METHODS AND APPARATUS FOR A PERMANENT MAGNET MACHINE WITH ADDED ROTOR SLOTS

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ABSTRACT
An internal permanent magnet machine ("IPM machine") of the type used, for example, with traction motors and hybrid electric vehicles, includes a rotor with additional, small rotor slots configured to provide an averaging effect with respect to rotor barriers provided therein.
METHODS AND APPARATUS FOR A PERMANENT MAGNET MACHINE WITH ADDED ROTOR SLOTS

CROSS-REFERENCE

This application claims priority to U.S. Provisional Patent Application Ser. No. 60/991,310, filed Nov. 30, 2007.

TECHNICAL FIELD

The present invention generally relates to magnetic devices such as electrical motors, and more particularly relates to interior permanent magnet machines.

BACKGROUND

Interior permanent magnet (IPM) machines are favored for fuel cell and hybrid electric vehicle operations due to their desirable characteristics—i.e., good torque density, good overall efficiency, good constant power range, etc. The rotor field in a permanent magnet machine is obtained by virtue of its structure, unlike other machines such as induction, switched or synchronous reluctance machines, in which the field is generated by a stator current supplied by a source. As a result, permanent magnet machines exhibit superior efficiency as compared to other such machines.

However, as with surface PM machines, an IPM machine is burdened by the fact that the permanent magnet field is present even when the machine is not powered, resulting in losses induced by the rotating permanent magnet field of the rotor. Furthermore, such structures are subject to ripple and cogging torque, which has two major sources. The first is the winding harmonics, the majority of which is the 6th harmonic and it’s integer multiples, generated from the 5th and 7th winding harmonics. These winding harmonics can be lowered by short-pitching the winding. For example, for a six slots per pole design, the winding can be short-pitched by one slot (½ short pitch).

The second and most significant source of torque ripple is slotting effect brought about by burying the magnet inside the rotor. The interaction between the rotor slots and the stator slots (the winding slots) generates significant torque ripple. One way to minimize this effect is to skew either the rotor or the stator, which results in some averaging, effectively cancelling much of the torque ripple and the cogging. Skewing is widely known in the industry and is routinely performed to lower cogging and ripple torque. This approach, however, lowers machine torque and adds manufacturing complexity and cost.

Accordingly, it is desirable to provide improved, manufacturable IPM machines that reduce cogging and torque ripple. Other desirable features and characteristics of the present invention will become apparent from the subsequent detailed description and the appended claims, taken in conjunction with the accompanying drawings and the foregoing technical field and background.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention may be derived by referring to the detailed description and claims when considered in conjunction with the following figures, wherein like reference numbers refer to similar elements throughout the figures.

FIG. 1 depicts, in cross-section, various internal permanent magnet (IPM) machines;

FIG. 2 depicts, in cross-section, an IPM machine in accordance with one embodiment; and

FIG. 3 depicts, in cross-section, an IPM machine in accordance with an alternate embodiment.

The following detailed description is merely illustrative in nature and is not intended to limit the invention or the application and uses of the invention. Furthermore, there is no intention to be bound by any expressed or implied theory presented in the preceding technical field, background, brief summary or the following detailed description. The invention may be described herein in terms of functional and/or logical block components and various processing steps. It should be appreciated that such block components may be realized by any number of hardware, software, and/or firmware components configured to perform the specified functions. For the purposes of conciseness, conventional techniques and systems related to electrical motors, magnetism, and the like are not described in detail herein.

In general, the various embodiments are directed to a permanent magnet machine (“PM machine”), and more specifically an internal permanent magnet machine (“IPM machine”) that includes a rotor with additional slots near the rotor surface, thereby creating an additional slotting effect. In this way, the structure can cancel or lower the slotting effect of the rotor barriers through an averaging effect. In this way, torque ripple and cogging can be reduced.

Interior PM machines often incorporate one or more rotor barriers (or simply “barriers”). FIGS. 1(a) and 1(b), for example, illustrate partial cross-sections through various exemplary IPM machines 100 with single and double barrier rotors 106. More particular, FIG. 1(a) illustrates a rotor 106 with magnets 110 and air slots (pockets) or air barriers 125 incorporated into the structure at various locations with respect to magnets 110. As is conventional, IPM 100 includes a stator 101 having a plurality of windings 102 magnetically interacting with magnets 110 within rotor 106. Various cavities are provided within region 104 of rotor 106, and all or a portion of these cavities are filled with permanent magnets in the conventional manner, depending upon the number of layers incorporated into the structure.

FIG. 1(b), more particularly, depicts a two-barrier PM rotor with the second barrier partially filled with magnets 110. Similarly, FIG. 1(c) illustrates a two-barrier PM rotor with no magnets in the second layer—i.e., the second layer comprises only an air-filled cavity. The added second barrier shown in FIG. 1(b) adds resistance to the lower magnet barrier, lowering the air-gap magnet flux. However, as mentioned previously, addition of the second barrier in the rotor can mechanically weaken the rotor. Also, for some machines, addition of any such second barrier is not geometrically feasible due to limited space (e.g., the rotor of FIG. 1(a)).

Rotors with more than two barriers may also be provided; however, such designs undesirably increase manufacturing complexity. Increasing the number of barriers improves rotor saliency, and thus improves machine torque. Moreover, the second rotor barrier often works as a barrier to the inner magnet layer, consequently lowering the magnet flux in the air-gap. Lowering of magnet flux in the air-gap reduces the magnet torque, but is somewhat compensated by the increased saliency of the rotor.

In hybrid applications, when the PM machine is part of a transmission, very often the machine is rotating in con-
junction with a different gear-set even though machine is producing no torque or is producing very low torque. If the no-load or light load operation is a substantial portion of the machine drive cycle, the overall efficiency of the transmission is affected. Rotating magnet flux also induces voltage in the stator winding, commonly referred to as back EMF. The high magnet flux of a permanent magnet rotor may induce very high voltage in the stator, especially during high speed operation of the machine. Therefore, lowering of the machine air-gap flux is very desirable for such machines.

[0017] FIGS. 2 and 3 depict various embodiments of an IPM machine 200 in accordance with one embodiment of the present invention in which additional rotor slots 235 are provided along the periphery—i.e., near the rotor surface 202.

[0018] As shown, a cavity within rotor 106 is filled or partially filled by magnet 110, in which case various air slots (pockets) or barriers are formed adjacent thereto, i.e.: air slots 125. The term “cavity” is thus used to refer to the empty regions existing prior to insertion of magnet 110. The term “rotor barriers” refers to all barriers or air slots 125 that are provided within the hub area of rotor 106 (i.e., excepting slots 235). While FIG. 2 illustrates a cross-sectional view of magnets 110 and air slots 125, it will be understood that the cavity extends into region 104 of the rotor of rotor 106 and will define a three-dimensional volume having any suitable shape.

[0019] The size, location, and geometry of each additional slot may be selected to achieve the desired design objectives. Such attributes are preferably chosen to produce an averaging effect with respect to the rotor barriers existing within rotor 106. Such optimization may be performed empirically or through conventional computer modeling methods known in the art.

[0020] FIGS. 2 and 3 show two different embodiments incorporating such additional slots in a single-barrier and double-barrier rotor, respectively. In FIG. 2, pairs of rectangular magnets 110 are configured angled toward each other—i.e., defining an obtuse angle facing outward toward the stator surface.

[0021] In one embodiment, two such additional slots 235 are included per pole; however, any number of such slots 235 may be used. Furthermore, the slots need not be distributed symmetrically or evenly with respect to magnets 110.

[0022] In the illustrated embodiment, the cross-sectional area of each slot 235 is preferably equal, though slots with varying sizes are comprehended by this invention. For example, the additional slots may have a cross-sectional area that is substantially less than an aggregate cross-sectional area of the rotor barriers.

[0023] FIG. 3 shows an alternate embodiment for a two-layer rotor, wherein two additional slots 235 are placed on the exterior of the two first layer magnets 110. As with the above embodiment, additional slots 235 are located at a radius substantially corresponding to the center of magnets 110 closest to surface 103.

[0024] The depth of slots 235 within region 104 of rotor 106 (i.e., the distance radially from surface 202) may also be selected to achieve particular design objectives. In one embodiment, for example, slots 235 are located 1-1.5 mm from surface 202. It will be appreciated, however, that the invention is not so limited.

[0025] While at least one example embodiment has been presented in the foregoing detailed description, it should be appreciated that a vast number of variations exist. For example, additional barrier layers may be incorporated in addition to the single layer illustrated. It should also be appreciated that the example embodiment or embodiments described herein are not intended to limit the scope, applicability, or configuration of the invention in any way. Rather, the foregoing detailed description will provide those skilled in the art with a convenient road map for implementing the described embodiment or embodiments. It should be understood that various changes can be made in the function and arrangement of elements without departing from the scope of the invention and the legal equivalents thereof.

What is claimed is:

1. An interior permanent magnet machine comprising:
   - a wound stator;
   - a rotor configured to magnetically interact with the wound stator, the rotor having an outer surface;
   - a plurality of rotor barriers provided within the rotor;
   - a plurality of permanent magnets disposed within the rotor, the plurality of permanent magnets having a minimum distance to the outer surface; and
   - a plurality of additional slots provided within the rotor at a distance from the outer surface that is less than or equal to the minimum distance of the plurality permanent magnets.

2. The interior permanent magnet machine of claim 1, wherein the additional slots have a cross-sectional area that is substantially less than an aggregate cross-sectional area of the rotor barriers.

3. The interior permanent magnet machine of claim 1, wherein the plurality of magnets are associated with a plurality poles, and wherein the plurality of additional slots comprises exactly two additional slots.

4. The interior permanent magnet machine of claim 1, wherein the plurality of magnets are configured in pairs defining a concave angle toward the outer surface of the rotor.

5. The interior permanent magnet machine of claim 1, wherein the plurality of additional slots are less than approximately 1.5 mm from the outer surface of the rotor.

6. The interior permanent magnet machine of claim 1, wherein the plurality of additional slots are evenly distributed around the outer surface of the rotor.

7. The interior permanent magnet machine of claim 1, wherein the plurality of additional slots are configured to average out the effect on torque ripple produced by the plurality of rotor barriers.

8. A method of making an interior permanent magnet machine, comprising:
   - providing a wound stator;
   - providing a rotor configured to magnetically interact with the wound stator, the rotor having an outer surface;
   - forming a plurality of rotor barriers within the rotor;
   - placing a plurality of permanent magnets within the rotor, the plurality of permanent magnets having a minimum distance to the outer surface; and
   - forming a plurality of additional slots within the rotor at a distance from the outer surface that is less than or equal to the minimum distance of the plurality permanent magnets.

9. The method of claim 8, wherein the additional slots have a cross-sectional area that is substantially less than an aggregate cross-sectional area of the rotor barriers.

10. The method of claim 8, wherein the plurality of magnets are associated with a plurality poles, and wherein the plurality of additional slots comprises exactly two additional slots.
11. The method of claim 8, wherein the plurality of magnets are configured in pairs defining a concave angle toward the outer surface of the rotor.

12. The method of claim 8, wherein the plurality of additional slots are less than approximately 1.5 mm from the outer surface of the rotor.

13. The method of claim 8, wherein the plurality of additional slots are evenly distributed around the outer surface of the rotor.

14. The method of claim 8, wherein the plurality of additional slots are configured to average out the effect on torque ripple produced by the plurality of rotor barriers.

15. A traction motor of the type used in connection with a hybrid electric vehicle, the traction motor comprising:
   a wound stator;
   a rotor configured to magnetically interact with the wound stator, the rotor having an outer surface;
   a plurality of rotor barriers provided within the rotor;
   a plurality of permanent magnets disposed within the rotor, the plurality of permanent magnets having a minimum distance to the outer surface; and
   a plurality of additional slots provided within the rotor at a distance from the outer surface that is less than or equal to the minimum distance of the plurality permanent magnets.

16. The traction motor of claim 15, wherein the additional slots have a cross-sectional area that is substantially less than an aggregate cross-sectional area of the rotor barriers.

17. The interior permanent magnet machine of claim 15, wherein the plurality of magnets are associated with a plurality poles, and wherein the plurality of additional slots comprises exactly two additional slots.

18. The interior permanent magnet machine of claim 15, wherein the plurality of magnets are configured in pairs defining a concave angle toward the outer surface of the rotor.

19. The interior permanent magnet machine of claim 15, wherein the plurality of additional slots are less than approximately 1.5 mm from the outer surface of the rotor.

20. The interior permanent magnet machine of claim 15, wherein the plurality of additional slots are configured to average out the effect on torque ripple produced by the plurality of rotor barriers.