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SYNCHRONOUS RELUCTANCE MOTOR HAVING A FERRITE ASSISTED RELUCTANCE ROTOR

Abstract

A motor includes a stator having a winding that when selectively energized produces an electromagnetic field within a rotor cavity, and a rotor disposed within the rotor cavity of the stator and in electromagnetic communication with the winding and the electromagnetic field. The rotor includes a drive shaft, a rotor body that extends around the drive shaft and that defines a plurality of reluctance voids, and magnet inserts that are disposed within the reluctance voids. The magnet inserts occupy at least a portion of a space defined by the reluctance voids. The magnet inserts and the reluctance voids cooperate with the electromagnetic field to produce an electromagnetic torque.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION [0001] This application claims priority to and the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Patent Application No. 63/551,632, filed on Feb. 9, 2024, entitled SYNCHRONOUS RELUCTANCE MOTOR HAVING A FERRITE ASSISTED RELUCTANCE ROTOR, the entire disclosure of which is hereby incorporated herein by reference.

FIELD OF THE INVENTION
[0002] The present invention generally relates to electric motors, and more specifically, a synchronous reluctance rotor having a series of stacked rotor laminations that are coupled together to form reluctance voids, and where permanent magnet inserts are disposed within the reluctance voids to form a rotor that produces a reluctance torque as well as a magnetic torque when acted upon by an electromagnetic field from a stator.
BACKGROUND OF THE INVENTION
[0003] Electric motors typically include a stator and a rotor, where the stator includes a winding that can be energized to form an electromagnetic field that interacts with a rotor. The interaction between the electromagnetic field of the stator and the rotor produces an electromotive force that rotates the rotor relative to the stator.
SUMMARY OF THE INVENTION
[0004] According to an aspect of the present disclosure, a motor includes a stator having a winding that when selectively energized produces an electromagnetic field within a rotor cavity, and a rotor disposed within the rotor cavity of the stator and in electromagnetic communication with the winding and the electromagnetic field. The rotor includes a drive shaft, a rotor body that extends around the drive shaft and that defines a plurality of reluctance voids, and magnet inserts that are disposed within the reluctance voids. The magnet inserts occupy at least a portion of a space defined by the reluctance voids. The magnet inserts and the reluctance voids cooperate with the electromagnetic field to produce an electromagnetic torque.
[0005] According to another aspect, a rotor includes a drive shaft and a plurality of stacked rotor laminations that form a rotor body. The rotor body extends around the drive shaft. Each stacked rotor lamination has connecting webs that form reluctance voids within the plurality of stacked rotor laminations. The rotor further includes magnet inserts that are disposed within the reluctance voids. The magnet inserts occupy at least a portion of a space defined by the reluctance voids. The magnet inserts and the reluctance voids are configured to cooperate with an electromagnetic field from a stator winding to produce an electromagnetic torque having a reluctance torque component and a magnetic torque component.
[0006] According to another aspect, a method for forming a rotor for an electric motor includes the steps of forming rotor laminations having reluctance portions removed from each of the rotor laminations to define connecting webs, stacking the rotor laminations to form a rotor body, wherein the connecting webs are aligned to define reluctance voids within the rotor body, positioning magnet inserts within the reluctance voids, disposing opposing end caps on the rotor body to enclose the reluctance voids, and overmolding the rotor body with an overmold material. The opposing end caps prevent infiltration of the overmold material into the reluctance voids.

[0007] These and other aspects, objects, and features of the present disclosure will be understood and appreciated by those skilled in the art upon studying the following specification, claims, and appended drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] In the drawings:

[0009] FIG. **1** is a perspective view of an electric motor that incorporates an aspect of the stator and rotor configurations described herein;

[0010] FIG. **2** is a schematic cross-sectional view of the electric motor of FIG. **1**, taken along line II-II;

[0011] FIG. **3** is a perspective view of a stator that incorporates an outer ring positioned around an outer circumference of teeth for a stator;

[0012] FIG. **4** is a partially exploded perspective view of the stator of FIG. **3**, with the stator separated from an overmold;

[0013] FIG. **5** is an exploded perspective view of the stator of FIG. **4**;

[0014] FIG. **6** is a schematic perspective view showing assembly of the stator teeth for the stator of FIG. **5** using the structural ring and stacked tooth laminations;

[0015] FIG. **7** is a top perspective view of the stator core of the stator of FIG. **5** is a side perspective view of a stack of tooth laminations that are positioned between adjacent structural rings for forming the stator of FIG. **2**;

[0016] FIG. **8** is an exploded perspective view of the stator core of FIG. **7**;

[0017] FIG. **9** is a schematic diagram illustrating assembly of the stator teeth of the stator core using structural rings and stacked tooth laminations;

[0018] FIG. **10** is a partially exploded view of a stator that incorporates a plurality of pre-wound tooth segments and showing the stator separated from an overmold;

[0019] FIG. **11** is an exploded perspective view of the stator of FIG. **10**;

[0020] FIG. **12** is an exploded perspective view of the stator core shown in FIG. **11**;

[0021] FIG. **13** is a perspective view of a pre-wound tooth segment of the stator of FIG. **10**;

[0022] FIG. **14** is an exploded perspective view of the pre-wound tooth segment of FIG. **13**;

[0023] FIG. **15** is a perspective view of a rotor that incorporated reluctance voids within a rotor body;

[0024] FIG. **16** is an exploded perspective view of the rotor of FIG. **15**;

[0025] FIG. **17** is a cross sectional view of the stator of FIG. **15** taken along XVII-XVII;

[0026] FIG. **18** is a cross sectional view of the stator of FIG. **15** taken along XVIII-XVIII;

[0027] FIG. **19** is a schematic flow diagram illustrating a method for forming a stator for an electric motor;

[0028] FIG. **20** is a schematic flow diagram illustrating a method for forming a stator for an electric motor;

[0029] FIG. **21** is a schematic flow diagram illustrating a method for forming a stator for an electric motor;

[0030] FIG. **22** is a perspective view of a rotor that incorporates magnet inserts within reluctance voids of a rotor body;

[0031] FIG. **23** is an exploded perspective view of a rotor of FIG. **22**;

[0032] FIG. **24** is a cross-sectional view of the rotor of FIG. **22** taken along the line XXIV-XXIV;

[0033] FIG. **25** is a cross-sectional view of the rotor of FIG. **22** taken along the line XXV-XXV;

[0034] FIG. **26** is a schematic cross-sectional view of a stator and rotor combination including an aspect of the rotor having linear reluctance voids in a two-pole rotor configuration;

[0035] FIG. **27** is a schematic diagram of the rotor and stator combination of FIG. **26** and showing a portion of the reluctance voids filled with magnet inserts;
[0036] FIG. **28** is a schematic cross-sectional view of the stator and rotor combination of FIG. **27** and showing additional magnet inserts disposed within the reluctance voids;
[0037] FIG. **29** is a schematic cross-sectional view of a stator and rotor combination showing a four-pole configuration of the ferrite-assisted reluctance rotor;
[0038] FIG. **30** is a schematic diagram illustrating an exemplary configuration of the magnet inserts disposed within the reluctance voids to produce a desired proportion of the magnetic torque component and the reluctance torque component;
[0039] FIG. **31** is a schematic diagram illustrating another exemplary configuration of the magnet inserts disposed within the reluctance voids to produce a desired proportion of the magnetic torque component and the reluctance torque component;
[0040] FIG. **32** is a schematic diagram illustrating another exemplary configuration of the magnet inserts disposed within the reluctance voids to produce a desired proportion of the magnetic torque component and the reluctance torque component;
[0041] FIG. **33** is a schematic cross-sectional view of a ferrite-assisted reluctance rotor having the reluctance voids entirely occupied by the magnet inserts;
[0042] FIG. **34** is a schematic cross-sectional view of a stator and rotor combination including an aspect of the ferrite-assisted reluctance rotor having a single cavity corresponding to each rotor pole; and
[0043] FIG. **35** is a schematic flow diagram illustrating a method for forming a rotor for an electric motor.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0044] As required, detailed embodiments of the present disclosure are disclosed herein; however, it is to be understood that the disclosed embodiments are merely exemplary of the invention that may be embodied in various and alternative forms. The figures are not necessarily to a detailed design; some schematics may be exaggerated or minimized to show function overview. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present invention.
[0045] For purposes of description herein, the terms “upper,” “lower,” “right,” “left,” “rear,” “front,” “vertical,” “horizontal,” and derivatives thereof shall relate to the concepts as oriented in FIGS. **1-35**. However, it is to be understood that the concepts may assume various alternative orientations, except where expressly specified to the contrary. It is also to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification are simply exemplary embodiments of the inventive concepts defined in the appended claims. Hence, specific dimensions and other physical characteristics relating to the embodiments disclosed herein are not to be considered as limiting, unless the claims expressly state otherwise.
[0046] The present illustrated embodiments reside primarily in combinations of method steps and apparatus components related to an electric motor having a formed and overmolded stator with pre-wound winding sections that are attached to the teeth of the stator and an overmolded rotor that includes reluctance voids that are contained between outer laminations and that are at least partially filled with magnet inserts. Accordingly, the apparatus components and method steps have been represented, where appropriate, by conventional symbols in the drawings, showing only those specific details that are pertinent to understanding the embodiments of the present disclosure so as not to obscure the disclosure with details that will be readily apparent to those of ordinary skill in the art having the benefit of the description herein. Further, like numerals in the description and drawings represent like elements.
[0047] As used herein, the term “and/or,” when used in a list of two or more items, means that any one of the listed items can be employed by itself, or any combination of two or more of the listed

items, can be employed. For example, if a composition is described as containing components A, B, and/or C, the composition can contain A alone; B alone; C alone; A and B in combination; A and C in combination; B and C in combination; or A, B, and C in combination.

[0048] In this document, relational terms, such as first and second, top and bottom, and the like, are used solely to distinguish one entity or action from another entity or action, without necessarily requiring or implying any actual such relationship or order between such entities or actions. The terms “comprises,” “comprising,” or any other variation thereof, are intended to cover a non-exclusive inclusion, such that a process, method, article, or apparatus that comprises a list of elements does not include only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. An element preceded by “comprises . . . a” does not, without more constraints, preclude the existence of additional identical elements in the process, method, article, or apparatus that comprises the element.

[0049] As used herein, the term “about” means that amounts, sizes, formulations, parameters, and other quantities and characteristics are not and need not be exact, but may be approximate and/or larger or smaller, as desired, reflecting tolerances, conversion factors, rounding off, measurement error and the like, and other factors known to those of skill in the art. When the term “about” is used in describing a value or an end-point of a range, the disclosure should be understood to include the specific value or end-point referred to. Whether or not a numerical value or end-point of a range in the specification recites “about,” the numerical value or end-point of a range is intended to include two embodiments: one modified by “about,” and one not modified by “about.” It will be further understood that the end-points of each of the ranges are significant both in relation to the other end-point, and independently of the other end-point.

[0050] The terms “substantial,” “substantially,” and variations thereof as used herein are intended to note that a described feature is equal or approximately equal to a value or description. For example, a “substantially planar” surface is intended to denote a surface that is planar or approximately planar. Moreover, “substantially” is intended to denote that two values are equal or approximately equal. In some embodiments, “substantially” may denote values within about 10% of each other, such as within about 5% of each other, or within about 2% of each other.

[0051] As used herein the terms “the,” “a,” or “an,” mean “at least one,” and should not be limited to “only one” unless explicitly indicated to the contrary. Thus, for example, reference to “a component” includes embodiments having two or more such components unless the context clearly indicates otherwise.

[0052] Referring now to FIGS. **1-35**, reference numeral **10** generally refers to a stator **10** that is incorporated within an electric motor **12**, where the stator **10** includes one or more windings **14** that are positioned on teeth **16** for the stator **10**. The windings **14** are energized to produce a magnetic field that rotates a rotor **18** that is positioned relative to the stator **10**. The windings **14** are typically energized by a controller that manages the delivery of an electrical current to the one or more phases of the winding **14**. The rotor **18** can be positioned within an inner circumference **20** of the stator **10** or can be positioned outside of the outer circumference **22** of the stator **10** depending upon the configuration of the electric motor **12**. Typically, the configurations described herein are directed to a rotor **18** that rotates within the inner circumference **20** of the stator **10**. Accordingly, the configurations described herein are directed to devices and methods for building a stator **10** and positioning a winding **14** for the stator **10** on an inner-rotor configuration motor **12**.

[0053] Referring now to FIGS. **3-9**, the motor **12** includes a stator **10** that is made up of a plurality of structural rings **24** that can define a number of stator teeth **16** that are included within the stator **10**. Tooth sections **26** are made up of stacks **28** of tooth laminations **30**. The stacks **28** of tooth laminations **30** are positioned within each tooth **16** and between adjacent structural rings **24**. Accordingly, each stator tooth **16** of the stator **10** is made up of an alternating configuration of structural rings **24** and stacks **28** of tooth laminations **30** that cooperate to form the stator teeth **16**. Bobbins **32** are positioned around a portion of each tooth **16** for the stator **10**. Winding sections **34** of electrically conducting material are slidably positioned over the bobbins **32**, respectively, for each tooth **16** of the stator **10**. At this point the winding sections **34** are separated from one another as they are installed onto the plurality of stator teeth, respectively. The winding sections **34** are coupled together to define a continuous winding **14** for the stator **10** that forms a plurality of stator poles **36** that are configured to be selectively energized to produce an electromagnetic field.

[0054] An outer ring **38** is positioned around the outer circumference **22** of the teeth **16** for the stator **10**. The outer ring **38** operates as a back iron **40** and also serves to contain the winding sections **34** within a stator cavity **42**. This stator cavity **42** is defined within the outer ring **38** and outside of the connecting portions **62** of the structural rings **24** that extend radially between adjacent stator teeth **16**. Stated another way, the stator cavity **42** is defined within the outer ring **38** and outside of a core **44** for the stator **10** from which the teeth **16** of the stator **10** extends, where the core **44** is made up of the connecting portions of the structural rings **24**. An overmold **46** extends around the outer ring **38**, the winding sections **34**, the plurality of teeth **16**, and the core **44** to form an overmolded stator **10**. In certain aspects of the device, the outer ring **38** can include alignment channels **52** that interact with alignment protrusions **54** of the tooth sections **26** that are made up of the structural rings **24** and the stacks of tooth laminations **30**. In this manner, the outer ring **38** can be aligned in one or more desired orientations with respect to the tooth sections **26** of the stator **10**. This can also be used as a securing device to ensure a secure fit between the outer ring **38** and the tooth sections **26** that form the stator cavity **42** that secured the winding sections **34**.

[0055] In certain aspects of the device, as exemplified in FIGS. **3-9**, the winding sections **34** can be connected together using a bus ring **48**. This bus ring **48** includes a plurality of connectors **50** that link particular winding sections **34** together. The connectors **50** attach to the wire ends **60** of the winding sections **34** to complete the winding **14**. Certain wire ends **60** are not attached to the connectors **50** so that they can be attached to the wiring for delivering current through the winding **14**. These wire ends **60** that are not connected to the connectors **50** of the bus ring **48** can be positioned to extend out from the overmold **46** to connect with the electrical leads to and from the power source. The winding sections **34** are coupled together by the bus ring **48** that defines subsets **64** of the winding sections **34**. These subsets **64** form the various phases of the winding **14** that are in electrical communication with one another. The bus ring **48** includes a plurality of winding connections **72** that form the subsets **64** of the winding sections **34**. Again, the subsets **64** of the winding sections **34** correspond to phases of the plurality of stator poles **36**. By way of example, and not limitation, the plurality of winding connections **72** can include three winding connections that correspond to three phases of the plurality of stator poles **36**. The winding connections **72** of the bus ring **48**, to define the various phases, are typically separated by an insulating spacer **82** that electrically separates the winding connections **72**. The insulating spacers **82** provide for the delivery of dedicated and separate electrical currents to the subsets **64** of winding sections **34** to produce the multi-phase operation of the stator **10**.

[0056] Through this configuration, the stator **10**, being an inner-rotor configuration, is able to be wound from the outer circumference **22** before the outer ring **38** is placed around the winding sections **34**. The outer ring **38** can then be placed around the stator **10** to contain the winding sections **34** on the teeth **16** of the stator **10**. This configuration allows the inner-rotor configuration of the stator **10** to be manufactured, without the need to locate the windings **14** within the confined space inside the rotor cavity **74** of the stator **10**. Additionally, the windings **14** can be applied as the pre-wound winding sections **34**, as is described more fully herein.

[0057] According to the various aspects of the device, as exemplified in FIGS. **4** and **5**, the winding sections **34** that are slidably positioned over each bobbin **32** and over each tooth **16** for the stator **10** can be pre-wound as a formed winding section **34**. Each winding section **34** is then placed over a bobbin **32** for a respective tooth **16** of the stator **10**. In certain aspects of the device, the winding section **34** can be placed on the bobbin **32** and the bobbin **32**, having the winding section **34** thereon, can be placed on the respective tooth **16** of the stator **10**. Accordingly, the winding section

34 and the corresponding bobbin **32** member form a bobbin assembly **76** that is placed, as a single component, over a corresponding stator tooth **16**. Using this configuration, a plurality of winding sections **34** and a plurality of bobbins **32** can be pre-manufactured and paired for installation on the stator teeth **16**. Wire ends **60** extend from each winding section **34** can be connected to the adjacent winding sections **34** to form one or more continuous windings **14** that extend around the stator **10**. After the winding sections **34** are connected together to form the continuous winding or windings **14**, the overmold **46** is defined by placing an overmold material over the components to form the now insulated stator **10**.

[0058] As exemplified in FIGS. **3-9**, the various bobbins **32** that extend over the teeth **16** for the stator **10** can be formed by one or more bobbin sections **70** or end caps that are slidably positioned over each tooth **16** having an enlarged tooth end **108**. As exemplified in FIGS. **13-14**, in various aspects of the device, the bobbin **32** can include two opposing bobbin sections **70** that slide over and encircle each tooth **16** and behind the tooth end from opposing directions, such as from above and below, or from side to side, to form the complete structure of the bobbin **32**. The winding section **34** of electrically conducting material is then positioned over the two-piece, or multi-piece, bobbin **32**. The winding section **34** can be wound around the bobbin sections **70** or, where the tooth does not include the enlarged tooth end, can be slidably installed on the bobbin sections **70**. The bobbin **32** serves to insulate the winding section **34** from the material of the stacks **28** of tooth laminations **30** and the structural rings **24** that form each tooth **16** for the stator **10**. In certain aspects of the device, such as where the tooth **16** does not have the enlarged tooth end **108**, a single-piece bobbin **32** can be used in place of the multi-part bobbin **32** having the bobbin sections **70**. In such an aspect of the device, the pre-wound winding section **34** can also be slidably disposed in the bobbin **32**.

[0059] Referring again to FIGS. **3-9**, during formation of the stator **10**, a die **130** in the shape of the finished stator **10** can be used for assembling the various components that make up the stator **10**. Within the die, a first outer structural ring **80** can be positioned within a base of a die. Tooth laminations **30** can then be added around the die in the position for each tooth **16** of the stator **10**. These tooth laminations **30** can be positioned one at a time for each tooth **16** or multiple tooth laminations **30** formed into a stack **28** can be positioned within each die as the various teeth **16** for the stator **10** are built up within the die. The number of tooth laminations **30** within a stack **28** can vary depending on the design of the stator **10**. Typically, the number of tooth laminations **30** stacked between adjacent structural rings **24** will be consistent. This is to ensure that the structural rings **24** are generally parallel through the stator **10**. The number of tooth laminations **30** in a particular stack **28** can be within a range of from approximately 3 tooth laminations to approximately 10 tooth laminations; or from between approximately 5 tooth laminations to approximately 8 tooth laminations; or from approximately 2 tooth laminations to approximately 15 tooth laminations.

[0060] Referring again to FIG. **9**, typically, a sheet of metallic stock is moved over the die. Successively, the structural rings **24** and the tooth laminations **30** are punched out of the sheet of metallic stock and directed into the die. This sheet stock is made of the ferrous metal that forms the stator **10**, as described herein. Using the metal stock, the stator **10** is built layer by layer. The structural ring **24** is punched and disposed in the die. Subsequently, successive layers of the punched tooth laminations **30** are directed into the cavity of the die. In addition, with each punched portion of the sheet of metal stock, an alignment protrusion **90** is punched in each lamination that forms one of the teeth **16** for the stator **10**. These protrusions **90** operate in a nesting configuration to lock the layers together to structurally support the stator **10**. In this manner, the process of stamping the components of the stator **10** and forming these components into the stator **10** is combined into a single operation.

[0061] During formation of the stator **10**, the assembly includes two punch configurations. One punch operates to form the structural rings **24** from the sheet of metallic stock. Another punch operates to form the layer of tooth laminations **30**. As the stator **10** is built up, layer by layer, the appropriate punch is positioned over the die to punch the next layer of the stator **10** into the die. Again, the punched components are directed into the die immediately after being punched.

[0062] During this assembly of the stator **10**, the layers of tooth laminations **30** are successively punched into the die to form the stacks **28** of tooth laminations **30** for each tooth **16**. Accordingly, these stacks **28** of tooth laminations **30** are formed contemporaneously to maintain a consistent height of each tooth **16** during assembly of the stator **10**. Stated another way, as the stator **10** is built up, each position of the die receives one tooth lamination **30** from the sheet of metal stock. In certain aspects of the device, multiple sheets can be punched simultaneously such that the same number of tooth laminations **30** are placed in the die. The structural ring **24** is then punched to rest on a predetermined number of tooth laminations **30** for the plurality of teeth **16** so that each structural ring **24** rests evenly on the various stacks **28** of tooth laminations **30**. In this manner, as the teeth **16** for the stator **10** are built up, the laminations and the structural rings **24** are allocated evenly among the tooth **16** positions of the die.

[0063] Periodically, additional structural rings **24** are positioned over stacks **28** of tooth laminations **30** to reinforce the structure of the stator **10**. When the desired height of the stator **10** is achieved, a final outer structural ring **80** is positioned on the stacks **28** of tooth laminations **30** and at the top of the stator **10** to complete the structure of the stator **10**. Through this configuration, the stator **10** is formed from a plurality of tooth laminations **30** that are positioned and reinforced through the use of the intermittent structural rings **24** and a pair of outer structural rings **80**.

[0064] To assist in the assembly of the various tooth laminations **30** and structural rings **24** for the stator **10**, each tooth lamination **30** of the various stator teeth **16** and a portion of the structural rings **24** can be punched to form a protrusion **90**. Each protrusion **90** forms a nesting configuration with the adjacent tooth laminations **30**. This nesting configuration further positions and reinforces the structure of the stator **10**. These protrusions **90** can also act as a locating feature for ensuring that the stacks **28** of tooth laminations **30** are properly aligned with respect to the other tooth laminations **30** as well as the structural rings **24** that form the stator **10**. Through the use of the protrusions **90**, lateral displacement or misalignment of the tooth laminations **30** and the structural rings **24** is largely minimized or eliminated.

[0065] Referring now to FIGS. **10-14**, the stator **10** can include a plurality of tooth segments **100**. Each tooth segment **100** can be formed from a plurality of tooth laminations **30** that are stacked to form a desired tooth height for the teeth **16** of the stator **10**. After the stacked tooth laminations **30** are positioned to form each tooth segment **100**, a bobbin **32** is slidably positioned over a tooth portion **102** of the tooth segment **100**. A pre-wound tooth winding **14** is then slidably positioned over the bobbin **32** to form a pre-wound stator segment **106**.

[0066] As discussed herein, the winding section **34** can be placed in the bobbin **32** and the assembled bobbin **32** and winding section **34** can be placed onto the tooth portion **102** of the tooth segment **100** to form a stator segment **106**. Each pre-wound stator segment **106** having the pre-attached bobbin **32** and winding section **34** is then coupled to two adjacent pre-wound stator segments **106** to form a stator core **44** with a plurality of pre-wound stator poles **36** that extend inward from the stator core **44**. Core portions **104** of the tooth segments **100** include mating geometries that interlock to form the core **44** of the stator **10**. The winding sections **34** of each tooth segment **100** are then connected together to form one or more windings **14** of the stator **10**. In this manner, a respective winding section **34** of a stator segment **106** is coupled with corresponding winding sections **34** to form a phase of the winding **14** of the plurality of stator segments **106**. Typically, the winding **14** has three phases. The phases of the winding **14** and the winding **14** in general defines a plurality of stator poles **36** that are configured to be selectively energized. After the windings **14** are attached together in the desired configuration, an overmold material is disposed over the plurality of stator segments **106** to form an overmold **46** for the stator **10**, which is insulated by the overmold **46**. In certain aspects of the device, the individual winding sections **34** can be attached together after the overmold **46** is complete. In such a configuration, the wire ends **60** of each winding section **34** can protrude from the overmold **46** and be connected together to form the desired winding configuration.

[0067] According to various aspects of the device, the desired winding configuration can be in the form of a single-phase winding **14**, a three-phase winding **14**, stepper motor **12**, or other similar motor configuration. Typically, the winding sections **34** are attached together prior to applying the overmold material that forms the insulated stator **10**. As discussed herein the bus ring **48** that is used to attach the winding sections **34** together can be used to define the phase configuration of the winding **14**. The bus ring **48** can be in the form of one or more busbars or other similar electrical bracket that is formed into a circular shape to match the profile of the stator **10**. The various busbars of the bus ring **48** for dedicated connections with the various winding sections **34** for defining the phases of the windings **14** of the stator **10**.

[0068] Use of the pre-wound winding sections **34** that are attached to tooth sections **26** of the stator **10** provides for more efficient winding of the desired motor configurations. In particular, the winding configurations described herein can achieve a more efficient fill of the slots **110** that are defined between the teeth **16** of the stator **10**. Additionally, the configurations described herein allow for the use of larger gauge wire for the pre-wound winding sections **34**. Larger gauged wire can be used since the assembly for winding the stator **10** does not need to weave between a stator core **44** having pre-positioned teeth **16** that may be difficult to navigate around and between. The pre-wound winding sections **34** can be formed into the desired shape and can then be slidably disposed onto a respective tooth **16** of the stator **10** or tooth portion **102** of a tooth segment **100**. This pre-assembled configuration of the stator segments **106** allows for the finished winding **14** to occupy more of each slot **110** as room is not needed to accommodate an assembly for weaving the wire for the winding **14** around the teeth **16** of the stator **10**.

[0069] Additionally, the motor **12** formed through the stator **10** described herein does not require the use of rare earth materials similar to permanent magnet motors. Competitive power density is achieved without the use of permanent magnets. Also, the insulated construction described herein through the use of the insulating overmold **46** allows for exposure to corrosive environments without damage to the components of the stator **10** that are surrounded by the overmold material. Because the stator **10** described herein utilizes higher gauge wire and has an increased fill of the slots **110** between the teeth **16**, power density is not lost as compared to other conventional electric motor systems.

[0070] According to the various aspects of the device, the configurations of the stator **10** described herein can be used with any one of various rotors **18**, including the rotor **18** configurations described herein. Additionally, the disclosure of the rotor **18** having the reluctance voids **122**, as described herein, is provided as an exemplary and non-limiting type of rotor **18** that can be used in connection with the stator **10** configurations described herein, as well as other types of stators **10**.

[0071] Referring now to FIGS. **2**, **15-18**, and **22-34**, the rotor **18** for the synchronous reluctance motor **12** includes a stack **28** of rotor laminations **120** that are typically made from an electrical grade steel to form a rotor body **140**. Reluctance voids **122** are punched from the rotor laminations **120** that form the rotor body **140** of the rotor **18**. The reluctance voids **122** can also be punched as part of each rotor lamination **120**. A single end lamination **124** can be positioned at each opposing end of the rotor **18** to act as a cover. The opposing end laminations **124** are generally solid within the cross section of the rotor **18** and do not include the reluctance voids **122**. The opposing end laminations **124** are installed to prevent windage noise that may otherwise occur if the reluctance voids **122** are exposed. Space is typically provided for a drive member, such as a drive shaft. After placement of the end laminations **124**, the rotor **18** is then encapsulated with an overmold material that at least partially encapsulates the outer surface **126** of the rotor **18** to form a rotor overmold **128**. Typically, the overmold material is in the form of a non-metallic resin material. The resin may also be in the form of a non-magnetic material, such as resin, a polymer, or other similar overmold materials. Because the ends of the rotor **18** are covered by the end laminations **124**, the overmold material is not able to infiltrate into the reluctance voids **122**. With the reluctance voids **122** being free of the overmold material, the rotor **18** remains balanced with a consistent thickness of the overmold around the rotor body **140**. Infiltration of the overmold material into one or more of the reluctance voids **122** can have the effect of causing an imbalance in the rotor **18** that may result in unwanted vibration or wobbling. Accordingly, the shape and size of the reluctance voids **122** can be maintained throughout the assembly and overmold process of the rotor **18**. The use of the overmold around the rotor body **140** also limits the occurrence of corrosion within the rotor laminations **120** and the opposing end laminations **124**.

[0072] As described herein, the reluctance voids **122** can be maintained as hollow spaces within the rotor body **140**. Additionally, magnet inserts **162** can be installed within one or more of the reluctance voids **122**. These magnet inserts **162** can partially or fully occupy the space defined by the reluctance voids **122**. The presence of the magnet inserts **162** and the size of the magnet inserts **162** relative to the space defined by the reluctance voids **122** can vary as particular magnetic interaction is desired between the electromagnetic field **164** of the charged winding **14** and the rotor **18** for operating the rotor **18** within the stator **10**.

[0073] Referring now to FIGS. **15-18**, during formation of the rotor **18** having the hollow reluctance voids **122**, the connecting webs **150** of the rotor body that define the reluctance voids **122** can be demagnetized, or at least partially demagnetized, to increase the reluctance properties of the rotor **18**. Stated another way, demagnetizing the connecting webs **150** decreases the reluctance of the connecting webs **150** to, in turn, provide a more defined path of least reluctance **152** through which the magnetic flux **154** can flow through the rotor **18**. This demagnetization of the connecting webs **150** has the effect of making the interaction more effective between the electromagnetic field **164** produced by the stator **10** and the rotor **18**. The demagnetization of the rotor can be accomplished through localized heating, such as with a laser or other heat source, or by imparting additional induced mechanical stresses within the rotor body.

[0074] Referring still to FIGS. **15-18**, during operation of the stator **10** and rotor **18**, the controller operates to control the delivery of electrical current to the one or more phases of the winding **14**. The controller can also operate in conjunction with a position sensor that monitors the rotational position of the rotor **18** with respect to the stator **10** or the one or more windings **14** of the stator **10**. Commutation of the electrical current can be accomplished by electrically energizing the electromagnetic phases of the winding **14** to selectively attract and align the reluctance of the rotor **18** in a desired direction to induce rotation of the rotor **18**. Additionally, sensor feedback of the position of the rotor **18** delivered to the controller permits a smooth and controllable electrical current to the windings **14**. This, in turn, can be used to control the speed and torque output of the motor **12**.

[0075] In certain aspects of the device, the controller operates in a sensorless configuration. In an exemplary and non-limiting aspect of the device, a voltage sensor or voltage monitor can be used at the centerpoint of the back Electro-Motive Force (EMF) voltage. This is compared to typically half of the supplied DC bus voltage to calculate the relative inductances for determining the position of the rotor **18** with respect to the phases of the winding **14**. When the position of the rotor **18** is known, a smooth and controllable electrical current to the windings **14** can be used to control the speed and torque of the motor **12** without separate position sensing components.

[0076] Referring now to FIGS. **1-19**, having described various aspects of the stator **10** and rotor **18** for the electric motor **12**, a method **400** is disclosed for forming a stator **10** for an electric motor **12**. According to the method **400**, a step **402** includes placing a bottom outer structural ring **80** within a die. Layers of stacked tooth laminations **30** are then placed onto the bottom outer structural ring **80** (step **404**). Intermittent structural rings **24** are placed in an alternating configuration between adjacent layers of stacked tooth laminations **30** (step **406**). As discussed herein, the various tooth laminations **30** are positioned in a contemporaneous fashion with respect to each tooth **16** to maintain a consistent height of each tooth **16** for the stator **10** during assembly of the stator **10**. A top outer structural ring **80** is then placed on a top layer of the layers of stacked tooth laminations **30** to form the laminated stator **10** (step **408**). The laminated stator **10** is then removed from the die (step **410**). A bobbin assembly **76** is positioned on each tooth **16** of the laminated stator **10** (step **412**). As described herein, the bobbin **32** can be in the form of a single-piece bobbin **32** or a multi-part bobbin **32** that can be assembled over each tooth **16** of the laminated stator **10**. The bobbin assembly **76** can include the bobbin **32** and the pre-wound winding section **34** that can be slidably disposed into the tooth **16** as a single assembly. It is contemplated that the bobbin **32** and the winding section **34** can be sequentially disposed onto the tooth **16**, in an alternative aspect. With all of the bobbin assemblies **76** installed on the stator teeth **16**, the winding sections **34** form a segmented stator winding. The pre-wound winding sections **34** of the segmented stator winding are then attached using the bus ring **48** to form the completed stator winding **14** (step **414**). An outer ring **38** is placed around the stator winding **14** and the laminated stator **10** (step **416**). This outer ring **38** prevents outward movement of the winding sections **34** along each tooth **16** for the stator **10**. The laminated stator **10** and the stator winding **14** are then overmolded with an overmold material (step **418**). As described herein, the use of pre-wound winding sections **34** provides for greater slot fill and also provides for the use of larger gauge wire that can produce more effective electromagnetic field when energized with an electrical current.

[0077] As part of the method **400** for forming the stator **10**, the structural rings **24** and the tooth laminations **30** can be made to be less magnetic. By way of example and not limitation, the thin sections, such as the connecting portions of the structural rings **24**, can be metallurgically changed to be less magnetic. This is typically performed through heating the steel, such as through use of a laser. In certain aspects of the device, the connecting portions of the structural rings **24** can be upset using a laser or through mechanical de-bridging means to diminish or eliminate the magnetic effect that may be produced by the presence of the connecting portions. It is contemplated that only a portion of the connecting portion are upset or removed to provide structure to the stator **10**.

[0078] Referring now to FIGS. **1-18** and **20**, having described various aspects of the electric motor **12**, a method **500** is disclosed for forming a stator **10** for the electric motor **12**. According to the method **500**, laminated tooth sections **26** are formed (step **502**). A bobbin **32** is placed onto a tooth portion **102** of each of the laminated tooth segment **100** (step **504**). The pre-wound winding section **34** is then placed on the tooth portion **102** of each laminated tooth segment **100** and over the respective bobbin **32** (step **506**). The laminated tooth segments **100** having the pre-wound winding section **34** are then attached together to form a circular core **44** of the stator **10** (step **508**). The pre-wound winding sections **34** are then attached together to form the desired configuration of winding **14** for the stator **10** (step **510**). The core **44**, the teeth **16** and the windings **14** are then overmolded using an overmold material (step **512**).

[0079] Typically, use of the laminated winding sections **34** that are pre-wound and then attached together is utilized in an inner-rotor configuration that is generally exemplified in FIGS. **11-18**. The star configuration of the structural rings **24** for the stator **10**, exemplified in FIG. **4**, can be used in an inner-rotor configuration or an outer-rotor configuration depending upon the design of the motor **12**.

[0080] Referring now to FIGS. **1-18** and **21**, having described various aspects of the device, a method **600** is disclosed for forming a rotor **18** for an electric motor **12**. According to the method **600**, steel rotor laminations **120** are formed having sections removed from each of the rotor laminations **120** to form reluctance voids **122** (step **602**). The rotor laminations **120** are stacked to form the structure of the rotor **18** (step **604**). The sections of the rotor laminations that are removed are arranged or otherwise aligned to define reluctance voids **122** within the rotor **18**. Opposing end laminations **124** or end caps are then disposed on ends of the rotor **18** to enclose the reluctance voids **122** (step **606**). As discussed herein, closure of the reluctance voids **122** prevents infiltration of overmold material from entering into and occupying the reluctance voids **122**. The rotor **18** is then overmolded with an overmold material (step **608**). The opposing end laminations **124**, as described herein, prevent infiltration of the overmold material into the reluctance voids **122**. This infiltration of overmold material can negatively affect the operation and efficiency of the reluctance voids **122** when operated in conjunction with the energized windings **14** of the stator **10**.

[0081] The assembly methods described herein for the synchronous reluctance motor **12** allow for bobbin winding of the motor assembly that offers additional and more efficient fill of the slots **110** for the stator **10**. The configurations described herein also allow for more efficient use and easier winding of heavier gauge wire and improved slot fill over conventional needle-wound stators **10**. Overmolding of the stator **10** and overmolding of the rotor **18** allows for the motor **12** to be exposed to corrosive fluids without corroding the ferrous stator **10** or the ferrous rotor **18**. Additionally, as described herein, closing each end of the stack **28** of rotor laminations **120** before overmolding prevents the injection molded non-metallic resin material from flowing into the reluctance voids **122**. This infiltration can cause potential rotor imbalance. The use of overmolding with respect to the rotor **18** provides a smooth overmold surface that lowers windage noise that can be caused from voids **122** in the rotor **18** as well as an elimination of “paddle” resistance within wet rotor designs, especially where the voids **122** are exposed to the fluids that may cause increased drag on the rotor **18** as it rotates with a wet-rotor setting.

[0082] Additionally, when the non-metallic resin material is overmolded to surround the stator **10** and the windings **14**, the overmold material is configured to at least partially encapsulate the inner diameter of the stator teeth **16**. As described herein, this configuration provides for use of the stator **10** within liquid and corrosive environments. Use of the overmold **46** at the inner diameter of the stator teeth **16** prevents these materials from corroding or otherwise damaging the laminations of the stator **10**.

[0083] Referring now to FIGS. **22-34**, the electric motor **12** can include a stator **10** having one or more windings **14** that when selectively energized produces an electromagnetic field **164** within a rotor cavity **74**. A ferrite-assisted reluctance rotor **160** is disposed within the rotor cavity **74** of the stator **10**. This ferrite-assisted reluctance rotor **160** is in electromagnetic communication with the windings **14** and the electromagnetic field **164** produced thereby. The ferrite-assisted reluctance rotor **160** can include a drive shaft **202** and a rotor body **140** that extends around the drive shaft **202**. The rotor body **140** can define the plurality of reluctance voids **122**. Magnet inserts **162** can be positioned within the reluctance voids **122**. The magnet inserts **162** occupy at least a portion of the space defined by the reluctance voids **122**. The magnet inserts **162** and reluctance voids **122** cooperate with the electromagnetic field **164** to produce an electromagnetic torque **170**.

[0084] Referring again to FIGS. **22-34**, the electromagnetic torque **170** produced by the ferrite-assisted reluctance rotor **160** includes the magnetic torque components **172** that is defined by electromagnetic interaction between the electromagnetic field **164** and the magnet inserts **162**. In addition, the electromagnetic torque **170** includes the reluctance torque component **174** that is defined by an electromagnetic interaction between connecting webs **150** that define the reluctance voids **122** and the electromagnetic field **164**. As described herein, the connecting webs **150** define the path of least reluctance **152** through which the magnetic flux **154** tends to travel, and, in turn, align the flux path with the electromagnetic field **164** to generate the reluctance torque component **174** of the electromagnetic torque **170**. The combination of this magnetic torque component **172** and the reluctance torque component **174**, taken together, produce the entire electromagnetic torque **170** of the rotor **18**.

[0085] According to the various aspects of the device, the reluctance torque component **174** can be within a range of from approximately 20% to approximately 60% of the entire electromagnetic torque **170**. It is also contemplated that the reluctance torque component **174** can be from approximately 30% to approximately 50% of the entire electromagnetic torque **170**. It is further contemplated that the reluctance torque component **174** can be approximately 40% of the entire electromagnetic torque **170**. It should be understood that the ranges of the ratio of the reluctance torque component **174** and the magnetic torque component **172** can be achieved through various configurations of the reluctance voids **122** and the magnet inserts **162**, as will be described more fully herein.

[0086] Using the combination of the reluctance voids **122** and the magnet inserts **162**, the ferrite-assisted reluctance rotor **160** produces a hybrid torque configuration that includes both the reluctance torque component **174** and the magnetic torque component **172**. Using this configuration, the magnet inserts **162** can be made of a range of magnetic material, other than rare-earth magnets, and still produce an electromagnetic torque **170** that is similar in performance to conventional brushless DC (BLDC) electric motors **12** using rare-earth magnets. In this manner, the hybrid ferrite-assisted reluctance rotor **160** described herein produces similar electromagnetic torque **170**, using magnets having a lower magnetic output, as compared to conventional motors that use more expensive rare-earth magnets that have a greater magnetic output. The use of the magnet inserts **162**, in part, is used to produce a back electromagnetic force (Back EMF). As described herein, by creating the Back EMF within the motor **12**, a sensorless control can be implemented for monitoring the rotational position of the rotor **18** with respect to the stator **10** and the electromagnetic field **164**. Accordingly, the lower output magnet inserts **162** are effective at producing the desired magnetic torque component **172**, while also generating the Back EMF needed for the sensorless control. These advantages of the motor **12** described herein are achieved by using relatively low cost materials for the magnet inserts **162**.

[0087] In addition, to achieve these advantages of the motor **12** described herein, the magnet inserts **162** can be designed and installed to occupy only a portion of the reluctance voids **122**. Also, for the reluctance voids **122** that do include a magnet insert **162**, the magnet insert **162** may only occupy a portion of the space defined by the reluctance void **122**. Accordingly, the reluctance voids **122** typically contain a combination of air and the magnet inserts **162**.

[0088] According to the various aspects of the device, as exemplified in FIGS. **15-18** and **23-28**, the reluctance voids **122** can be positioned in a two-pole configuration. In this configuration, the reluctance voids **122** are oriented in a generally parallel configuration with respect to a central plane **220** of the rotor body **140**. The reluctance voids **122** can include enlarged outer sections **222** of the reluctance voids **122**. A central section **224** of the reluctance voids **122** can include an arcuate section **226** that extends congruently about the drive shaft **202** of the rotor **18**. In this manner, the generally parallel configuration extends along the central plane **220** of the rotor body **140**. These reluctance voids **122** in the generally parallel configuration can be linear and parallel with one another. The reluctance voids **122** in the generally parallel configuration may also include undulations **230** that conform to the geometry of the rotor body **140** and the drive shaft **202**. In this manner, the central plane **220** of the rotor body **140** that extends along the central axis **232** of the two-pole configuration is accentuated to define the path of least reluctance **152** for defining the reluctance torque component **174** or the electromagnetic torque **170** of the motor **12**. Additionally, in areas where the reluctance voids **122** are larger, such as proximate the enlarged outer sections **222**, the connecting webs **150** have a smaller thickness. This smaller thickness can be used to more precisely define the paths of least reluctance that can interact with the stator poles **36** of the stator **10** and the aspects of the electromagnetic field **164**. This configuration can be used to provide greater resolution of the ferrite-assisted reluctance rotor **160** as the rotor **18** operates within the stator **10**.

[0089] Studies of the disclosed device have shown that this comparable output between the hybrid ferrite-assisted reluctance rotor **160** described herein and conventional BLDC rotors **18** can be achieved through a comparable electrical input. Accordingly, the overall system utilizing the hybrid ferrite-assisted reluctance rotor **160** provides greater efficiency and produces electromagnetic torque **170** using less costly magnetic material having a lesser magnetic output.

[0090] According to various aspects of the device, as exemplified in FIGS. **22-34**, the ferrite-assisted reluctance rotor **160** achieves similar performance, with respect to electromagnetic torque

170, as compared to conventional BLDC motors that utilize more costly rare-earth magnets. In addition, the inclusion of the magnet inserts **162** within the ferrite-assisted reluctance rotor **160** produces the Back EMF. The generation of Back EMF by the magnet inserts **162** allows the ferrite-assisted reluctance rotor **160** to be used in combination with a sensorless configuration of electric motors **12**. Conventional reluctance rotors **18** require a sensor to determine the rotational position of the rotor **18** within the rotor cavity **74** at any particular time. Again, the inclusion of the magnet inserts **162** within the ferrite-assisted reluctance rotor **160** produces the Back EMF to provide for a sensorless operation of the ferrite-assisted reluctance rotor **160**.

[0091] According to various aspects of the device, the air gap **180** defined between the outer surface **126** of the rotor **18** and the inner surface of the stator **10** may increase in the ferrite-assisted reluctance rotor **160**. The inclusion of the magnetic torque component **172** of the electromagnetic torque **170**, in combination with the reluctance torque components **174** of the electromagnetic torque **170**, can provide for a greater tolerance in the air gap **180** thickness. This increased tolerance can provide for an increased air gap **180**, as compared to conventional reluctance rotors **18**. This may also serve to decrease the noise produced by the ferrite-assisted reluctance rotor **160** due to the wider tolerance and air gap **180** between the ferrite-assisted reluctance rotor **160** and stator **10**. At the same time, the configuration of the enlarged outer sections **222** of the reluctance voids **122**, and, where present, the magnet inserts **162**, assists in providing this greater resolution of the ferrite-assisted reluctance rotor **160** with respect to the stator poles **36**.

[0092] According to various aspects of the device, as exemplified in FIGS. **24-34**, the magnet inserts **162** can occupy a portion of the reluctance voids **122** or can occupy the entirety of the reluctance voids **122**. Various ratios of air space within the reluctance voids **122** as compared to the space occupied by the magnet inserts **162** can achieve varying ranges of electromagnetic torque **170** and different ratios of the reluctance torque component **174** and the magnetic torque component **172**. Additionally, placement of the magnet inserts **162** within the enlarged outer section **222** and/or the arcuate section **226** of the two-pole configuration of the rotor **18** can also be used to adjust the ratio of the reluctance torque component **174** and the magnetic torque component **172**.

[0093] As described herein, the reluctance voids **122** of the ferrite-assisted reluctance rotor **160** can be positioned in the two-pole configuration (exemplified in FIGS. **24-28**), a four-pole configuration (exemplified in FIGS. **29-34**), and other pole configurations within the ferrite-assisted reluctance rotor **160**. The configuration of the reluctance voids **122** and the magnet inserts **162** of the ferrite-assisted reluctance rotor **160** can vary depending upon the design of the stator **10**, the stator windings **14**, and other components of the electric motor **12**. As described herein, the reluctance voids **122** and the magnet inserts **162** cooperate to define a plurality of rotor poles that can be manufactured in a variety of configurations. The two-pole configuration, as described herein, can include a generally parallel configuration of the reluctance voids **122**. The generally parallel configuration of the reluctance voids **122** tends to align with a central plane **220** of the rotor body **140**. This central plane **220** tends to align with an axis of symmetry **240** of the reluctance voids **122**. The four-pole configuration of the reluctance voids **122** tends to define a series of arcuate sections **226** that extend in a symmetrical and non-concentric configuration about a central axis **232** of the drive shaft **228** of the rotor **18**.

[0094] According to various aspects of the device, the magnetic poles that are formed within the hybrid ferrite-assisted reluctance rotor **160** can be made up of a plurality of magnet inserts **162** that are positioned within a plurality of corresponding reluctance voids **122**. It is also contemplated that each magnet pole of the plurality of magnet poles can include a single magnet insert **162** that is positioned within a corresponding reluctance void **122** (as shown in FIG. **34**).

[0095] Referring again to FIGS. **22-34**, the rotor body **140** includes a plurality of stacked rotor laminations **120**. Each lamination of the plurality of stacked rotor laminations **120** includes connecting webs **150** that align to form the reluctance voids **122**. Stated another way, when configured as the plurality of stacked rotor laminations **120**, the connecting webs **150** of each rotor lamination **120** align with one another to form reluctance voids **122** that extend substantially through the rotor body **140**, or entirely through the rotor body **140**.

[0096] It should be understood that use of the term substantially through the rotor body **140** in this context indicates that at least one end of the rotor body **140** defines apertures that provide access into the reluctance voids **122** for disposing the magnet inserts **162** into the reluctance voids **122**. The reluctance voids **122** may extend the majority of the distance through the rotor body **140** or may extend through the majority of the stacked rotor laminations **120**. In certain aspects of the device, the ferrite-assisted reluctance rotor **160** may include reluctance voids **122** that are accessible from each end of the rotor body **140**, or may be accessible from only one end of the rotor body **140**. Still further, the rotor body **140** may have a first set of reluctance voids **122** that are accessible from one end of the rotor body **140** and a second set of reluctance voids **122** that are accessible from an opposing end of the rotor body **140**.

[0097] The magnet inserts **162** of the ferrite-assisted reluctance rotor **160** can be made of various magnetic materials that are typically in the form of Aluminum Nickel Cobalt (AlNiCo) magnets, ferrite magnets, and other similar magnets. Typically, the magnet inserts **162** are free of rare-earth magnets. As discussed herein, the configuration of the ferrite-assisted reluctance rotor **160** achieves a comparable electromagnetic torque **170** without the need for using rare-earth magnets. Accordingly, the ferrite-assisted reluctance rotor **160** can be manufactured while using non-rare-earth magnets to achieve a comparable electromagnetic torque **170**.

[0098] To contain the magnet inserts **162** within the rotor body **140**, opposing end laminations **124** can be positioned at opposing ends of the rotor body **140** to close off the reluctance voids **122**. The opposing end laminations **124** are configured to reduce windage noise during operation of the rotor **18** within the rotor cavity **74**. This is particularly true where the magnet inserts **162** occupy only a portion of the reluctance voids **122** within the rotor body **140** and empty space exits within the reluctance voids **122**. Additionally, the end laminations **124** provide closure of the reluctance voids **122** such that the overmold material of the rotor overmold **128** disposed around the rotor body **140** does not infiltrate into the reluctance voids **122** during manufacture of the ferrite-assisted reluctance rotor **160**.

[0099] According to the various aspects of the device, the ferrite-assisted reluctance rotor **160** that includes the reluctance voids **122** as well as the magnet inserts **162** provides for a hybrid operation of the ferrite-assisted reluctance rotor **160** with respect to an electromagnetic field **164** produced by an energized winding **14** of the stator **10**. The reluctance portion **190** of the ferrite-assisted reluctance rotor **160** that extends around the reluctance voids **122** produces the reluctance path around the reluctance voids **122** and through the rotor body **140**. The rotor **18** tends to align with the electromagnetic field **164** to produce a path of least reluctance **152** such that a reluctance path of the ferrite-assisted reluctance rotor **160** tends toward an aligned orientation with respect to the electromagnetic field **164** of the stator **10**. Contemporaneously, the magnet inserts **162** that are disposed within the reluctance voids **122** provide for a separate interaction with the electromagnetic field **164** of the stator **10**. In this manner, the magnetic field of the respective magnet inserts **162** tends toward an aligned orientation with respect to the electromagnetic field **164** of the energized portion of the winding **14** of the stator **10**. The path of least reluctance **152** and the magnetic fields of the magnet inserts **162** are at different radial positions with respect to the ferrite-assisted reluctance rotor **160**. Accordingly, the magnetic fields of the magnet inserts **162** and the paths of least reluctance **152**, also referred to herein as the reluctance portions **190** of the rotor body **140** each tend to align, separately, but in cooperation, with an energized portion of the winding **14** for the stator **10**. This provides for numerous electromagnetic interactions between the ferrite-assisted reluctance rotor **160** and the stator **10** to produce the hybrid electromagnetic torque **170**.

[0100] Again, as discussed herein, the electromagnetic torque **170** is made up of the reluctance torque components **174** that occurs by the tendency for the reluctance portions **190**, or the paths of least reluctance **152**, of the ferrite-assisted reluctance rotor **160** to align with the electromagnetic field **164** of the winding **14** for the stator **10**. Additionally, the magnetic torque components **172** operates where the magnetic fields of the magnet inserts **162** tend to align with the electromagnetic field **164** of the winding **14** for the stator **10**. These torque components combined produce the electromagnetic torque **170** that allows the rotor **18** to achieve a similar torque output as compared to conventional BLDC motors utilizing rare-earth magnets.

[0101] According to various aspects of the device, as exemplified in FIGS. **22-34**, the ferrite-assisted rotor for an electric motor **12** can include the drive shaft **202**, the plurality of stacked rotor laminations **120** that form the rotor body **140**. The rotor body **140** extends around the drive shaft **202**. Each rotor lamination **120** of the plurality of stacked rotor laminations **120** includes connecting webs **150** that form reluctance voids **122** within the plurality of stacked rotor laminations **120**. The magnet inserts **162** are disposed within the reluctance voids **122**. The magnet inserts **162** occupy at least a portion of the space defined by the reluctance voids **122**. The magnet inserts **162** and the reluctance voids **122** are configured to cooperate with the electromagnetic field **164** generated by the energized winding **14** for a stator **10**. This interaction produces an electromagnetic torque **170** having the reluctance torque components **174** and the magnetic torque components **172**.

[0102] Within conventional reluctance motors, the reluctance rotor is typically much longer than the stator to provide for a greater interaction between the paths of least reluctance within the rotor body.

[0103] According to the various aspects of the device, as exemplified in FIGS. **22-34**, the inclusion of the magnet inserts **162** have been shown to provide a consistent and comparable electromagnetic torque **170** with the ferrite-assisted reluctance rotor **160** having a rotor body **140** that is substantially similar or equal to the height of the rotor cavity **74** of the stator **10**. Accordingly, using the ferrite-assisted reluctance rotor **160**, the motor **12** can be made more compact than other conventional reluctance motors. Again, this comparable electromagnetic torque **170** can be achieved without the need for rare-earth magnets. Rather, the ferrite-assisted reluctance rotor **160** described herein can utilize non-rare-earth magnet inserts **162** within the reluctance voids **122** to produce a comparable electromagnetic torque **170**.

[0104] Referring now to FIGS. **22-35**, having described various aspects of the ferrite-assisted reluctance rotor **160**, a method **700** for forming a rotor **18** for an electric motor **12** is disclosed. According to the method **700**, step **702** includes forming rotor laminations **120** having reluctance blanks **200** or sections removed from each of the rotor laminations **120**. These reluctance blanks **200** or sections also define the connecting webs **150** that extend around each of the removed reluctance blanks **200**. After the laminations are formed, the rotor laminations **120** are stacked to form the rotor body **140** that is made up of the plurality of stacked rotor laminations **120** (step **704**). As discussed herein, the connecting webs **150** of the reluctance portions **190** for each of the laminations are aligned to define the reluctance voids **122** that extend through or extend substantially through the rotor body **140**. After the plurality of stacked rotor laminations **120** are positioned to form the rotor body **140**, and the reluctance voids **122** are defined therein, magnet inserts **162** are positioned within the reluctance voids **122** (step **706**). In order to maintain the magnet inserts **162** within the reluctance voids **122**, at least one, and typically two, opposing end caps **70** are disposed on the rotor body **140** for enclosing the reluctance voids **122** and any space that may be unoccupied by the magnet inserts **162** within the reluctance voids **122** (step **708**). Typically, the entire space defined by the reluctance voids **122** are occupied by the magnet inserts **162** such that little to no space is left over. It is contemplated that the opposing end caps **70** are disposed on the ends of the rotor body **140** to prevent movement of the magnet inserts **162** during operation of the ferrite-assisted reluctance rotor **160** and during placement of the overmold **46** around the rotor body **140** and the magnet inserts **162**. After disposing the magnet inserts **162** within the rotor body **140**, the rotor body **140** is overmolded with an overmold material (step **710**).

As discussed herein, the opposing end caps **70** prevent infiltration of the overmold material into the reluctance voids **122** and also prevents movement of the magnet inserts **162** within the reluctance voids **122**.
[0105] According to an aspect of the present disclosure, a motor includes a stator having a winding that when selectively energized produces an electromagnetic field within a rotor cavity, and a rotor disposed within the rotor cavity of the stator and in electromagnetic communication with the winding and the electromagnetic field. The rotor includes a drive shaft, a rotor body that extends around the drive shaft and that defines a plurality of reluctance voids, and magnet inserts that are disposed within the reluctance voids. The magnet inserts occupy at least a portion of a space defined by the reluctance voids. The magnet inserts and the reluctance voids cooperate with the electromagnetic field to produce an electromagnetic torque.
[0106] According to another aspect, the magnet inserts are free of rare-earth magnets.
[0107] According to another aspect, the magnet inserts are at least one of Aluminum Nickel Cobalt (AlNiCo) magnets and ferrite magnets.
[0108] According to another aspect, the stator and the rotor are free of position sensors for sensing a rotational position of the rotor relative to the stator.
[0109] According to another aspect, the rotational position of the rotor relative to the stator is estimated using a back electromotive force that is generated by the magnet inserts.
[0110] According to another aspect, the electromagnetic torque includes a magnetic torque component that is produced by an interaction of the magnet inserts and the electromagnetic field.
[0111] According to another aspect, the electromagnetic torque includes a reluctance torque component that is produced by the interaction of the rotor body and the electromagnetic field.
[0112] According to another aspect, the rotor body includes connecting webs that define the reluctance voids.
[0113] According to another aspect, the reluctance torque component of the electromagnetic torque is produced by the interaction of the connecting webs of the rotor body and the electromagnetic field.
[0114] According to another aspect, at least one magnet insert of the magnet inserts occupies only a portion of the space of a corresponding reluctance void of the reluctance voids.
[0115] According to another aspect, opposing end laminations and an overmold layer enclose the reluctance voids of the rotor and fix a position of the magnet inserts within the reluctance voids.
[0116] According to another aspect of the present disclosure, a rotor includes a drive shaft and a plurality of stacked rotor laminations that form a rotor body. The rotor body extends around the drive shaft. Each stacked rotor lamination has connecting webs that form reluctance voids within the plurality of stacked rotor laminations. The rotor further includes magnet inserts that are disposed within the reluctance voids. The magnet inserts occupy at least a portion of a space defined by the reluctance voids. The magnet inserts and the reluctance voids are configured to cooperate with an electromagnetic field from a stator winding to produce an electromagnetic torque having a reluctance torque component and a magnetic torque component.
[0117] According to another aspect, each magnet insert occupies only a portion of a respective reluctance void of the reluctance voids.
[0118] According to another aspect, the rotor includes a two-pole configuration, and the reluctance voids are positioned in a generally parallel configuration with respect to a central plane of the rotor body.
[0119] According to another aspect, the magnet inserts include at least 4 magnet inserts that are positioned in the generally parallel configuration.
[0120] According to another aspect, the rotor includes a four-pole configuration, and the reluctance voids are positioned in a non-concentric configuration with respect to a rotational axis of the rotor body.
[0121] According to another aspect, the magnet inserts are free of rare-earth magnets.

[0122] According to another aspect, the magnet inserts are at least one of Aluminum Nickel Cobalt (AlNiCo) magnets and ferrite magnets.
[0123] According to yet another aspect of the present disclosure, a method for forming a rotor for an electric motor includes the steps of forming rotor laminations having reluctance portions removed from each of the rotor laminations to define connecting webs, stacking the rotor laminations to form a rotor body, wherein the connecting webs are aligned to define reluctance voids within the rotor body, positioning magnet inserts within the reluctance voids, disposing opposing end caps on the rotor body to enclose the reluctance voids, and overmolding the rotor body with an overmold material. The opposing end caps prevent infiltration of the overmold material into the reluctance voids.
[0124] According to another aspect, the step of forming the rotor laminations includes stamping out the reluctance blanks to form at least 6 reluctance voids that are positioned in a generally parallel configuration with respect to the rotor body.
[0125] It is to be understood that variations and modifications can be made on the aforementioned structure without departing from the concepts of the present invention, and further it is to be understood that such concepts are intended to be covered by the following claims unless these claims by their language expressly state otherwise.

Claims

1. A motor comprising: a stator having a winding that when selectively energized produces an electromagnetic field within a rotor cavity; and a rotor disposed within the rotor cavity of the stator and in electromagnetic communication with the winding and the electromagnetic field, the rotor comprising: a drive shaft; a rotor body that extends around the drive shaft, the rotor body defining reluctance voids; and magnet inserts that are disposed within the reluctance voids, wherein the magnet inserts occupy at least a portion of a space defined by the reluctance voids, wherein the magnet inserts and the reluctance voids cooperate with the electromagnetic field to produce an electromagnetic torque.
2. The motor of claim 1, wherein the magnet inserts are free of rare-earth magnets.
3. The motor of claim 1, wherein the magnet inserts are at least one of Aluminum Nickel Cobalt (AlNiCo) magnets and ferrite magnets.
4. The motor of claim 1, wherein the stator and the rotor are free of position sensors for sensing a rotational position of the rotor relative to the stator.
5. The motor of claim 4, wherein the rotational position of the rotor relative to the stator is estimated using a back electromotive force that is generated by the magnet inserts.
6. The motor of claim 1, wherein the electromagnetic torque includes a magnetic torque component that is produced by an interaction of the magnet inserts and the electromagnetic field.
7. The motor of claim 6, wherein the electromagnetic torque includes a reluctance torque component that is produced by the interaction of the rotor body and the electromagnetic field.
8. The motor of claim 7, wherein the rotor body includes connecting webs that define the reluctance voids.
9. The motor of claim 8, wherein the reluctance torque component of the electromagnetic torque is produced by the interaction of the connecting webs of the rotor body and the electromagnetic field.
10. The motor of claim 1, wherein at least one magnet insert of the magnet inserts occupies only a portion of the space of a corresponding reluctance void of the reluctance voids.
11. The motor of claim 1, wherein opposing end laminations and an overmold layer enclose the reluctance voids of the rotor and fix a position of the magnet inserts within the reluctance voids.
12. A rotor comprising: a drive shaft; a plurality of stacked rotor laminations that form a rotor body, the rotor body extending around the drive shaft, each stacked rotor lamination having connecting webs that form reluctance voids within the plurality of stacked rotor laminations; and magnet

inserts that are disposed within the reluctance voids, wherein the magnet inserts occupy at least a portion of a space defined by the reluctance voids, wherein the magnet inserts and the reluctance voids are configured to cooperate with an electromagnetic field from a stator winding to produce an electromagnetic torque having a reluctance torque component and a magnetic torque component.

13. The rotor of claim 12, wherein each magnet insert occupies only a portion of a respective reluctance void of the reluctance voids.

14. The rotor of claim 12, wherein the rotor includes a two-pole configuration, and wherein the reluctance voids are positioned in a generally parallel configuration with respect to a central plane of the rotor body.

15. The rotor of claim 14, wherein the magnet inserts include at least 4 magnet inserts that are positioned in the generally parallel configuration.

16. The rotor of claim 12, wherein the rotor includes a four-pole configuration, and wherein the reluctance voids are positioned in a non-concentric configuration with respect to a rotational axis of the rotor body.

17. The rotor of claim 12, wherein the magnet inserts are free of rare-earth magnets.

18. The rotor of claim 12, wherein the magnet inserts are at least one of Aluminum Nickel Cobalt (AlNiCo) magnets and ferrite magnets.

19. A method for forming a rotor for an electric motor, the method comprising the steps of: forming rotor laminations having reluctance blanks removed from each of the rotor laminations to define connecting webs; stacking the rotor laminations to form a rotor body, wherein the connecting webs are aligned to define reluctance voids within the rotor body; positioning magnet inserts within the reluctance voids; disposing opposing end caps on the rotor body to enclose the reluctance voids; and overmolding the rotor body with an overmold material, wherein the opposing end caps prevent infiltration of the overmold material into the reluctance voids.

20. The method of claim 19, wherein the step of forming the rotor laminations includes stamping out the reluctance blanks to form at least 6 reluctance voids that are positioned in a generally parallel configuration with respect to the rotor body.