MOTOR WITH AXIALLY ADUSTABLE ROTOR ASSEMBLY

RELATED APPLICATION

[0001] This application claims the benefit of priority to the Singapore application no. 10202400827Q filed March 22, 2024, the contents of which are hereby incorporated herein by reference in their entirety for all purposes.

TECHNICAL FIELD

[0002] The present disclosure relates to motors and, more particularly, axially adjustable rotor assemblies for motors.

BACKGROUND

[0003] Variable flux electric motors are useful in many practical applications, e.g., in electric vehicles. Theoretically, changing the air-gap magnetic flux can enable adjustment in the torque output of a motor. In practice, there are substantial torque forces and stress placed on components in a motor such that loose components easily result in eccentricity in the mass distribution in the motor, which may lead to catastrophic failure of the motor.

SUMMARY

[0004] A motor includes a housing, a stator, and a rotor assembly. The housing defines a first end and a second end, and a primary axis extending axially from the first end to the second end. The stator includes windings. The stator is fixedly disposed in the housing at the first end of the housing. The stator is axially spaced apart from the second end of the housing. The rotor assembly includes a support frame and a rotor. The support frame is rotatable about the primary axis relative to the housing. The support frame includes a plurality of rods. The plurality of rods are constrained from an axial displacement relative to the housing. The rotor includes a plurality of rotor magnets. The rotor is disposed on the support frame. The rotor and the support frame are rotatable as a body about the primary axis, in which the rotor is axially displaceable relative to the support frame.

[0005] The motor as described above, in which each one of the plurality of rods may be coupled to the first end of the housing and the second end of the housing, and in which the rotor assembly may further include a rotor shaft in slidable engagement with the plurality of rods.

[0006] The motor according to any of the embodiments described above, in which in operation, a rotation of the rotor assembly relative to the stator may produce a torque distributed among torque-bearing components. The torque-bearing components may include the four or more cylindrical rods.

[0007] The motor according to any of the embodiments described above, further including a motor shaft. The motor shaft may be coupled to the rotor and may extend beyond the first end of the housing. In operation, the motor shaft may be rotatable at a variable torque. The variable torque may be controllably variable according to the rotor axial displacement.

[0008] The motor according to any of the embodiments described above, in which the rotor shaft defines a plurality of channels, and in which the support frame includes a plurality of rods extending parallel to and equidistantly spaced apart from the primary axis. Each of the plurality of rods may be slidably engaged with a respective one of the plurality of channels.

[0009] The motor according to any of the embodiments described above, further including angular bearings and a rotor adjustment shaft. The rotor adjustment shaft may be coupled to the rotor shaft via the angular bearings, in which the rotor adjustment shaft is axially displaceable relative to the housing.

[0010] The motor according to any of the embodiments described above, further including a linear bearing disposed to interface between each of the plurality of rods and respective one of the plurality of channels.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Various embodiments of the present disclosure will be described with reference to the following figures:

[0012] FIG. 1A is a perspective view of a motor according to embodiments of the present disclosure, in which the motor includes an axially adjustable rotor assembly.

[0013] FIG. 1B is a perspective view of the motor according to other embodiments of the present disclosure, in which the motor includes an axially adjustable rotor assembly.

[0014] FIG. 2 is a perspective view of the motor exploded along a primary axis to better show the various components in the motor.

[0015] FIG. 3 is a cross-sectional view of the motor of FIG. 2.

[0016] FIG. 4 is a cross-sectional view of the motor showing a concentric arrangement of the plurality of rods, the rotor, and the stator.

[0017] FIG. 5 is a perspective view of the rotor assembly.

[0018] FIG. 6A to FIG. 6F are images showing a method of assembling the distributed torque mechanism.

[0019] FIG. 7A to FIG. 7D are images illustrating the modularity and scalability of the support frame enabling a distributed torque mechanism.

[0020] FIG. 8A and FIG. 8B illustrate forces acting on the rods.

[0021] FIG. 9 is a cross-sectional view of the motor to highlight the shifting mechanism.

[0022] FIG. 10A, FIG. 10B, and FIG. 10C show the rotor displaced axially to various different positions along the primary axis.

[0023] FIG. 11 shows the rotor adjustment shaft in greater detail.

[0024] FIG. 12A and FIG. 12B illustrate the stress concentrations in the motor.

[0025] FIG. 13A and FIG. 13B illustrate the centering support provided in the motor.

[0026] FIG. 14A to FIG. 14H are images showing a prototype of the proposed motor.

[0027] FIG. 15A and FIG. 15B are images showing the motor in a compact state and in an extended state during an experiment.

[0028] FIG. 16A and FIG. 16B are images to more clearly show the rotor adjustment shaft in an unextended state and in a fully extended state, respectively.

[0029] FIG. 17A and FIG. 17B are images of an experimental set-up showing the prototype from a side view and from the first end of the housing, respectively.

[0030] FIG. 18 is an image showing the complete experimental set-up for testing the prototype.

[0031] FIG. 19A and FIG. 19B show the respective performance of a benchmark conventional motor and the prototype, respectively.

[0032] FIG. 20 is a side view of the motor configured to enable motorised axial adjustment of the rotor, according to embodiments of the present disclosure.

DETAILED DESCRIPTION

[0033] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration and to aid understanding, and not to be limiting. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0034] As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0035] The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments.

[0036] As used herein, the singular 'a' and 'an' may be construed as including the plural "one or more" unless apparent from the context to be otherwise.

[0037] The terms "about" and "approximately" as applied to a stated numeric value encompasses the exact value and a reasonable variance as will be understood by one of ordinary skill in the art, and the terms "generally" and "substantially" are to be understood in a comparable manner, unless otherwise specified.

[0038] Some processes may be described in terms of steps merely to aid understanding and/or for convenient reference. The delineation between one step and another step may be described as such merely for convenient reference in the present disclosure. It will be understood that in actual implementation there may not be a clear division or transition from one step to another subsequent step. There

may be a certain amount of overlap among the steps and/or more than one step may occur or be performed concurrently in time, etc.

[0039] As used herein, the term "concurrent", or "concurrently", is used loosely to refer to two or more occurrences (or events) that at least partially overlap in time. The occurrences may or may not start at the same time instant and/or end at the same time instant.

[0040] Terms such as "first" and "second" are used in the description and claims only for the sake of brevity and clarity, and do not necessarily imply a priority or order, unless required by the context.

[0041] All examples described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding and are not intended to be limiting or exhaustive. Modifications not involving inventive effort may be made by one of ordinary skill in the art without departing from the scope of the claimed invention.

[0042] **FIG. 1A** and **FIG. 1B** are perspective views of a motor 200 according to various embodiments of the present disclosure. The motor 200 includes a motor shaft (also referred to as the output motor shaft 250) at a first end 211 of a housing 210 to deliver a torque output of the motor 200. The motor 200 includes a rotor adjustment shaft 300 at a second end 212 of the housing 210 for adjustment of the rotor. **FIG. 1A** shows a handle 231 to enable manual operation of the rotor adjustment shaft 300. **FIG. 1B** shows an actuator 232 to enable motorized operation of the rotor adjustment shaft 300.

[0043] **FIG. 2** is a perspective view of the motor 200 exploded along a primary axis 101 to better show the various components in the motor 200. For the sake of brevity and convenient reference, the primary axis 101 is defined as an axially oriented axis extending through the center of the motor 200, e.g., extending axially from the first end 211 of the housing 210 to the second end 212 of the housing 210. In the present disclosure, terms such as "axial", "axially oriented", "axial direction", etc., may be used interchangeably to refer to a direction along or parallel to the primary axis 101.

[0044] A stator 240 of the motor 200 is disposed in a first casing 213 of the housing 210. The stator 240 may form a generally ring-like shape (also referred to

herein as annular shape for the sake of brevity). For example, the stator 240 may include an annular structure. The stator 240 may include stator teeth 242. In the example shown, a plurality of stator teeth 240 extending radially (e.g., from an outer perimeter of the stator toward the center of the motor or toward the primary axis or along radial axes 103). The stator 240 may include windings (stator windings) disposed on or about the stator teeth 242.

[0045] The motor 200 includes a rotor 410. The rotor 410 includes a plurality of permanent magnets (rotor magnets 420). In operation, the rotor 410 and the stator 240, or more specifically, the magnetic flux of the rotor magnets 420 and the stator windings (not shown in FIG. 2 to avoid obfuscation) interact to produce a torque which drives a rotational motion of the motor shaft.

[0046] The motor 200 includes a shifting mechanism 131 and a distributed torque rotor slider assembly 133. Relative to the fixed stator 240 (e.g., fixed relative to the housing 210 of the motor 200), the shifting mechanism 131 and the distributed torque rotor slider assembly 133 cooperate to provide an axial displacement 135, e.g, an rotor axial shift or a shift of the rotor 410 away from the first casing 213 of the housing 210 toward a second casing 214 of the housing 210. The shifting mechanism 131 and the distributed torque rotor slider assembly 133 may be described as integrated with one another. For example, the same physical component may serve as a part of the shifting mechanism 131 as well as a part of the distributed torque rotor slider assembly 133. The overall motor can be relatively compact with this efficient use of the limited space within the housing 210 of the motor 200.

[0047] **FIG. 3** is a cross-sectional view of the motor 200 of **FIG. 2**. The housing 210 of the motor may include the first casing 213 and the second casing 214. The first casing 213 and the second casing 214 may be coupled together to form an enclosed space. The stator 240 is disposed in the enclosed space. The stator 240 may be fixedly disposed at the first end 211 of the housing 210. The enclosed space extends axially beyond the stator 240, e.g., the housing 210 is configured to be longer than a length of the stator 240 (measured along the primary axis 101). The stator 240 is axially spaced apart ("d") from the second end 212 of the housing 210.

[0048] The motor 200 includes a rotor assembly 400. The rotor assembly 400 includes a rotor 410 and a rotor shaft 430, with the rotor 410 disposed on the rotor shaft 430. The rotor assembly 400 further includes a distributed torque mechanism (also referred to herein as a support frame 500). The rotor 410 is disposed on the support frame 500.

[0049] The support frame 500 is rotatable about the primary axis 101 relative to housing 210. The support frame 500 includes a plurality of rods 510. Each rod 510 has a first rod end 511 and a second rod end 512. The first rod end 511 is fixedly coupled to a rod base 530 of the support frame 500, which is in turn disposed at the first end 211 of the housing 210. The second rod end 512 is fixedly coupled to a rod cap 540 of the support frame 500, which is in turn disposed at the second end 212 of the housing 210. The plurality of rods 510 are constrained from an axial displacement relative to the housing 210. Each of the plurality of rods 510 extends from the first end 211 of the housing 210 to the second end 212 of the housing 210 along an axial direction 101, e.g., each rod 510 is axially disposed or disposed parallel to the primary axis 101. The rod cap 540, the plurality of rods 510, and the rod base 530 collectively forms a cage-like assembly that is rotatable as one body about the primary axis 101, relative to the housing 210 and the stator 240.

[0050] The rod cap 540 may be rotatably coupled with the housing 210 via a second bearing coupling 642. For example, the rod cap 540 may be rotatably engaged with the housing 210 via a groove bearing 640. The rod base 530 may be rotatably coupled with the housing 210 via a first bearing coupling 632. For example, the rod base 530 may be rotatably engaged with the housing 210 via cross roller bearings 630.

[0051] The rotor 410 and the support frame 500 are rotatable as a body about the primary axis 101. For example, the rotor shaft 430 may define a plurality of channels 450 (FIG. 4). Each of the plurality of rods 510 passes through one of the plurality of channels 450. Rotation of the rotor 410 about the primary axis 101 (e.g., as a result of electromagnetic flux interaction with the stator 240) carries the rods 510 in a corresponding rotation about the primary axis 101.

[0052] The rotor shaft 430 is slidable relative to the support frame 500 in either direction parallel to the primary axis 101. The rotor shaft 430 is in slidable

engagement with the plurality of rods 510. The support frame 500 may include a plurality of rods 510 extending parallel to and equidistantly spaced apart from the primary axis 101, each of the plurality of rods 510 being slidably engaged with a respective one of the plurality of channels 450. For example, each corresponding rod and channel pair may be slidably engaged with a linear bearing 650 disposed therebetween.

[0053] **FIG. 4** is a cross-sectional view of the motor 200 showing a concentric arrangement of the plurality of rods 510, the rotor 410, and the stator 240. The support frame 500 may include two or more rods 510 distributed in radial symmetry. In this example, the support frame 500 includes four cylindrical rods 510 distributed in radial symmetry about the primary axis 101. In the present disclosure, for the sake of brevity, reference to components being circumferentially distributed or in distributed in radial symmetry refers to the components being disposed in a regular pattern or array, with the components equally spaced apart from one another and from a reference center 105. For example, as schematically illustrated in FIG. 4, the rotor assembly 400 is configured with radial symmetry about the center of the cross-section, the center of the cross-section coinciding with the primary axis 101. As schematically illustrated, the channels 450 are defined in the rotor shaft 430 to be in radial symmetry about the primary axis 101.

[0054] The distribution of the rods may define a first circumferentially distributed arrangement, the plurality of rotor magnets 420 (or the rotor 410) may define a second circumferentially distributed arrangement that circumscribes the first circumferentially distributed arrangement. For example, the plurality of rotor magnets 420 may be distributed circumferentially on the rotor shaft 430. For example, the plurality of rotor magnets 420 may be disposed on a curved surface of the rotor shaft 430, equidistant from the primary axis 101. For example, the plurality of rods 510 may define a first circle, and the rotor 410 may define a second circle, the first circle and the second circle being concentrically defined. The stator 240 forms another annular concentric with the rotor 410.

[0055] **FIG. 5** is a perspective view of the rotor assembly 400. In this example, the rod base 530 is rotatably coupled to the housing 210 via cross roller bearings 630. The rod cap 540 is rotatably coupled to the housing 210 via groove bearings

640. Each of the rods 510 is slidably coupled to a respective channel 450 via linear bearings 650.

[0056] In some embodiments, the motor shaft 250 may be integrally formed with the rod base 530. In some embodiments, the motor shaft 250 extends fixedly from the rod base 530 (which is disposed interior of the housing 210) to an exterior of the housing 210. In some embodiments, the plurality of rods 510 extend from an interior side of the rod base 530 and the motor shaft 250 extends from an exterior side of the rod base 530, the interior side and the exterior side being opposing sides of the rod base 530. The motor shaft 250 is configured to rotate as a body with the support frame 500. The motor shaft 250 is coupled to the rotor assembly 400 such that the motor shaft 250 is not axially displaced by an axial displacement 135 of the rotor shaft 430. For example, the motor shaft 430 may be coupled to the support frame 500 or the rod base 530 of the support frame 500, and decoupled from the rotor shaft 430.

[0057] **FIG. 6A** to **FIG. 6F** are images showing a method of assembling the support frame 500. The rod base 530 may be machined or 3D printed as a substantially circular article with recesses to receive respective ends of a plurality of the rods 510 (**FIG. 6A**). The plurality of rods 510 may be fixedly coupled to the rod base 530 (**FIG. 6B**). A rotor shaft 430 (**FIG. 6C**) defining a corresponding number of channels 450 (e.g., circular through holes). The rotor shaft 430 may be assembled with the plurality of rods 510 threaded through corresponding ones of the channels 450 (**FIG. 6D**), with linear bearings 650 disposed in each of the channels 450 between the rod 510 and the channel wall (**FIG. 6E**). The rod cap 540 may be assembled to respective remaining exposed ends of the plurality of rods 510 (**FIG. 6F**).

[0058] **FIG. 7A** to **FIG. 7D** illustrate the modularity and scalability of the support frame 500 enabling a distributed torque mechanism. Multiple rods 510 can be added to the support frame 500, depending on the torque requirement.

[0059] **FIG. 8A** is an image and **FIG. 8B** is a schematic diagram illustrating the distribution of the torque among the plurality of rods 510. The distributed torque forces act normally to the surface of the rod which advantageously minimizes stress concentrations.

[0060] **FIG. 9** is a cross-sectional view of the motor 200 to highlight the shifting mechanism 131 (also referred to as an axial displacement mechanism) to enable a rotor axial displacement (displacement of the rotor 410 parallel to the primary axis 101). The shifting mechanism 131 includes a rotor adjustment shaft 300. The rotor adjustment shaft 300 is coupled to the rotor shaft 430 and axially extends parallel to the rods 510. The rotor adjustment shaft 300 is disposed in the center of the rotor assembly 400, e.g., coincidental with the primary axis 101. The rotor adjustment shaft 300 is disposed so that it does not interfere with the motor shaft 250. For example, the rotor adjustment shaft 300 may extend from the second end 212 of the housing 210.

[0061] In some examples, the rotor adjustment shaft 300 is configured as a leadscrew 302 that is axially displaced by rotational threaded engagement with a threaded nut 350. The rotation of the leadscrew 302 may be operated by an actuator 232 (FIG. 1B), e.g., a stepper motor. The rotation of the leadscrew 302 may be operated by other mechanisms. In some examples, the rotor adjustment shaft 300 may be operated manually or by hand. To aid understanding, the manually operable prototype is described herein. For example, the shifting mechanism 131 may include a handle 231 at a terminal end of the rotor adjustment shaft 300.

[0062] The rotor adjustment shaft 300 may be coupled to the rotor shaft 430 via angular bearings 660 (arranged in a series along the rotor adjustment shaft) that support and centralize the rotor adjustment shaft 300 relative to the rotor shaft 430. The shifting mechanism 131 includes a locknut 304 engaging the rotor adjustment shaft 300 and the rotor shaft 430. The locknut 304 may be disposed adjacent to or in proximity to the angular bearings 660 to prevent the angular bearings 660 from disengaging from either or both of the rotor adjustment shaft 300 and the rotor shaft 430.

[0063] The shifting mechanism 131 may include a clamp 330 disposed at the second end 212 of the housing 210. In some embodiments, the clamp 330 may be a collar clamp 332. The clamp 330 may be fixedly coupled to the housing 210. The clamp 330 and the rotor adjustment shaft 300 may be in a releasable clamping engagement. For example, if the clamp 330 is in a clamped state, the rotor adjustment shaft 300 is prevented from axial displacement 135 relative to the

housing 210. For example, if the clamp 330 is in an unclamped state, the rotor adjustment shaft 300 may be operated to be axially displaceable relative to the housing 210. The housing 210 has an axial dimension (d) to allow the rotor assembly 400 to be axially displaced away from the stator 240.

[0064] With the clamp 330 in an unclamped state, the rotor adjustment shaft 300 may be axially displaced to an axial position at which the motor torque (torque at the output motor shaft) is at a desired level. With the clamp 330 in a clamped state, the rotor axial position (position of the rotor assembly 400 along the primary axis 101) relative to the stator 240 is secured. The motor 200 may then be operated to generate the desired level of motor torque.

[0065] **FIG. 10A**, **FIG. 10B**, and **FIG. 10C** show the rotor assembly 400 displaced axially to various different positions along the primary axis 101. At each of these positions, the axial position of the rotor can be fixed, i.e., the rotor assembly 400 can be prevented from axial displacement 135 along the primary axis 101. At each of these positions, the motor 200 may be operated to rotate by electromagnetic flux interaction between the rotor assembly 400 and the stator 240. The amount of motor torque produced can thus be controllably varied by adjusting the shifting or the axial position of the rotor assembly 400.

[0066] For example, with the stator 240 disposed at the first end 211 of the housing 210, the motor 200 may have the greatest torque when the rotor assembly 400 is positioned at an axial position nearest to the first end 211 of the housing 210, and the motor 200 may have the least torque when the rotor assembly 400 is positioned at an axial position furthest possible away from the first end 211 of the housing 210.

[0067] **FIG. 11** shows the rotor adjustment shaft 300 in greater detail. The rotor adjustment shaft 300 may be configured with a radial symmetry about an adjustment shaft axis that is parallel to the primary axis 101. In assembly with the rest of the motor 200, the rotor adjustment shaft 300 preferably has a radial symmetry about the primary axis 101, e.g., with the rotor adjustment shaft 300 disposed with the adjustment shaft axis coincidental with the primary axis 101. Angular bearings 660 may be disposed in a series at a first end of the rotor adjustment shaft 300. The proposed motor 200 can be scalable to form a larger

motor and/or to deliver greater torque. For example, the rotor adjustment shaft 300 may be coupled with various numbers of angular bearings 660. A wheel, handle, or an actuator may be coupled to a second end of the rotor adjustment shaft 300.

[0068] Optionally, the second end 212 of the housing 210 may include an elongate extension 216. The elongate extension 216 may provide additional support to the rotor adjustment shaft 300. The clamp 330 may be a collar clamp disposed at a terminal of the elongate extension 216. The clamp 330 may directly releasably engage the rotor adjustment shaft 300 to put the shifting mechanism 131 in either a clamped state or an unclamped state.

[0069] The shifting mechanism provide additional centering support apart from the bearings at the rod cap 540 (e.g., groove bearings) and the bearings at the rod base 530 (e.g., cross roller bearings). The rotor adjustment shaft 300 or the rotor assembly is kept axially oriented, and the center of rotation thereof is maintained at the centerline of the motor by at least the angular bearings, the cross-roller bearings, and the groove bearings. **FIG. 12A** shows the stress concentrations on the ball spline groove, where F represents a force on the ball bearings and G represents the force on the groove bearings, in the presence of a torque force (τ) on the rod cap. **FIG. 12B** is another schematic representation showing that the stress in the proposed motor is distributed as forces act normally to the surfaces of the plurality of rods, where F represents a force on a rod and L represents the force on the linear bearings, in the presence of a torque force (τ) on the rotor shaft. **FIG. 13A** is a schematic cross-sectional view of the motor showing the trio of centering support described. To further aid understanding, **FIG. 13B** is a diagram with images of the motor 200, showing the positions of the centering supports, namely, the first bearing coupling 632, the second bearing coupling 642, and the angular bearings 660. As shown, the motor 200 is configured with a distributed torque mechanism (also referred to as a distributed torque rotor slider assembly 133) enabling a torque distribution among torque-bearing components, in which the torque-bearing components include, but are not limited to, the four or more rods 510.

[0070] Experiments were conducted with prototypes of the proposed motor and the viability and performance of the motor was verified. **FIG. 14A** to **FIG. 14H** are images showing the prototype in one experimental set-up. **FIG. 14A** shows the

axially adjustable rotor assembly. **FIG. 14B** shows the integrated rotor adjustment mechanism or the shifting mechanism. **FIG. 14C** shows another view of the prototype with an integrated shifting mechanism that includes centering support, the integrated mechanism being formed by the rotor adjustment shaft (**FIG. 14D**) and the rotor assembly (**FIG. 14E**). **FIG. 14F** is an image showing the housing of the motor with the distributed torque rotor-slider mechanism. **FIG. 14G** is an image of the assembled motor prototype with a dynamometer attached. **FIG. 14H** shows the proposed motor, also described as a variable flux motor (VFM), connected with an external motor drive motor connected to the output motor shaft of the VFM.

[0071] The rotor adjustment mechanism allows for the axial displacement of the rotor relative to the stator (rotor axial displacement) to stop at any point within a range of extensions so that the motor may be operated at a corresponding torque output. **FIG. 15A** and **FIG. 16A** are images of the VFM in a compact state, e.g., with the rotor at a default axial position. In particular, **FIG. 16A** shows the VFM in an unextended state, e.g., at a minimum extension. **FIG. 15B** and **FIG. 16B** are images of the VFM in an extended state, e.g., with an extended rotor, e.g., the rotor being axially adjusted or axially displaced to provide a variable electromagnetic flux interaction in the VFM. In particular, **FIG. 16B** shows the VFM in a fully extended state, e.g., at a maximum extension.

[0072] **FIG. 17A** and **FIG. 17B** are images showing an experimental set-up in which a coupler connects the output motor shaft of the prototype to a load motor.

[0073] **FIG. 18** shows a complete experimental set-up for testing the prototype in which a speed/torque sensor is disposed at the output motor shaft.

[0074] A comparison of the efficiency of the prototype motor against a benchmark (conventional) motor. As the benchmark (conventional) motor did not include variable flux capabilities, a flux weaking (FW) technique was used to simulate the conditions at different levels of torque/speed. In the case of the prototype motor, the speed of the motor could be adjusted using the rotor adjustment mechanism. The speed and torque were measured at the output motor shaft. The resulting torque versus speed efficiency maps were plotted. As shown in **FIG. 19A** for the benchmark (conventional) motor and in **FIG. 19B** for the prototype (VFM) motor of the present disclosure, the efficiency of the protoype (VFM) motor is comparable or

higher than that of the benchmark (conventional) motor. For example, the prototype (VFM) motor has efficiency over 90% for a wider range of speeds (e.g., beyond 400 RPM).

[0075] Advantages

[0076] Embodiments of the axially adjustable rotor mechanism is disclosed. The disclosure describes a built-in mechanism in an electric motor that can vary the axial position of the rotor in relation to the fixed stator which leads to altering the airgap magnetic flux of the motor. The ability to control the air gap magnetic flux by adjusting the rotor position leads to several advantages. Firstly, the range of speed whereby the constant power output speed range of the device is extended. Secondly, the efficiency of the machine at various operating points can be further regulated by adjusting the air-gap magnetic flux. Finally, the ability to vary the position of the rotor dynamically allows for real-time control of the machine's electromechanical characteristics to match the changing demands of the application such as in an electric vehicle.

[0077] An exemplary embodiment of the motor 200 is schematically shown in **FIG. 20** to illustrate a possible implementation. The output motor shaft 250 and the rotor adjustment shaft 300 extend from different ends of the motor 200. The rotor adjustment shaft 300 may be coupled to and be configured to be operable by an actuator 232 (e.g., an external actuator). The actuator 232 can be configured to controllably displace the rotor adjustment shaft 300 along the primary axis 101. The actuator 232 may be coupled to a telescopic slotted shaft 244 via a coupler 246. The telescopic slotted shaft 244 may be configured with a slot to slidably receive the rotor adjustment shaft 300. Advantageously, the housing 210 of the VFM and the actuator 232 may remain fixed, e.g., relative to the chassis and other components of the electric vehicle. Advantageously, the entire assembly illustrated in FIG. 20 remains relatively compact even as it provides for a variable flux in the motor 200.

[0078] Distributed torque peripheral rotor slider assembly enables the shifting mechanism to perform rotary and linear motion of the rotor at high torques. This is an improvement in comparison to existing spline-like mechanisms which have lower torques of the same size. The mechanism makes the axial shifting configuration

compact without sacrificing the torque achievable. The mechanism design includes multiple rods in assembly which centralizes the rotor precisely with respect to the stator. The configuration enables the axial motion of the rotor to be smooth, with less friction. This mechanism is easily scalable to bigger and higher torque motors, enabling flexibility and versatility in motor design and manufacturing. This means that the same assembly concept can be utilized in motors ranging from small and low-torque applications to larger and higher-torque ones.

[0079] The proposed integrated central shifting mechanism with centering support enables precise axial displacement of the rotor (rotor axial displacement) and helps maintain the concentricity of the shifting assembly. This configuration makes the motor symmetric and maintains rotor balance. The configuration utilizes internal rotor space (e.g., space in the housing) and is scalable for large torque motors. The output shaft of the motor remains fixed despite the motion of the rotor.

[0080] The proposed variable flux motor (also referred to as a variable flux electric motor) that has a built-in mechanism to adjust rotor position axially is shown. The motor may have a standard 3-phase winding in a slotted stator assembly and rotor magnets 420 on the rotor, e.g., similar to an alternating-current magnet synchronous electric machine. The rotor can be axially shifted to adjust the flux density. The proposed motor has a high torque capacity rotor shifting configuration, which has a symmetric and integrated shifting mechanism that is scalable. The shifting mechanism is built into the rotor assembly to enable adjustment of the axial position of the rotor relative to the stator assembly. This allows for direct control of the air gap magnetic flux at different operating speeds.

[0081] The motor may be described as including two assemblies: (i) a distributed torque rotor slider assembly and (ii) an integrated shifting mechanism assembly. Multiple cylindrical rods are diametrically placed at the periphery of the rotor from the base of the assembly. The rods are connected to a rod base (which may be shaped like a container) with multiple slots to contain the rods. The rotor is connected to the rotor shaft which is customized to contain multiple slots that help the rotor move axially on the rod assembly via linear bearings. With the help of linear bearings, the rotor shaft can slide up and down within a span of 43 millimeters (mm). The linear bearings can maintain uniform contact between each of the rotor

slots and the cylindrical rod. The linear bearings are installed and fixed in the rotor shaft slot. To avoid twisting and maintain the uniformity of the position of each rod, another part (rod cap) is used to connect the assembly at the other end. The multiple rods and the corresponding linear bearings enable the higher concentricity of the rotor.

[0082] The entire rotor slider assembly may be secured together by two bearings, e.g., a first bearing may be a large cross-roller bearing which is attached to the base container of the rotor slider assembly and sits on the motor housing groove. This bearing helps the rotor slider assembly to support the weight of the rotor and maintain its position. The other bearing (e.g., a second bearing) may be a centering bearing which is a deep groove bearing that is fixed to the upper casing and is attached to the rod cap (also referred to as a groove bearing). When the shifting mechanism is in operation, various forces and moments are generated, which can create bending or cantilever effects in the rod components. The centering bearing, being fixed to the upper casing and attached to the rod cap, provides support and resists these moments. When the motor shaft is attached to the rotor slider assembly, the entire sub-assembly rotates along these two bearings.

[0083] The integrated shifting mechanism may include a lead screw of 2 mm pitch and 20 mm diameter which is attached to the rotor sliding assembly via a series of three angled contact bearings. A first two of the three angled contact bearings may be placed in the back-to-back (BTB) arrangement and a third of the angular bearing may be placed in series to provide extra support. The angular bearings help keep the rotor assembly in place against the strong magnetic forces acting radially between the rotor and the stator. These angled contact bearings may be fixed in a cylindrical slot in the rotor and clamped, which ensures the rotor can be pulled. The nut of the lead screw assembly is connected to the upper casing which is attached to the motor housing, ensuring the rotor is centered in the assembly. The lead screw assembly is connected to the handle at one end to allow easy rotation of the screw with minimal effort from the user to change the position of the rotor. The use of angular bearings connected in series to the lead screw provides a triple-centering support surface for the rotor. This ensures that the rotor remains precisely centered during axial shifting, leading to better rotational balance

and reduced asymmetry in the motor design. The lead screw pulls the rotor slider assembly by performing the screwing action within the fixed nut to the upper casing.

[0084] The lead screw mechanism may be equipped with a collar clamp near the terminal of the assembly installed concentrically at the smooth cylindrical surface of the screw. The collar clamp locking mechanism is included to secure the rotor position after the rotor position adjustment is completed. The lead screw is also attached to a spoked handwheel at the end to make the rotation of the screw and adjustment convenient for the user, particularly when the rotation allows the motion of the rotor against the magnetic forces of attraction between the rotor and the stator. Utilizing this integrated shifting mechanism, the rotor can move accurately and up to 60% of its length, e.g., up to 43 mm with respect to the stator which is fixed to the motor housing. The amount of shift of the rotor may be controlled by the number of rotations of the lead screw with each rotation shifting the rotor 2mm axially.

[0085] The physical movement of the rotor can lead to a reduction in magnetic flux by up to 60% from the maximum value. Extending and retracting the rotor would yield a higher and lower magnetic flux respectively. With this mechanism, it is possible to adjust the air gap magnetic flux level dynamically. The mechanism is designed to move the whole rotor assembly to achieve an almost linear adjustment of the magnetic flux density with respect to the rotor position.

[0086] Further advantages are described below.

[0087] The distributed torque rotor and slider assembly described above appears to be a promising mechanism for efficiently handling high torque in rotor-shifting-based electric motors. By using multiple rods, the torque is divided among the rods, reducing the individual stress on each rod compared to a simple spline-like mechanism. This distributed torque approach allows the assembly to handle higher torque levels without compromising its structural integrity.

[0088] Additionally, the forces in the distributed torque rotor slider assembly act normally on the rod surface, which means that the rods primarily experience axial loading rather than bending moments. This contrasts with ball spline mechanisms, where the forces often act as bending moments on the central rod, leading to higher stress concentrations and potential failure points.

[0089] Overall, the distributed torque rotor slider assembly offers several advantages for handling high torque in electric motors:

[0090] (i) High Torque Capacity: The torque is distributed among multiple rods, allowing the assembly to handle higher torque levels compared to conventional spline-like mechanisms.

[0091] (ii) Reduced Stress Concentration: The forces acting normally on the rod surface minimize stress concentrations and reduce the likelihood of failure due to bending moments.

[0092] (iii) Improved Structural Integrity: The division of torque and axial loading helps maintain the structural integrity of the rods and the assembly, ensuring long-term reliability.

[0093] (iv) Utilization of Large Bearings: due to the radial placement of the rods, larger bearings can be incorporated at the terminal ends enhancing the assembly's ability to withstand high torque and moments.

[0094] (v) Scalability: The configuration of the assembly allows for scalability, making it adaptable to various motor sizes and torque requirements.

[0095] The built-in central shifting mechanism is such that the axial motion of the rotor is smooth and requires minimal effort to change the configuration of the motor. The integrated central shifting mechanism with centering support is a compact and efficient mechanism designed for large motors. It offers the following benefits:

[0096] (i) Centering Support: The mechanism provides the support surface to maintain the concentricity of the rotor. This ensures smooth and stable operation.

[0097] (ii) Radially Compact Design: The mechanism is a radially compact design and hence features a clever partial integration within the rotor space. This approach optimizes space utilization and allows for only a 60% increase in the volume of the motor.

[0098] (iii) Symmetric Inertia: The inertia of the mechanism is symmetric, contributing to balanced performance and reducing potential imbalances in the motor, and suitable for hub wheels, making it versatile and adaptable.

[0099] (iv) Scalability: The mechanism is easily scalable to accommodate larger motors. The uniform design allows for consistent performance across different motor sizes.

[00100] The distributed torque peripheral rotor slider assembly efficiently transfers torque across multiple rods, enhancing load distribution and reducing stress concentration. The distributed torque peripheral rotor slider assembly enables high-performance in systems requiring reliable power transmission. Multiple rods result in higher torque dispersion and lower stress concentration. The multiple cylindrical rods and slider assembly constrain the rotor in a fixed radial position and maintain concentricity throughout the length of the rotor. The linear bearings make it easier to move the rotor smoothly with less mechanical force and minimize misalignment or bending of the rods when the rotor is moving especially under dynamic loads. The assembly is secured from both sides using cross-roller and groove bearings, providing double support on both sides which helps avoid any bending or cantilever effects in the rods. The assembly's configuration enables scaling by merely increasing the number of rods in relation to the motor's size or torque requirements, making it adaptable to different motor sizes and torque requirements. It is simple to increase the number of rods to accommodate larger motors with high torque. This makes adaptation of the proposed motor to suit various applications easily scalable and relatively straightforward.

[00101] The integrated central shifting mechanism with centering support includes a lead screw-based mechanism in series with a set of angular bearings that helps to move the rotor axially. The configuration is radially compact and fits partially within the internal space of the rotor assembly. Multiple angular bearings can be fitted within the shaft to enhance the concentricity of the shifting assembly. Additional support (up to 3 surfaces) are provided for centering the rotor shaft with respect to the housing. The motor is symmetric in shape, rendering inertia along the vertical axis which promotes balanced performance and lessens the possibility of motor failure.

[00102] The design is easily scalable to larger motors since it has high load-taking capacity bearings in series and locknut to pull the rotor of motors of significant sizes due to the precise and smooth lead screw action. The number of angular bearings in series of the screw can be increased or decreased easily depending on the size of the motor making the motor scalable. The axial position of the output motor shaft remains fixed with reference to the stationary frame so that adjustment of the torque

does not affect the relative placement of other components that are driven by the motor shaft.

[00103] The distributed torque peripheral rotor-slider assembly provides peripheral and distributed pin positioning of rods around the rotor's diameter, allowing the rotor to exert higher torque while linear bearings allow smooth motion axially. Compared to conventional axial shift motors, there is a higher torque dispersion and lower stress concentration in the proposed motor. The multiple rods are diametrically installed in the rotor to take up torsional forces, which together the rods better centralize the rotor and provide good rigidity and precise movement compared to conventional motors.

[00104] The proposed motor allows the rotor shifting mechanism to be installed within the rotor. This utilizes internal rotor volume and makes the design compact.

[00105] Long linear bearings used prevent twisting in the shifting mechanism when the motor is in high torque operation.

[00106] The motor is easy to scale due to its modular rods, which can be multiplied along with the corresponding linear bearings depending on the motor torque required. In contrast, conventional motors essentially have to be re-designed in order to suit different applications and torque requirements.

[00107] The proposed integrated central shifting mechanism with triple centering support uses a precise and easy-to-control lead screw mechanism to shift the rotor axially. Angular bearings are connected in series to the screw which helps to center the rotor and provide the third support for centering apart from the two radial bearings. The configuration is efficient in the use of space and components, and the mechanism is scalable for higher torque motors.

[00108] The mechanism is radially compact and partially placed inside the rotor shaft, at the center resulting in a compact, symmetric shape of the motor.

[00109] A motor 200 includes a housing 210, a stator 240, and a rotor assembly 400. The housing 210 defines a first end 211 and a second end 212, and a primary axis 101 extending axially from the first end 211 to the second end 212. The stator 240 includes windings. The stator 240 is fixedly disposed in the housing 210 at the first end 211 of the housing 210. The stator 240 is axially spaced apart from the second end 212 of the housing 210. The rotor assembly 400 includes a support

frame 500 and a rotor 410. The support frame 500 is rotatable about the primary axis 101 relative to the housing 210. The support frame 500 includes a plurality of rods 510. The plurality of rods 510 are constrained from an axial displacement relative to the housing 210. The rotor 410 includes a plurality of rotor magnets 420. The rotor 410 is disposed on the support frame 500. The rotor 410 and the support frame 500 are rotatable as a body about the primary axis 101, in which the rotor 410 is axially displaceable relative to the support frame 500.

[00110] The motor 200 according to any of the embodiments described above, in which each one of the plurality of rods 510 may be coupled to the first end 211 of the housing 210 and the second end 212 of the housing 210, and in which the rotor assembly 400 may further include a rotor shaft 430 in slidable engagement with the plurality of rods 510.

[00111] The motor 200 according to any of the embodiments described above, in which the support frame 500 may include four or more cylindrical rods 510 in a first circumferentially distributed arrangement, each of the four or more cylindrical rods 510 extending axially parallel to one another, and in which the rotor shaft 430 may define four or more channels 450, each of the four or more channels 450 and a respective one of the four or more cylindrical rods 510 being slidably engaged.

[00112] The motor 200 according to any of the embodiments described above, in which the plurality of rotor magnets 420 may be distributed circumferentially on the rotor shaft 430, and in which the stator 240 may include an annular structure circumscribing the plurality of rotor magnets 420.

[00113] The motor 200 according to any of the embodiments described above, further including angular bearings 660 and a rotor adjustment shaft 300. The rotor adjustment shaft 300 may be coupled to the rotor shaft 430 via the angular bearings 660. The rotor adjustment shaft 300 may be operable to dispose the rotor 410 at any one of a range of a rotor axial displacement relative to the stator 240.

[00114] The motor 200 according to any of the embodiments described above, in which in operation, a rotation of the rotor assembly 400 relative to the stator 240 may produce a torque distributed among torque-bearing components. The torque-bearing components may include the four or more cylindrical rods 510.

[00115] The motor 200 according to any of the embodiments described above, further including a motor shaft 250. The motor shaft 250 may be coupled to the rotor 410 and may extend beyond the first end 211 of the housing 210. In operation, the motor shaft 250 may be rotatable at a variable torque. The variable torque may be controllably variable according to the rotor axial displacement.

[00116] The motor 200 according to any of the embodiments described above, in which the rotor shaft 430 defines a plurality of channels 450, and in which the support frame 500 includes a plurality of rods 510 extending parallel to and equidistantly spaced apart from the primary axis 101. Each of the plurality of rods 510 may be slidably engaged with a respective one of the plurality of channels 450.

[00117] The motor 200 according to any of the embodiments described above, further including angular bearings 660 and a rotor adjustment shaft 300. The rotor adjustment shaft 300 may be coupled to the rotor shaft 430 via the angular bearings 660, in which the rotor adjustment shaft 300 is axially displaceable relative to the housing 210.

[00118] The motor 200 according to any of the embodiments described above, in which the support frame 500 further includes a rod base 530 and a rod cap 540. Opposing ends of the plurality of rods 510 may be respectively fixedly coupled to the rod base 530 and to the rod cap 540.

[00119] The motor 200 according to any of the embodiments described above, further including a cross roller bearing 630. The cross roller bearing 630 may rotatably couple the rod base 530 and the first end 211 of the housing 210.

[00120] The motor 200 according to any of the embodiments described above, further including a groove bearing 640. The groove bearing 640 may rotatably couple the rod cap 540 and the second end 212 of the housing 210.

[00121] The motor 200 according to any of the embodiments described above, further including a linear bearing 650 disposed to interface between each of the plurality of rods 510 and respective one of the plurality of channels 450.

[00122] The motor 200 according to any of the embodiments described above, in which the rotor adjustment shaft 300 may extend beyond the second end 212 of the housing 210, and in which rotation of the rotor adjustment shaft 300 may axially displace the rotor shaft 430 along the plurality of rods 510.

[00123] The motor 200 according to any of the embodiments described above, further including a clamp 330. The clamp 330 may be fixedly coupled to the housing 210, in which the clamp 330 and the rotor adjustment shaft 300 may be in a releasable clamping engagement.

[00124] The motor 200 according to any of the embodiments described above, in which the rotor adjustment shaft 300 is axially displaceable relative to the housing 210 if the clamp 330 is in an unclamped state.

[00125] The motor 200 according to any of the embodiments described above, further including a locknut 304. The locknut 304 may be coupled to the rotor adjustment shaft 300 and may prevent decoupling of the angular bearings 660 from the rotor adjustment shaft 300.

[00126] The motor 200 according to any of the embodiments described above, further including a handle 231. The handle 231 may be coupled to the rotor adjustment shaft 300 to enable manual rotation of the rotor adjustment shaft 300.

[00127] The motor 200 according to any of the embodiments described above, further including an actuator 232. The actuator 232 may be coupled to the rotor adjustment shaft 300 to enable motorized rotation of the rotor adjustment shaft 300.

[00128] All examples and embodiments described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding and are not intended to be limiting or exhaustive. Modifications may be made by one of ordinary skilled in the art without departing from the scope of the application as claimed.

CLAIMS

1. A motor comprising:

a housing defining a first end and a second end, and a primary axis extending axially from the first end to the second end;

a stator, the stator including windings, the stator being fixedly disposed in the housing at the first end of the housing, the stator being axially spaced apart from the second end of the housing; and

a rotor assembly, the rotor assembly including;

a support frame, the support frame being rotatable about the primary axis relative to the housing, the support frame including a plurality of rods, the plurality of rods being constrained from an axial displacement relative to the housing; and

a rotor, the rotor including a plurality of rotor magnets, the rotor being disposed on the support frame, the rotor and the support frame being rotatable as a body about the primary axis,

wherein the rotor is axially displaceable relative to the support frame.

2. The motor as recited in claim 1, wherein each one of the plurality of rods is coupled to the first end of the housing and the second end of the housing, and wherein the rotor assembly further comprises a rotor shaft in slidable engagement with the plurality of rods.

3. The motor as recited in claim 2, wherein the support frame comprises four or more cylindrical rods in a first circumferentially distributed arrangement, each of the four or more cylindrical rods extending axially parallel to one another,

and wherein the rotor shaft defines four or more channels, each of the four or more channels and a respective one of the four or more cylindrical rods being slidably engaged.

4. The motor as recited in claim 3, wherein the plurality of rotor magnets are distributed circumferentially on the rotor shaft, and wherein the stator includes an annular structure circumscribing the plurality of rotor magnets.

5. The motor as recited in claim 4, further comprising:

angular bearings; and

a rotor adjustment shaft, the rotor adjustment shaft being coupled to the rotor shaft via the angular bearings, wherein the rotor adjustment shaft is operable to dispose the rotor at any one of a range of a rotor axial displacement relative to the stator.

6. The motor as recited in claim 5, wherein in operation, a rotation of the rotor assembly relative to the stator produces a torque distributed among torque-bearing components, wherein the torque-bearing components include the four or more cylindrical rods.

7. The motor as recited in claim 6, further comprising a motor shaft, the motor shaft being coupled to the rotor and extending beyond the first end of the housing, wherein in operation the motor shaft is rotatable at a variable torque, the variable torque being controllably variable according to the rotor axial displacement.

8. The motor as recited in claim 2,

wherein the rotor shaft defines a plurality of channels,

and wherein the support frame comprises a plurality of rods extending parallel to and equidistantly spaced apart from the primary axis, each of the plurality of rods being slidably engaged with a respective one of the plurality of channels.

9. The motor as recited in claim 8, further comprising:

angular bearings; and

a rotor adjustment shaft, the rotor adjustment shaft being coupled to the rotor shaft via the angular bearings, wherein the rotor adjustment shaft is axially displaceable relative to the housing.

10. The motor as recited in claim 9, wherein the support frame further comprises:

a rod base; and

a rod cap, opposing ends of the plurality of rods being respectively fixedly coupled to the rod base and to the rod cap.

11. The motor as recited in claim 10, further comprising a cross roller bearing, the cross roller bearing rotatably coupling the rod base and the first end of the housing.

12. The motor as recited in claim 10, further comprising a groove bearing, the groove bearing rotatably coupling the rod cap and the second end of the housing.

13. The motor as recited in claim 10, further comprising a linear bearing disposed to interface between each of the plurality of rods and respective one of the plurality of channels.

14. The motor as recited in claim 10, wherein the rotor adjustment shaft extends beyond the second end of the housing, and wherein rotation of the rotor adjustment shaft axially displaces the rotor shaft along the plurality of rods.

15. The motor as recited in claim 10, further comprising a clamp, the clamp being fixedly coupled to the housing, wherein the clamp and the rotor adjustment shaft are in a releasable clamping engagement.

16. The motor as recited in claim 15, wherein the rotor adjustment shaft is axially displaceable relative to the housing if the clamp is in an unclamped state.

17. The motor as recited in claim 15, further comprising a locknut, the locknut being coupled to the rotor adjustment shaft and prevents decoupling of the angular bearings from the rotor adjustment shaft.

18. The motor as recited in claim 15, further comprising a handle, the handle being coupled to the rotor adjustment shaft to enable manual rotation of the rotor adjustment shaft.

19. The motor as recited in claim 15, further comprising an actuator, the actuator being coupled to the rotor adjustment shaft to enable motorized rotation of the rotor adjustment shaft.