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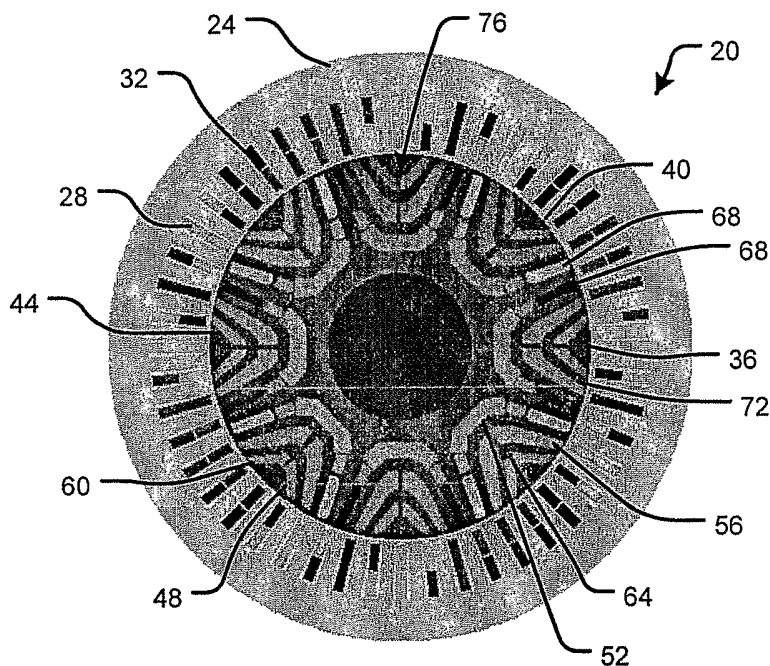
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(54) Title: ROTOR MAGNET PLACEMENT IN INTERIOR PERMANENT MAGNET MACHINES



(57) Abstract: A machine includes a stator and a rotor having a plurality of poles. Each pole is formed at least in part by a plurality of permanent magnets recessed within the rotor at a predetermined distance from an outer surface of the rotor. The distance is predetermined to minimize rotor flux variation near the outer surface during rotation of the rotor relative to the stator. Eddy current losses are thereby reduced.

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ROTOR MAGNET PLACEMENT IN INTERIOR PERMANENT MAGNET MACHINES

FIELD OF THE INVENTION

[0001] The present invention relates generally to interior permanent magnet machines and, more particularly to placement of magnets in a rotor of an interior permanent magnet machine.

BACKGROUND OF THE INVENTION

[0002] Interior permanent magnet (IPM) machines have a number of operating characteristics that make them attractive for use in vehicle propulsion applications. Compared, for example, to AC induction and DC motors, IPM motors can provide high efficiency, high torque and high power densities. IPM machines also have a long constant power operating range. An IPM machine typically includes a stator with multiphase windings. A rotor having interior permanent magnets is separated from the stator by an air gap. A magnetic field, produced by the flow of current through the stator windings, interacts with a magnetic field produced by the rotor magnets, thereby causing the rotor to rotate.

[0003] Permanent magnets have low permeability and therefore exhibit high reluctance directly along a magnetic axis (d- axis) inside an IPM machine rotor. Along a q- axis, between the magnetic poles or magnet barriers of an IPM rotor, there exists no magnetic barrier, and so magnetic reluctance is very low. This variation of reluctance around a rotor provides saliency in the rotor structure of an IPM machine. This saliency causes the rotor to tend to align with a rotating magnetic field induced by the stator. Thus an IPM rotor exhibits reluctance torque in addition to permanent magnet torque generated by

magnets inside the rotor. Reluctance in a d- axis can be produced by one magnet per pole, for example, as utilized in single-barrier rotor designs. Reluctance in d-axis can also be produced with multiple barriers, where magnets are placed in one or more barriers.

5 **[0004]** Due to slotting effects between rotor and stator, the rotor of an interior permanent magnet (IPM) machine is subject to flux variation in the vicinity of the air gap as the rotor spins. Flux variation causes eddy currents to be induced in the rotor and the magnets, especially near the surface of the rotor, and can result in rotor losses
10 and magnet heating. For high-frequency operation, for example, in many automotive variable speed drive applications, eddy current losses can make the magnet vulnerable to demagnetization. To prevent demagnetization, a common industry practice is to break the magnet into smaller segments along the axial length of the machine,
15 thus increasing the resistance to eddy currents. This process, however, can make the rotor manufacturing more complicated where a large number of magnet segments are required to be inserted into the rotor.

SUMMARY OF THE INVENTION

20 **[0005]** The present invention, in one embodiment, is directed to a machine that includes a stator and a rotor having a plurality of poles. Each pole is formed at least in part by a plurality of permanent magnets recessed within the rotor at a predetermined distance from an outer surface of the rotor. The distance is predetermined to minimize
25 rotor flux variation near the outer surface during rotation of the rotor relative to the stator.

[0006] In another embodiment, a machine includes a stator and a rotor separated from the stator by an air gap and having a plurality of slots and a plurality of permanent magnets located in at
30 least several of the slots to form a rotor pole. Each magnet is recessed

within the rotor so as to minimize rotor flux variation inside the magnet during rotation of the rotor relative to the stator.

5 **[0007]** An embodiment of a method of constructing a rotor for an IPM machine includes determining a distance from a surface of the rotor at which to place a magnet within the rotor so as to limit rotor flux variation inside the magnet during rotation of the rotor relative to a stator. A plurality of slots are provided within the rotor at the determined distance, and a plurality of magnets are placed in at least several of the slots.

10 **[0008]** In another embodiment, a machine includes a stator and a rotor that rotates relative to the stator and having a plurality of slots recessed within the rotor. A plurality of sintered permanent magnets are located in at least several of the slots to form a rotor pole. Slots not occupied by the magnets are empty.

15 **[0009]** Further areas of applicability of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating exemplary embodiments of the invention, are intended for purposes of illustration only and are not
20 intended to limit the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The present invention will become more fully understood from the detailed description and the accompanying
25 drawings, wherein:

[0011] Figure. 1 is a cross-sectional view of an IPM synchronous machine according to a first embodiment of the present invention;

[0012] Figure. 2 is a cross-sectional view of an IPM
30 synchronous machine according to a second embodiment of the present invention;

[0013] Figure 3 is a graph comparing flux variation inside the rotor magnets shown in Figures 1 and 2; and

[0014] Figure 4 is a graph comparing torque produced by the machines shown in Figures 1 and 2.

5

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0015] The following description of various embodiments of the present invention is merely exemplary in nature and is in no way intended to limit the invention, its application, or uses.

10 [0016] As further described below, in multi-barrier designs for IPM machines, rotor magnets are provided in layers. Multi-barrier rotor designs can reduce leakage and increase rotor saliency and offer a number of advantages over single-barrier designs. Multi-barrier rotors are described in U.S. Patent Application No. 09/952,319 filed
15 September 14, 2001, U.S. Patent No. 6,674,205, issued January 6, 2004, and U.S. Patent Application No. 10/431,744, filed May 8, 2003, the disclosures of which are incorporated herein by reference in their entirety. The foregoing applications are assigned to the assignee of the present application.

20 [0017] A cross-sectional view of a first embodiment of a multi-barrier synchronous IPM machine is indicated generally in Figure 1 by reference number 20. The machine 20 includes a stator 24 having a plurality of slots 28 through which multiphase windings 32 are wound. In the embodiment shown in Figure 1, the stator 24 has forty-eight slots
25 28. A rotor 36 is separated from the stator 24 by an air gap 40. A plurality of slots 44 in the rotor 36 form a plurality of barriers 48, for example, inner barriers 52, middle barriers 56 and outer barriers 60. The slots 44 in a barrier 48 may be separated by bridges 64.

[0018] A plurality of sintered permanent magnets 68 are
30 located in slots 44 of the inner barriers 52 near an outer surface 72 of the rotor 36. The rotor 36 includes a plurality of magnetic poles, one of

which is indicated generally by reference number 76. Each pole 76 is formed at least in part by the magnets 68 in the slots 44. In the embodiment shown in Figure 1, the rotor 36 has eight poles 76.

[0019] The aforementioned U. S. Patent Application Nos. 5 09/952,319 and 10/431,744, and U.S. Patent No. 6,674,205 describe rotors including injection-molded magnets located in rotor barriers. In machines utilizing such rotors, magnetic flux can be maintained such that back EMF (electromotive force) at maximum speed(s) is kept below a predetermined limit. In the embodiment shown in Figure 1, the 10 sintered magnets 68 have a high magnetic energy product (MEP) compared, for example, to the injection-molded magnets described in U.S. Patent Application Nos. 09/952,319 and 10/431,744, and U.S. Patent No. 6,674,205. Accordingly, slots 44 of the rotor middle and outer barriers 56 and 60 can be left empty, *e.g.*, air-filled. Slots 44 of 15 the inner barriers 52 which are not occupied by the magnets 68 also can be left empty. Any or all empty slots 44 may be filled with a non-magnetic material, for example, epoxy, that exhibits thermal behavior conducive to improving thermal performance of the rotor 36. In some embodiments in which one or more slots 44 are filled with such 20 material, one or more bridges 64 between slots can be eliminated. When the magnets 68 are placed in slots 44, the rotor 36 can be magnetized, for example, as described in the foregoing U. S. Patent applications.

[0020] In the embodiment shown in Figure 1, slotting of the 25 stator 24 and rotor 36 causes variation of rotor flux near the air gap 40 as the rotor 36 spins. Such variation typically has a frequency higher than a fundamental frequency of the stator 24. For example, in the machine 20, frequency of the flux variation is twelve times the fundamental frequency of the stator 24 and forty-eight times the 30 mechanical rotational frequency. Flux variation amplitude typically is highest near the rotor surface 72 and gradually decreases with

distance from the surface 72. A high frequency of flux variation could result in significant eddy currents, particularly where low-resistivity sintered magnets are used in the rotor 36.

[0021] A cross-sectional view of a multi-barrier IPM machine according to a second embodiment is indicated generally in Figure 2 by reference number 100. The machine 100 includes a stator 124 having a plurality of slots 128 through which multiphase windings 132 are wound. In the embodiment shown in Figure 2, the stator 124 has forty-eight slots 128. A rotor 136 is separated from the stator 124 by an air gap 140. A plurality of slots 144 in the rotor 136 form a plurality of barriers 148, for example, inner barriers 152, middle barriers 156 and outer barriers 160. The slots 144 in each barrier 148 may be separated by bridges 164.

[0022] A plurality of sintered permanent magnets 168 are located in slots 144 of the inner barriers 152. The rotor 136 includes a plurality of magnetic poles, one of which is indicated generally by reference number 172. Each pole 172 is formed at least in part by the magnets 168 in the slots 144. In the embodiment shown in Figure 2, the rotor 136 has eight poles 172.

[0023] The magnets 168 are recessed from an outer surface 176 of the rotor 136 by a predetermined distance 180. The distance 180 is determined based on rotor size and is calculated to minimize flux variation of the rotor 136 inside the rotor magnet 168 during rotation of the rotor relative to the stator 124. In the present embodiment, the distance is about one-tenth of a radius 184 of the rotor 136. Thus, for example, where the rotor 136 has a radius of about fifty millimeters, the distance 180 of the magnets 168 from the rotor outer surface 176 is about five millimeters. Since flux variation decreases with distance from the surface 176, it should be clear that the distance 180 is a minimum distance useful for limiting flux variation in accordance with principles of the present invention.

[0024] As previously discussed with reference to Figure 1, slots 144 of the middle and outer barriers 156 and 160 can be left empty, *e.g.*, air-filled. Slots 144 of the inner barriers 152 which are not occupied by the magnets 168 also can be left empty. Any or all empty
5 slots 144 may be filled with a non-magnetic material, for example, epoxy, that exhibits thermal behavior conducive to improving thermal performance of the rotor 136. In some embodiments in which one or more slots 144 are filled with such material, one or more bridges 164 between slots can be eliminated. When the magnets 168 are placed in
10 slots 144, the rotor 136 can be magnetized, for example, as described in the foregoing U. S. Patent applications.

[0025] Compared to the machine 20, the machine 100 exhibits lower flux variation inside the rotor magnet and therefore lower eddy current losses. For example, a graph comparing flux variation
15 inside magnets of rotors 36 and 136 is indicated generally in Figure 3 by reference number 200. Flux variation is shown in Figure 3 for two points inside the magnets at which flux variation tends to be highest for the rotors 36 and 136.

[0026] A graph comparing peak torque capability of the
20 machines 20 and 100 is indicated generally in Figure 4 by reference number 300. For the same current and control angles, the machines 20 and 100 produce the same or similar amounts of average torque. It also can be seen that the machine 100 exhibits lower peak-to-peak torque ripple than the machine 20. Because a rotor magnet 168 of the
25 machine 100 has a shorter moment arm than a rotor magnet 68 of the machine 20, rotor mechanical stress tends to be less for the machine 100 than for the machine 20.

[0027] Because sintered magnets are used in the foregoing embodiments, it is possible to use less magnetic material than is used
30 in rotors of the prior art and to leave unused barrier slots empty. In embodiments wherein rotor magnets are recessed within the rotor as

described above, eddy current losses in the magnet can be minimized, since magnets are located inside the rotor where the flux variation is low. Thus eddy-induced losses can be minimized without compromising machine performance or complicating the rotor manufacturing. Rotor manufacturing is easier because rotor magnetization can be performed after the magnets are placed inside the rotor. Torque ripple and rotor stress due to centrifugal force also are reduced.

[0028] Those skilled in the art can now appreciate from the foregoing description that the broad teachings of the present invention can be implemented in a variety of forms. Therefore, while this invention has been described in connection with particular examples thereof, the true scope of the invention should not be so limited since other modifications will become apparent to the skilled practitioner upon a study of the drawings, specification, and the following claims.

CLAIMS

What is claimed is:

1. A machine comprising:
a stator; and
a rotor having a plurality of poles, each said pole formed
5 at least in part by a plurality of permanent magnets recessed within
said rotor at a predetermined distance from an outer surface of the
rotor, said distance predetermined to minimize rotor flux variation
inside the rotor magnets during rotation of said rotor relative to said
stator.
2. The machine of claim 1 wherein said distance comprises
a distance greater than or equal to one-tenth of a radius of said rotor.
3. The machine of claim 1 wherein said rotor comprises a
multi-barrier rotor.
4. The machine of claim 1 wherein said magnets comprise
one or more sintered magnets.
5. The machine of claim 1 wherein said rotor has a radius
having a length of about fifty millimeters and said distance comprises
about five millimeters.
6. The machine of claim 1 wherein said rotor further
comprises a plurality of slots recessed within said rotor to form a
plurality of barriers for each said pole, said magnets of one of said
poles located in one of said barriers.

7. The machine of claim 6 wherein several of said slots are left empty.

8. The machine of claim 6 wherein several of said slots are at least partially filled with a non-magnetic material.

9. A machine comprising:
a stator; and
a rotor separated from the stator by an air gap and having a plurality of slots and a plurality of permanent magnets located in at least several of said slots to form a rotor pole;
5 wherein each said magnet is recessed within said rotor so as to minimize rotor flux variation inside the magnets during rotation of said rotor relative to said stator.

10. The machine of claim 9 wherein said magnets comprise one or more sintered magnets.

11. The machine of claim 9 wherein said magnets are recessed from an outer surface of said rotor by about one-tenth of a radius of said rotor.

12. The machine of claim 9 wherein said magnets are recessed within the rotor at least five millimeters from an outer surface of said rotor.

13. The machine of claim 9 wherein said rotor pole comprises a plurality of barriers defined by said slots, each said magnet located in the same barrier.

14. The machine of claim 13 wherein said rotor pole comprises three barriers.

15. The machine of claim 13 wherein at least one said barrier comprises one or more empty slots.

16. The machine of claim 13 wherein at least one said barrier comprises one or more slots filled at least partially with epoxy.

17. The machine of claim 9 wherein said magnets are arranged within one of said slots such that another of said slots between said magnet and an outer surface of said rotor is empty.

18. A method of constructing a rotor for an IPM machine, said method comprising:

5 determining a distance from a surface of the rotor at which to place a magnet within the rotor so as to limit rotor flux variation inside the magnet during rotation of the rotor relative to a stator;

providing a plurality of slots within the rotor at the determined distance; and

10 placing a plurality of magnets in at least several of the slots.

19. The method of claim 18 further comprising:
using the slots to form one or more barriers; and
placing several of the plurality of magnets in the one or more barriers to form a rotor pole.

20. The method of claim 18 further comprising orienting the slots such that the magnets placed in the slots form a plurality of rotor poles.

21. The method of claim 18 wherein the magnets are sintered.

22. The method of claim 18 wherein determining a distance from a surface of the rotor comprises:

determining a radius of the rotor; and

5 multiplying the determined rotor radius by a predetermined ratio to obtain the distance.

23. The method of claim 22 wherein the ratio comprises 1/10.

24. The method of claim 18 further comprising leaving one or more of the slots empty.

25. The method of claim 18 further comprising filling one or more of the slots at least partially with a non-magnetic material.

26. A machine comprising:

a stator;

a rotor that rotates relative to said stator and having a plurality of slots recessed within said rotor; and

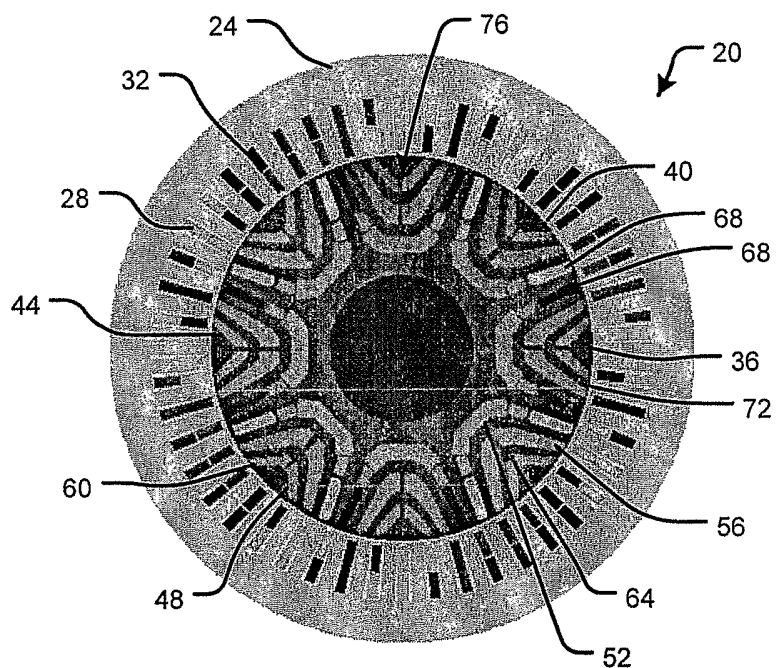
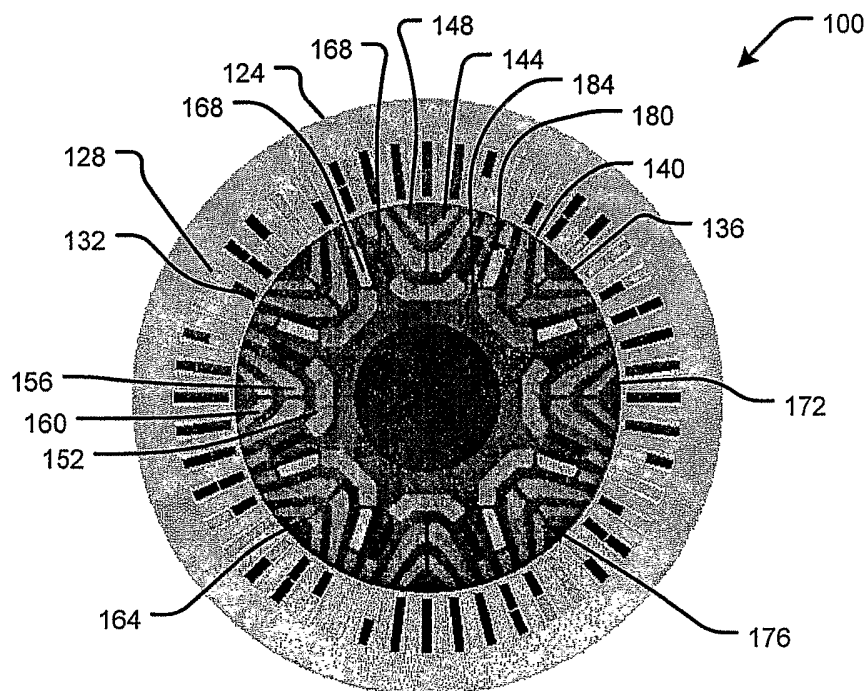
5 a plurality of sintered permanent magnets located in at least several of said slots to form a rotor pole;

wherein said slots not occupied by said magnets are empty.

27. The machine of claim 26 wherein each said magnet is recessed within said rotor so as to minimize rotor flux variation inside the magnet during rotation of said rotor relative to said stator.

28. The machine of claim 26 wherein each said magnet is recessed within said rotor by a distance of at least about one-tenth of a radius of said rotor.

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**FIG. 1****FIG. 2**

200

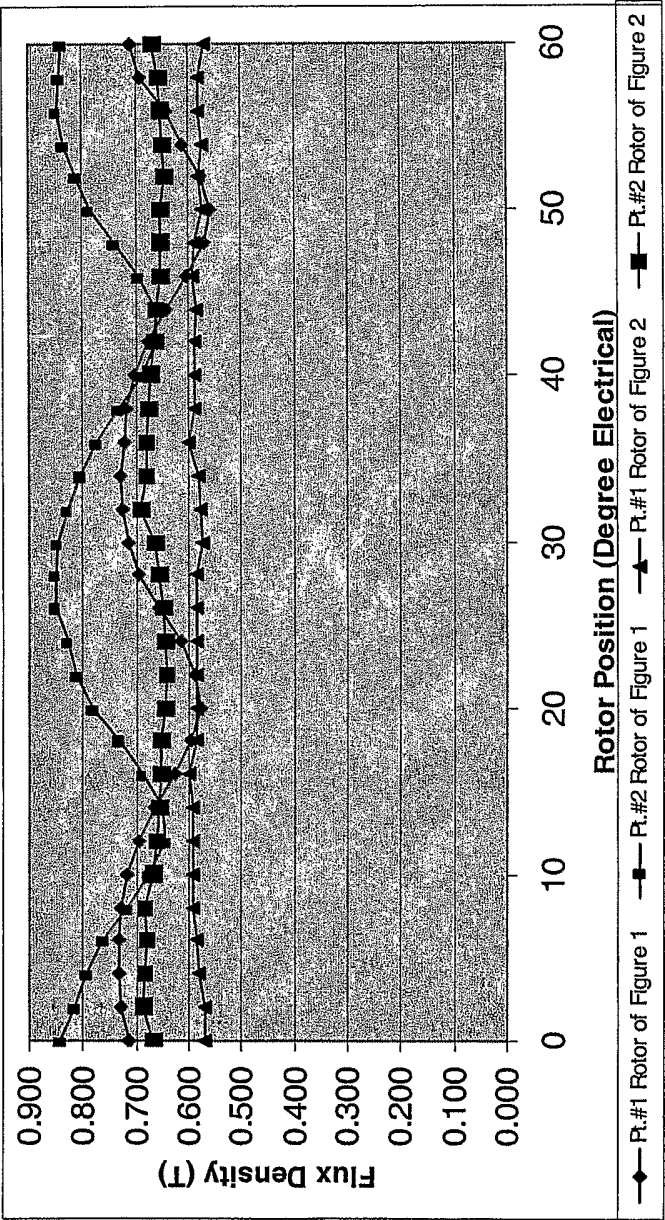


FIG. 3

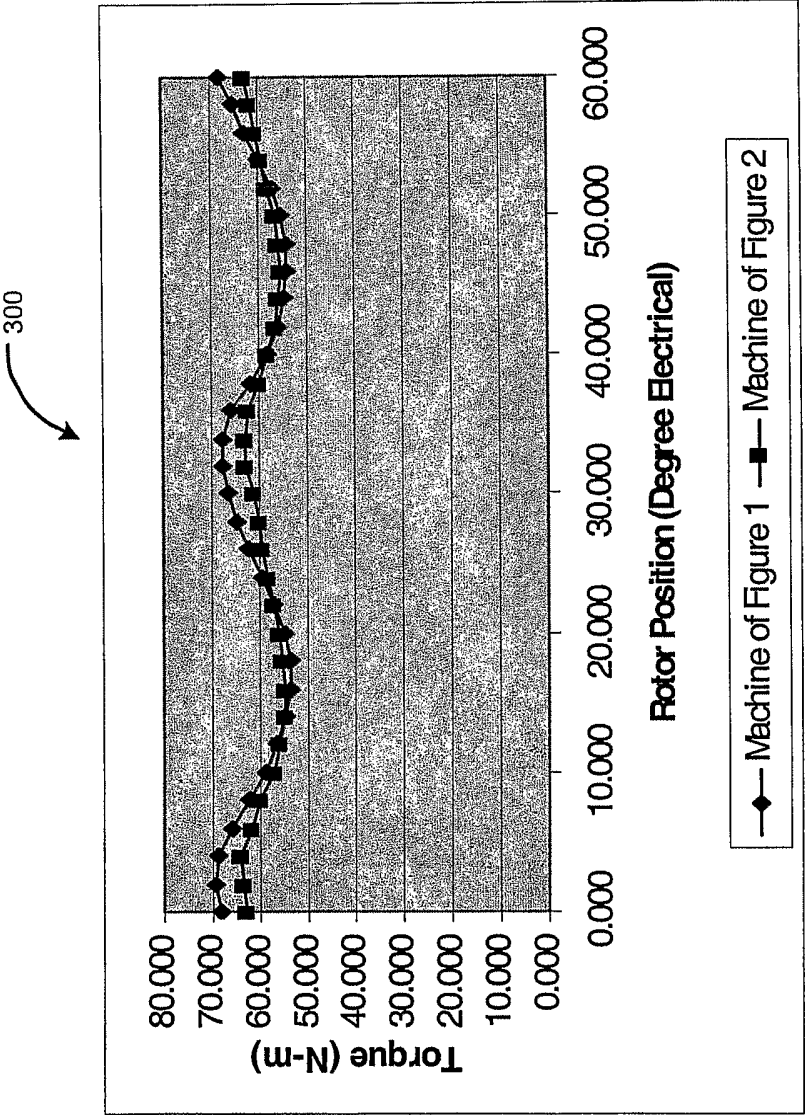


FIG. 4