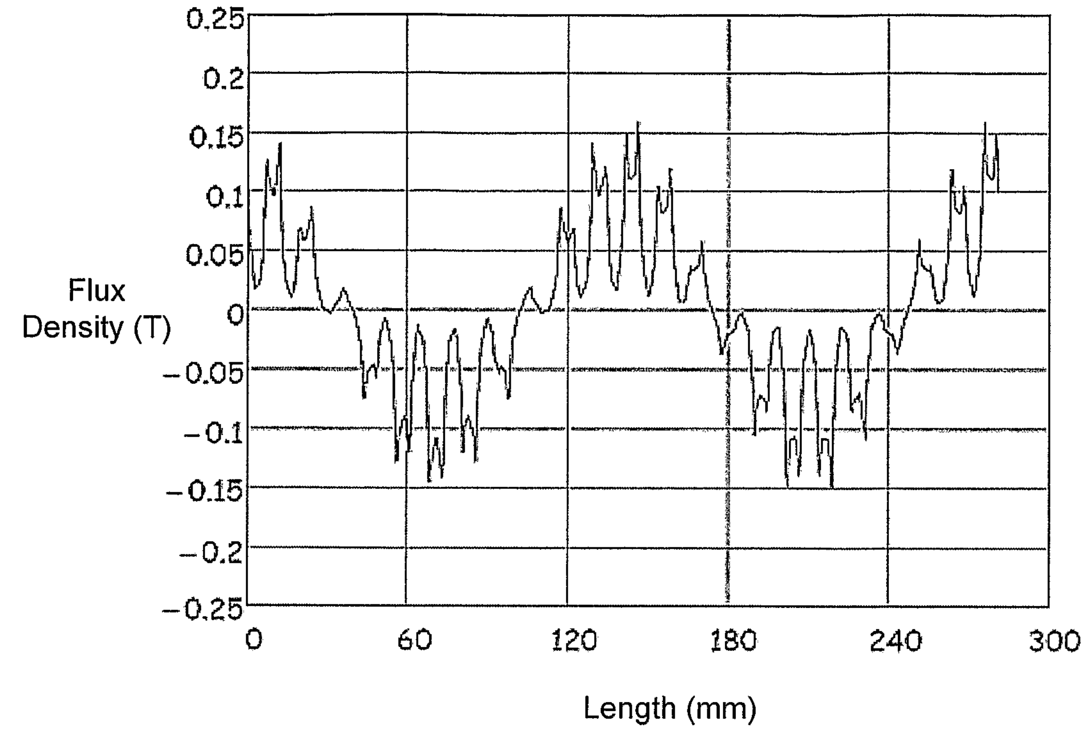

Figure 12a

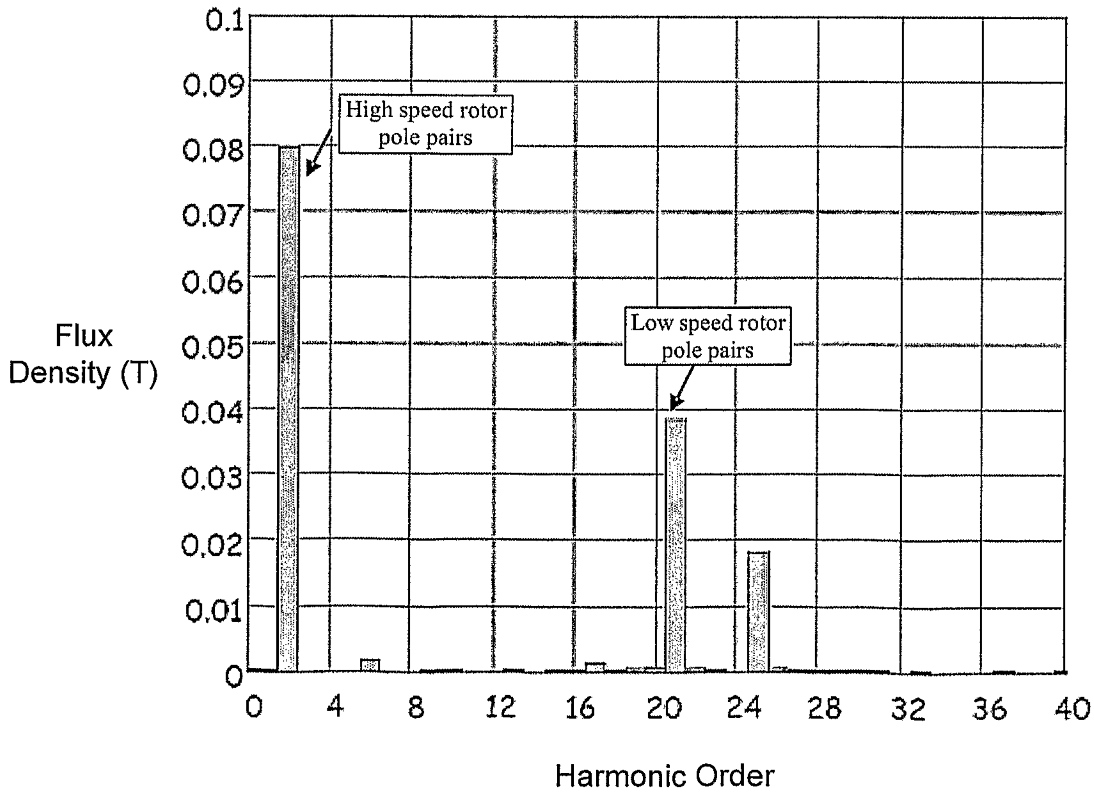

Figure 12b

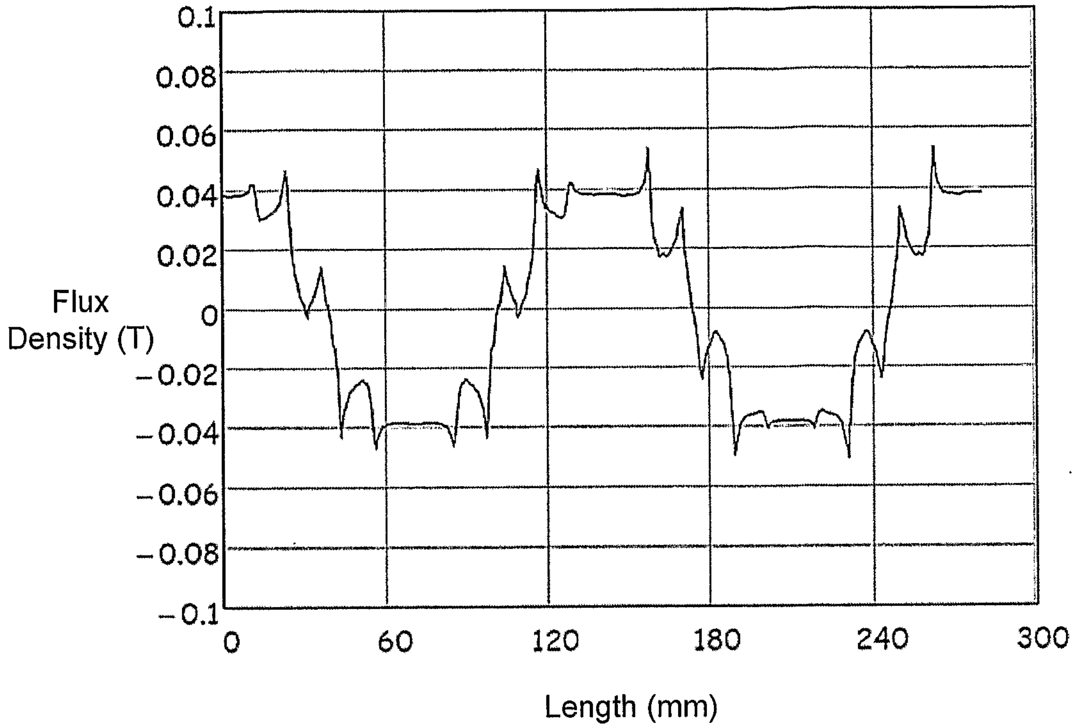

Figure 13a

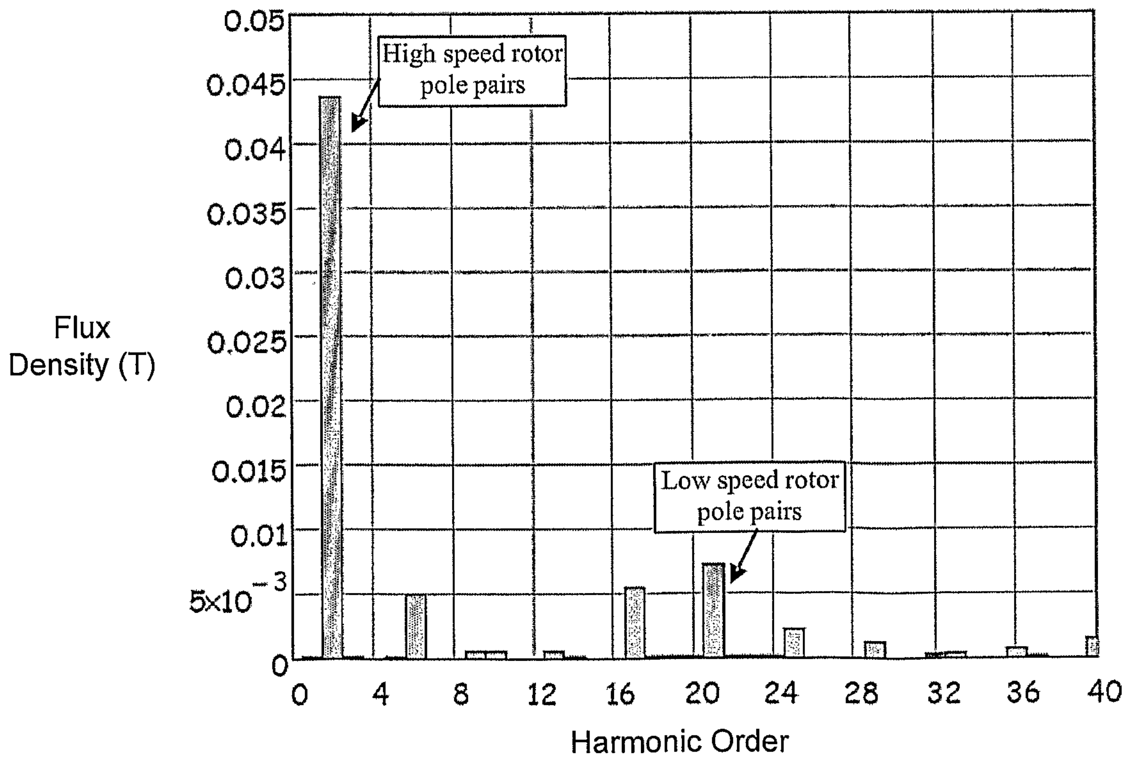

Figure 13b

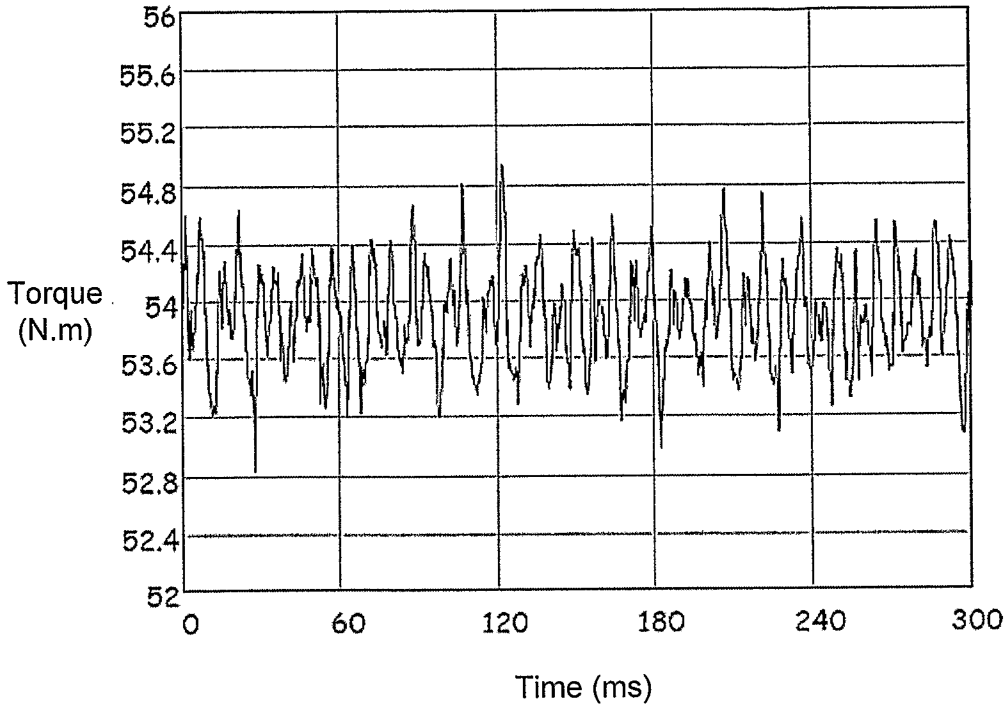

Figure 14a

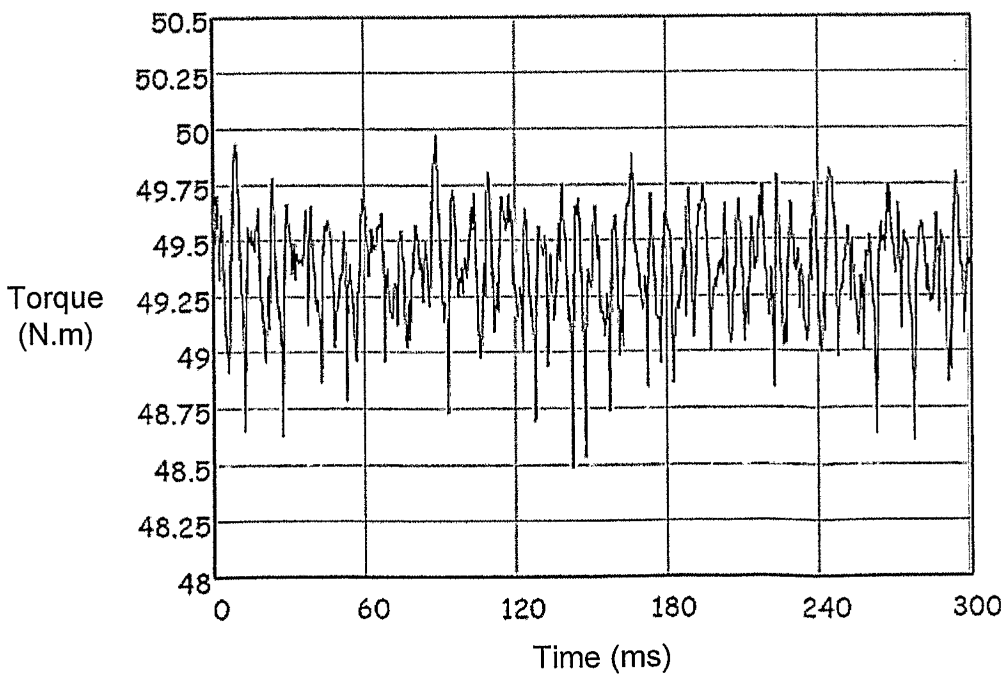

Figure 14b

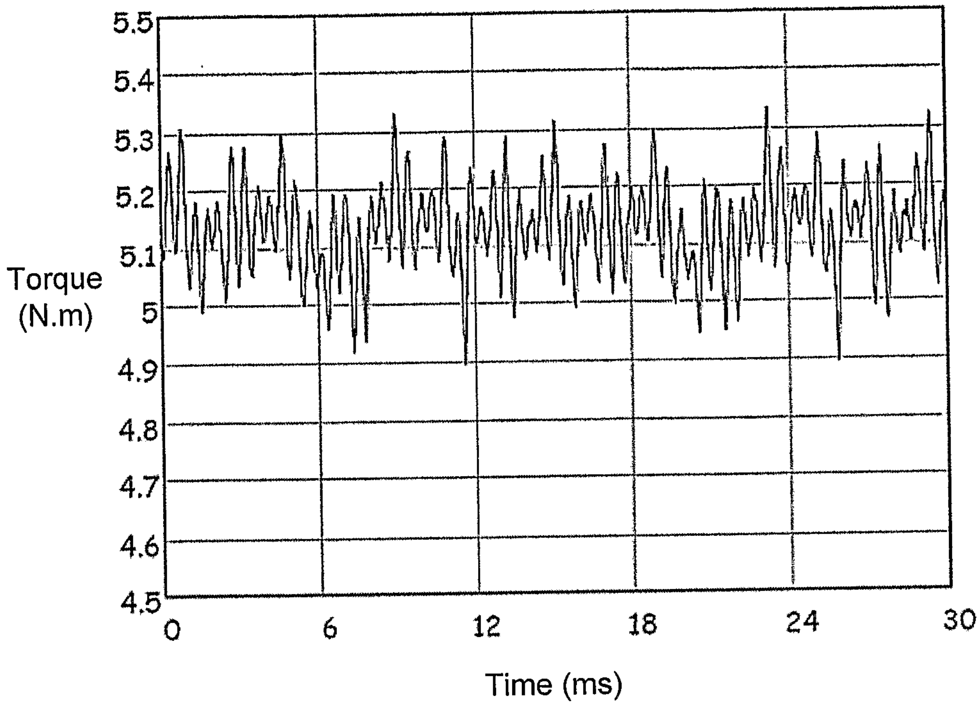

Figure 15a

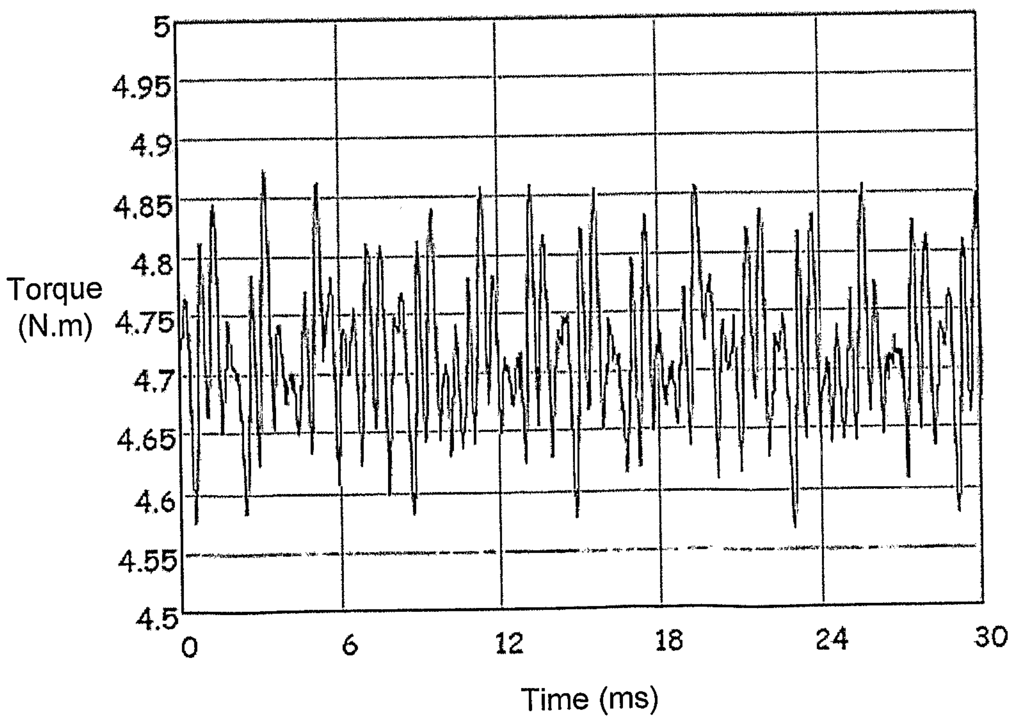

Figure 15b

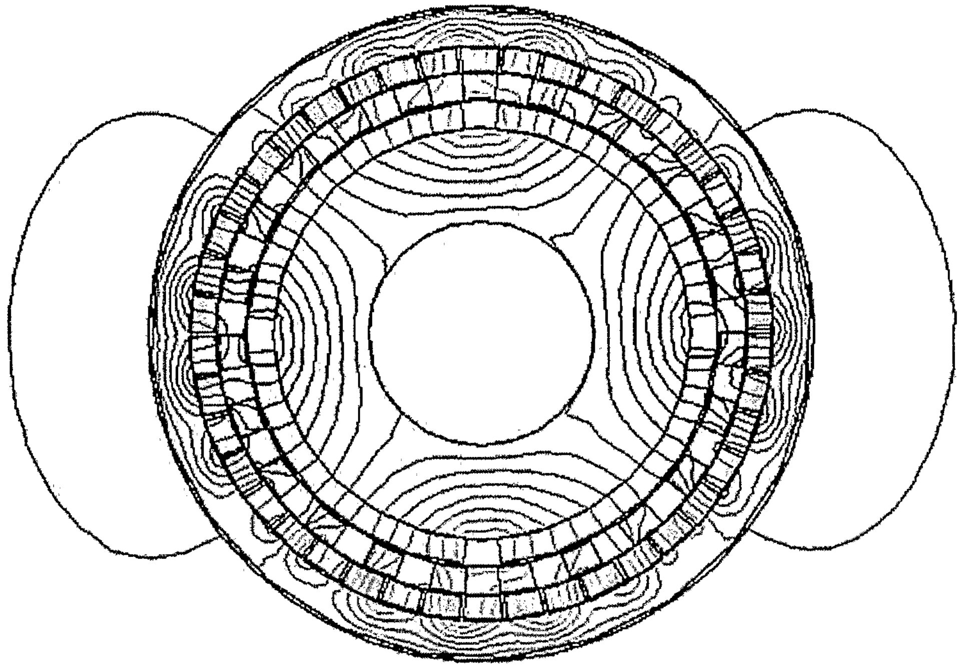

Figure 16

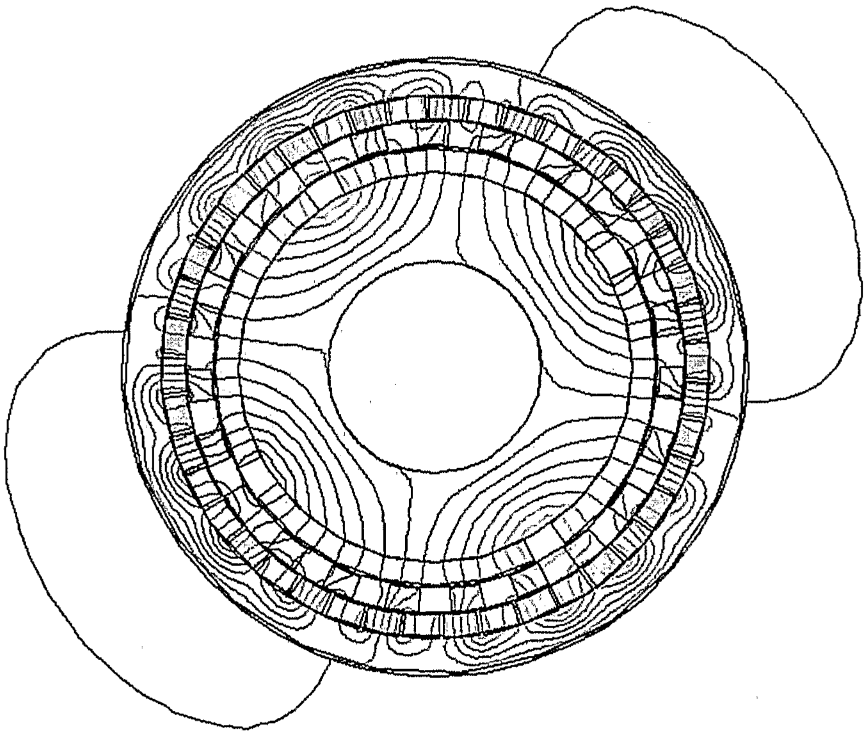

Figure 17

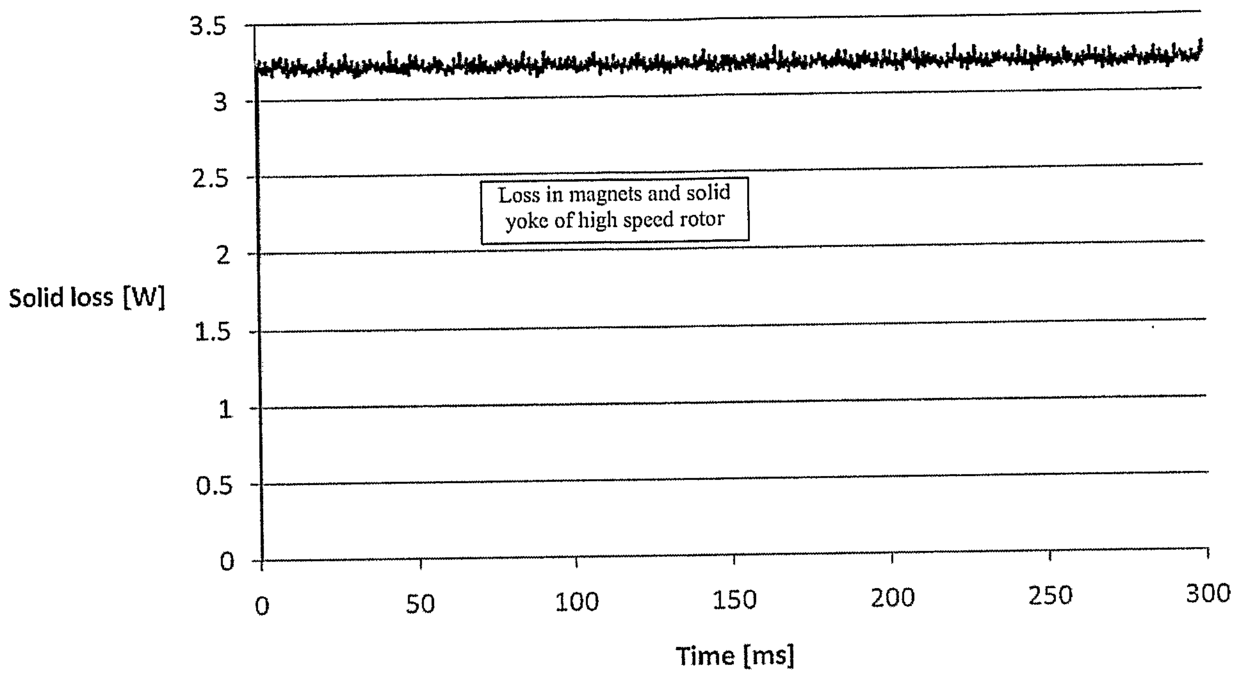

Figure 18a

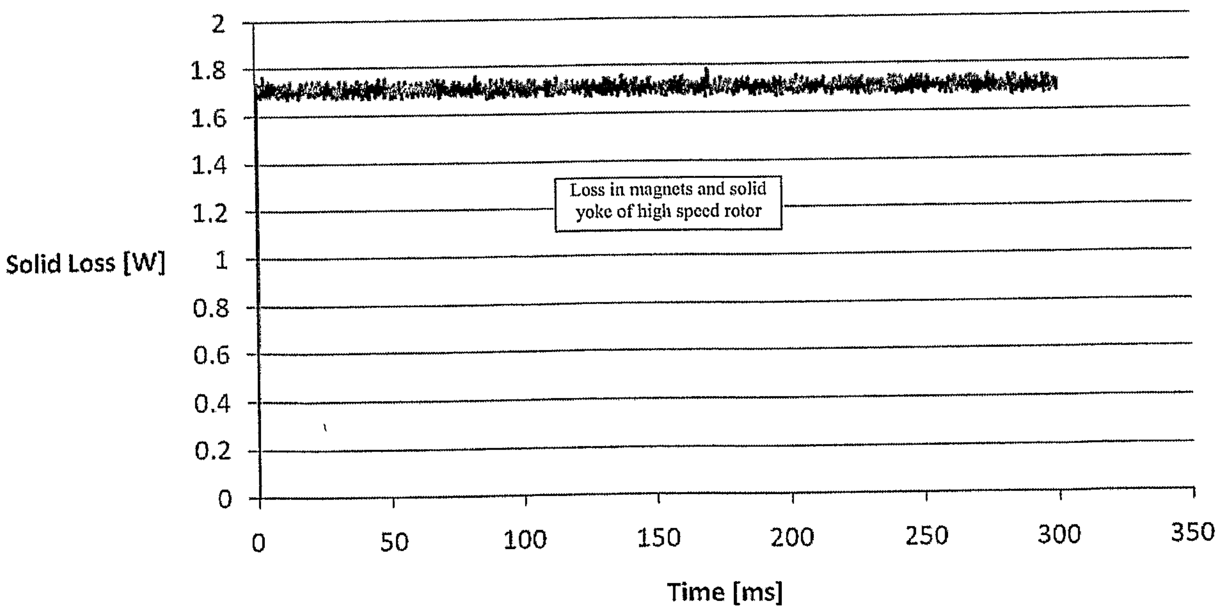

Figure 18b

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB2010/002433

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

H02K 51/00 (2006.01) ***F16H 49/00*** (2006.01) ***H02K 49/10*** (2006.01)

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)

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)
WPI & EPODOC, IPC and ECLA H02K 51/00, H02K 49/10, F16H 49/00 using key words magnetic, modulate, couple, transfer, transmission, stator, laminate, plates, sandwich, leaves, stack, disc, sheet and like terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	US 3301091 A (REESE) 31 January 1967	
X	Title, column 4 lines 30 to 40, column 12 lines 34 to 38, figure 1, 11	1-9
Y	Column 11 lines 70 to 75, column 12 lines 34 to 38, figure 11	2-5
	US 5633555 A (ACKERMANN et al) 27 May 1997	
Y	Title, figure 1	2-5
A	WO 2009/103993 A1 (MAGNOMATICS) LTD 27 August 2009 Page 1 lines 15 to 19, page 4 lines 20 to 24, figures 1 and 2	
A	FR 2518688 A (COMPAGNIE DE CONSTRUCTION MECANIQUE SULZER) 24 June 1983	

[X] Further documents are listed in the continuation of Box C   [X] See patent family annex

* Special categories of cited documents:

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 December 2010	17 DEC 2010

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB2010/002433

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SU 846892 A (VSEVOLOD et al) 15 July 1981 EPOQUE Abstract	

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	3301091	GB	1063330				
WO	2009103993	EP	2250724	EP	2255107	GB	2457682
		WO	2009103994	WO	2009130456	WO	2009147377
		WO	2009147378				
FR	2518688	NONE					
SU	846892	NONE					
US	5633555	DE	4405701	EP	0669700	JP	7264838

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX