Title: AXIAL FLUX ELECTRICAL MACHINE AND ANCILLARY COMPONENTS

Abstract: The present invention relates to a stator housing for an axial flux electrical machine, the stator housing being tubular and substantially cylindrical in shape, the inner surface of the housing comprising a plurality of recesses, each recess configured to receive an outer part of a conductive coil of a stator of an axial flux electrical machine. 

FIG. 22 [Continued on next page]

Published:
— with international search report (Art. 21(3))
Axial Flux Electrical Machine and Ancillary components

Technical Field

The invention relates to axial flux electrical machines, and features thereof.

Background

5 Electrical machines, including electric motors and electric generators, are already very widely used. However, concerns over our reliance on and the pollution caused by the fossil fuels that power internal combustion engines is creating political and commercial pressures to extend the use of electrical machines to new applications, and to expand their use in existing ones. Electrical machines are increasingly being used in vehicles, such as electric cars, motorbikes, boats and aircraft. They are also used in energy generation applications, for example generators in wind turbines.

In order to meet the needs of these applications, it will be necessary to design electrical machines that have both suitable performance properties, such as speed and torque, and high efficiency. The efficiency of electrical machines is critically important in almost all applications: it can, for example, both increase an electric vehicle’s range and decrease the required battery capacity. Decreasing the required battery capacity can in turn decrease the weight of the vehicle, which leads to further efficiency gains.

One known type of electrical machine is the axial flux machine. As the name suggests, the direction of the lines of magnetic flux that are cut during the operation of an axial flux machine is parallel to the axis of rotation of the machine. This is in contrast to radial flux machines, in which the direction of the lines of magnetic flux that are cut during the operation of the machine is perpendicular to the rotation axis of the machine. While radial flux machines are more common, axial flux machines have been used for some applications where their form factor (a relatively small axial extent) and performance properties (such as a high torque to weight ratio) are appreciated.

One example of a yokeless axial flux machine which utilizes a concentrated winding arrangement is described in International Patent Application with publication number WO 2018/015293 A1. The stator assembly of the axial flux machine includes circumferentially distributed discrete stator teeth which each have a ferromagnetic material around which there is an electrical winding. This is commonly referred to as a yokeless and segmented armature machine. Radially-inward-extending elongated portions of the stator housing are
provided for cooling and to provide a structure for receiving the stator teeth. While axial flux machines of this kind are able to achieve high efficiencies, it would be desirable to improve the efficiency, especially over a broader range of operating parameters. Further, even though the inwardly radially extending elongated portions of the housing provide some structure for receiving the discrete stator teeth, there are difficulties associated with positioning and bonding each stator tooth accurately into the stator housing, and each stator tooth must be wound around a bobbin-like structure that contains the ferromagnetic material. It would be desirable to provide a stator which can be more easily and accurately assembled.

Summary of the Invention

Embodyments described herein provide a rotor, housing, cooling arrangements, flux guides, and mechanical stacking, for an axial flux machine comprising a plurality of conductive coils which provide for high machine efficiencies and ease of manufacture.

Throughout this disclosure, unless otherwise qualified, terms such as “radial”, “axial”, “circumferential” and “angle” are used in the context of a cylindrical polar coordinate system (r, θ, z) in which the direction of the axis of rotation of the electrical machine is parallel to the z-axis. That is, “axial” means parallel to the axis of the rotation (that is, along the z-axis), “radial” means any direction perpendicular to the axis of rotation, an “angle” is an angle in the azimuth direction θ, and “circumferential” refers to the azimuth direction around the axis of rotation.

Terms such as “radially extending” and “axially extending” should not be understood to mean that a feature must be exactly radial or exactly parallel to the axial direction. To illustrate, while it is well-known that the Lorentz force experienced by a current carrying conductor in a magnetic field is at a maximum when the direction of the current is exactly perpendicular to the direction of the magnetic flux, a current carrying conductor will still experience a Lorentz force for angles less than ninety degrees. Deviations from the parallel and perpendicular directions will therefore not alter the underlying principles of operation.

The invention is defined in the independent claims to which reference should now be made. Preferred features are set out in the dependent claims.
Rotor

According to a first aspect of the present disclosure, there is provided a rotor for an axial flux electrical machine, the rotor comprising a substantially planar disc portion, the outer edge having a lip formed thereupon, the lip extending away from the disc portion along an axis of rotation of the electrical machine, the rotor further including a plurality of circumferentially distributed permanent magnets affixed thereto, wherein the permanent magnets are affixed to the substantially planar disc portion on the same side as that from which the lip extends therefrom, the outer circumferential edge of each permanent magnet abutting the lip.

Preferably, each permanent magnet of the plurality of permanent magnets is formed of a single permanent magnet. Alternatively, each permanent magnet may be formed of a plurality of separate segments. The separate segments may be stacked adjacent each other in the radial or circumferential direction.

Preferably, the plurality of permanent magnets comprises an even number of permanent magnets. Preferably, circumferentially adjacent magnets are arranged such that they have opposite polarity. That is to say each north pole is circumferentially adjacent to two south poles and each south pole is circumferentially adjacent to two north poles.

Preferably, the permanent magnets are affixed to the planar surface of the rotor by adhesive.

The plurality of permanent magnets are preferably circumferentially spaced apart. The rotor may further comprise a plurality of non-magnetic spacers configured to circumferentially space apart adjacent ones of the plurality of permanent magnets. Each non-magnetic spacer is preferably affixed to the planar surface of the rotor. The spacers may be affixed by adhesive, or a mechanical fastener. Each spacer is preferably elongate, and arranged such that the major dimension extends substantially along the radial direction. Each spacer preferably has a thickness substantially equal to the thickness of one of the permanent magnets. The opposed sides of each said spacer are preferably substantially parallel.

Alternatively, the planar surface of the rotor may comprise a plurality of protrusions configured to circumferentially space apart adjacent ones of the plurality of permanent magnets. The height of each protrusion in a direction extending axially from the rotor plate
is preferably less than that thickness of a permanent magnet. For example, the ratio of the permanent magnet thickness to the height of each protrusion may be between 2 and 10, more preferably between 4 and 10. Advantageously, ensuring the height of the protrusion is less than the thickness of a permanent magnet may ensure that there is not excessive flux leakage between the permanent magnets.

Each protrusion may be elongate, and arranged such that the major dimension extends substantially along the radial direction. In this example, a single protrusion may be provided between adjacent permanent magnets. Alternatively, a plurality of protrusions may be provided between adjacent magnets. In this example, each protrusion may be: circular having a diameter substantially equal to the width of the space between adjacent magnets; elliptical having a minor dimension substantially equal to the width of the space between adjacent magnets; rectangular substantially equal to the width of the space between adjacent magnets, and a major dimension substantially less than the radial length of a permanent magnet; or any other suitable shape.

Preferably, the permanent magnets are be shaped such that they are narrower toward the centre of the rotor and wider toward the edge of the rotor, such that the profile of the plurality of permanent magnets tapers evenly from the narrow end thereof to the wider end thereof.

Stator housing

According to a second aspect of the present disclosure, there is provided an extruded stator housing for an axial flux electrical machine, wherein the housing is tubular and substantially cylindrical in shape, the inner surface of the housing comprising a plurality of recesses, each recess configured to receive at least an outer part of a conductive coil of a stator of an axial flux electrical machine.

According to an aspect of the present invention, there is provided a stator housing for an axial flux electrical machine, the housing being tubular and substantially cylindrical in shape, the inner surface of the housing comprising a plurality of recesses, each recess configured to receive an outer part of a conductive coil of a stator of an axial flux electrical machine.

The cross-section of each recess, perpendicular to the axis of rotation of the axial flux electrical machine, is preferably elongate, the major dimension of each elongate recess
extending substantially in the radial direction of the axial flux electrical machine. Each elongate recess preferably has an aspect ratio of between about 5 and about 15. The aspect ratio of each recess may be between about 7 and about 12, more preferably between about 7 and about 10.

The side walls of each recess are preferably substantially parallel to the rotational axis of the axial flux electrical machine.

The circumferential distance between adjacent recesses is between about 1 times and about 3 times the width of each recess.

The stator housing preferably further comprises an annular ring configured to form an annular channel adjacent the circumferential outer surface of said stator housing. The stator housing preferably further comprises a spacer configured to divide said annular channel, the spacer extending from a first axial end of said stator housing to a second axial end of said stator housing. In this way, the spacer positions the annular ring relative to the stator housing outer surface to form the annular channel, and divides the annular channel such that it forms a C-shape. The spacer preferably mechanically couples the stator housing to the annular ring. The annular ring preferably comprises a cooling fluid inlet disposed adjacent a first side of said spacer, and a cooling fluid outlet disposed adjacent a second side of said spacer, the inlet and the outlet being in fluid communication with the annular channel. As will now be appreciated, the spacer divides the annular channel such that cooling fluid flow proceeds circumferentially around the annular channel.

In a preferred example of the present invention, the stator housing is formed by extrusion. In this preferred example, the plurality of recesses are preferably formed from a first set of protrusions extending from the inner surface of the stator housing and a second set of protrusions extending from the inner surface of the stator housing, wherein the first set of protrusions are formed integrally with said stator housing, and the second set of protrusions are formed separately and positioned within said stator housing. The second set of protrusions are preferably mechanically attached to said stator housing. The first set of protrusions are preferably interlaced with said second set of protrusions.

Advantageously, forming the stator housing and recesses in this manner improves the manufacturability of the stator housing. The minimum thickness of any feature of the extrusion tool used to form the stator housing may be increased, such that the tool life is significantly increased.
The first set of protrusions are preferably interlaced with said second set of protrusions such that each protrusion from the first set of protrusions is adjacent a protrusion from the second set of protrusions.

Each of the second set of protrusions may comprise a key configured to engage with a corresponding slot formed in the inner surface of the extruded stator housing to mechanically attach each protrusion thereto. Alternatively, each of the second set of protrusions comprises a slot configured to engage with a corresponding key formed on the inner surface of the extruded stator housing to mechanically attach each protrusion thereto.

The second set of protrusions may be formed by extrusion.

The stator housing may be extruded as a single part. That is to say, the main tubular body of the stator housing may be formed as a single part. Alternatively, the stator housing may be formed of a plurality of circumferentially-interlocking extruded segments. In an example, the housing may be extruded as a plurality of interlocking arcuate segments. The housing may be formed of two, three, four, five or more interlocking arcuate segments. In one further example, the extruded housing may be formed of two sections, a first outer section and a second inner section, the inner section comprising the plurality of recesses. The inner section may comprise a plurality of sub-sections, each sub-section comprising at least one recess. The second inner section preferably interlocks with said first outer section.

When the stator housing comprises an annular ring, the annular ring is preferably formed by extrusion. When the annular ring is spaced apart from the outer surface of the tubular body of the stator housing by a spacer, the spacer is preferably formed of a slot and key, the slot being formed on one of an inner surface of said annular ring and the outer surface of said stator housing, the key being formed on the other of the inner surface of said annular ring and the outer surface of said stator housing.

Preferably, the extruded housing has an outer surface which is shaped so as to increase the overall surface area of the outer surface of the extruded housing.

The outer surface of the extruded housing may include cooling fins or a heatsink.

Cooling
According to a third aspect of the present disclosure, there is provided a stator housing for an axial flux electrical machine, wherein the housing further includes at least one recess or channel in which a liquid cooling arrangement is accommodated.

The housing may comprise at least two recesses or channels, in which the liquid cooling arrangement is accommodated, arranged on opposed axial ends of said housing.

The or each recess or channel may be substantially annular. The or each recess or channel may be substantially adjacent the outer parts of conductive coils in a stator of an axial flux electrical machine.

An inner surface of the housing preferably comprises a plurality of recesses, each recess configured to receive at least an outer part of a conductive coil of a stator of an axial flux electrical machine. Each recess is preferably elongate, the major dimension of each elongate recess extending substantially in the radial direction of the axial flux electrical machine. The sides of each recess are preferably substantially parallel to the rotational axis of the axial flux electrical machine. The circumferential distance between adjacent recesses is preferably between about 1 times and about 3 times the width of a recess.

Preferably, the liquid cooling arrangement within the housing comprises a pipe for receiving cooling liquid, the pipe being in contact with the housing or, in addition, via a thermally conductive material to improve the heat transfer between the housing and the pipe. The thermally conductive material may be one of: a resin; a paste; and a putty.

Preferably, the pipe forming the liquid cooling arrangement provides an inlet and outlet on an outer face of the housing.

Alternatively, the recess or channel may be configured to directly receive cooling liquid, the housing further comprising at least one plate configured to seal said at least one recess or channel.

The housing may further comprise at least one further channel provided on an axial end of said housing. Preferably said further channel is in fluid communication with said at least one recess or channel. The further channel may be axially located between a rotor of an axial flux electrical machine and a controller of the axial flux electrical machine. In this way, the single liquid cooling arrangement may cool both the axial flux electrical machine and the controller for the axial flux electrical machine.
The housing may yet further comprise an external annular channel provided adjacent the circumferential face of said housing. Preferably, the external annular channel is in fluid communication with the or each other recess or channel.

Preferably, the liquid cooling arrangement is connected to a closed loop cooling system, wherein a cooling liquid is passed into the inlet of the cooling arrangement within the housing, around the pipe, and out of the outlet of the cooling arrangement, into a radiator or heat exchanger, through a pump, and then back in to the inlet of the cooling arrangement.

The stator housing may be formed by extrusion as described above, the at least one recess or channel being subsequently machined.

Mechanical Stacking

According to a fourth aspect of the present disclosure, there is provided a stacked axial flux electrical machine assembly, comprising a plurality of axial flux electrical machines as described herein mechanically stacked in series.

In this way, where the stacked axial flux electrical machine assembly is a motor, the total torque provided to an output shaft by the axial flux electrical machine assembly is a sum of the torque provided to the shaft by the rotors of each axial flux electrical machine.

Alternatively, where the stacked axial flux electrical machine assembly is a generator, the total torque provided to an input shaft of the axial flux electrical machine assembly is distributed substantially equally to the rotors of each axial flux electrical machine.

Preferably, the axial flux electrical machines each comprise a shaft mechanically coupled to the rotors of said axial flux electrical machine, wherein each shaft is mechanically coupled to a respective shaft of the adjacent axial flux electrical machine.

Alternatively, the stacked axial flux electrical machine assembly comprises a single shaft, said shaft being mechanically coupled to each rotor of each axial flux electrical machine. In some embodiments, the stacked axial flux electrical machine assembly may comprise N stators, where N is an integer greater than 1, arranged about a common shaft, and M rotors, where M = N + 1, wherein the or each rotor disposed between adjacent stators comprising permanent magnets on opposed sides of said rotor.

Preferably, the plurality of stacked axial flux machines are controlled by a single controller.
Preferably, the plurality of stacked axial flux machines are controlled by a single controller integrated into the stacked axial flux assembly.

Alternatively, each of the plurality of stacked axial flux machines is controlled by a corresponding controller. The controllers may be integrated into their corresponding axial flux electrical machine.

**Laminated Flux Guide**

According to a fifth aspect of the present disclosure, there is provided a laminated flux guide for an axial flux electrical machine as described herein, the flux guide comprising a plurality of laminations. The flux guide having a base surface and an opposing surface tapered relative to the base surface, the laminations being parallel to said base surface. In use, the flux guide is arranged such that each lamination is substantially in a plane extending in the radial and axial directions of an axial flux electrical machine.

Preferably, the laminations are arranged such that three edges of each lamination are substantially co-planar in a direction perpendicular to said base surface. The flux guide is preferably shaped so as to maximally fill a space defined by adjacent circumferential conductive coils of a stator of an axial flux electrical machine as described herein.

Preferably, the laminations are formed from electrical steel. For example, the electrical steel may be grain-orientated electrical steel. The laminations are preferably stacked such that the grains of each lamination in the stack have the same grain direction. In particular, the stacking is such that, when provided in a stator of an axial flux electrical machine, the grain orientation of the stack is substantially parallel to the axis of rotation of the axial flux machine so as to align with the axial flux lines produced by the permanent magnets of the rotors.

Preferably, the flux guide comprises an outer layer of, preferably electrically insulating, material. The outer layer preferably covers at least the tapered surface. More preferably the outer layer is configured to extend around the base surface and tapered surface, and thus wrap the flux guide.

There is also provided a stator for an axial flux electrical machine as described herein, the stator comprising a plurality of flux guides as described.
A method of manufacture of the flux guide is also provided comprising cutting a sheet of electrical steel to provide a plurality of laminations, and stacking the laminations so as to provide a base surface and a tapered surface, relative to said base surface, to form a tapered stack of laminations. The laminations are preferably affixed to each other using adhesive. The laminations are preferably arranged such that three edges of each lamination are substantially co-planar in a direction perpendicular to said base surface.

Preferably, the method of manufacture comprises providing laminations comprising grain-orientated electric steel (such as C.R.G.O transformer core steel) and stacking the laminations such that the grain direction of every lamination in the stack substantially aligns. The stack of laminations may then be insulated by wrapping the stack of laminations in an outer casing of electrically insulating material.

According to a sixth aspect of the present disclosure, there is provided a conductive coil for a yokeless axial flux electrical machine stator with distributed windings. The conductive coil comprises a first active section and a second active section. Each active section extends in a generally radial direction substantially perpendicular to an axis of rotation of the electrical machine and comprises a plurality of winding turn portions stacked parallel to the axis of rotation such that a cross-section perpendicular to the radial direction of each active section is elongate with a major dimension parallel to the axis of rotation. The second active section is pitched apart in a circumferential direction and axially offset from the first active section.

Conductive coils of this type provide for ease of manufacture of a stator that is constructed using the conductive coils, as well as high machine efficiency. For example, the conductive coils can form a structure into which flux guides, such as lamination packs, can be placed. This allows for the stator to be manufactured quickly, and also with a high degree of accuracy which improves the efficiency of the electrical machine. Additionally, the axial offset of the active sections facilitates stacking of the coils in the axial and circumferential direction. The use of axially stacked winding turns also mitigates skin and proximity effects in the active sections. This is because the cross-section of each winding turn is smaller and, given that the winding turns are series connected, the current is deterministically governed to flow over the full axial extent of each active section. This reduces heating and improves flux linkage.

According to this sixth aspect, the conductive coil may optionally comprise a plurality of pairs of active sections connected to each other in series. Adjacent pairs of active sections
may circumferentially overlap so as to define a space of a second type for receiving a flux guide. The space of the second type is a circumferential space between two adjacent active sections of different pairs of active sections of the coil. The circumferential space is, like the active sections defining it, substantially radially extending and may be elongate in the radial direction. Each such additional pair of active sections per coil advantageously increases the number of slots per pole per phase by one. This can reduce losses and therefore improve efficiency because a higher number of slots per pole per phase can result in a more accurately sinusoidal magnetic flux density. Further, the number of active sections per coil can be scaled with the radius of machine.

According to a seventh aspect of the present disclosure, there is provided a conductive coil for a stator of a yokeless axial flux electrical machine. The conductive coil comprises two pairs of active sections. Each active section extends in a generally radial direction substantially perpendicular to an axis of rotation of the electrical machine. The generally radially extending active sections of each pair are pitched apart in a circumferential direction. The two pairs of active sections partially circumferentially overlap so as to define a space of a second type for receiving a flux guide. The space of the second type is a circumferential space between two adjacent active sections of different pairs of active sections of the coil. The circumferential space is, like the active sections defining it, substantially radially extending and may be elongate.

Conductive coils according the seventh aspect type provide for ease of manufacture of a stator that is constructed using the conductive coils, as well as high machine efficiency. For example, when a plurality of such coils are circumferentially distributed around a stator-ring, the resulting coil structure will have circumferentially distributed spaces (of the second type) into which flux guides can be provided. This allows for the stator to be manufactured quickly, with a large number of flux guides, and also with a high degree of accuracy which improves the efficiency of the electrical machine. Further, since each coil has (at least) two pairs of pitched apart active sections, the coils will provide a stator with (at least) two slots per pole per phase, which makes the magnetic flux density generated by the stator more sinusoidal, with less significant harmonic components. For sinusoidally-varying current, the average torque produced by the electrical machine results from the interaction of the fundamental magnetic field components and not from the harmonic components. This is advantageous because harmonic components in the circumferential spatial magnetic flux density result in larger eddy currents in the permanent magnets of the rotors, which in turn causes higher losses and increased heating. Furthermore, any additional harmonic
components in the winding magnetomotive force distribution can cause increased losses in
the flux guides. Further still, the number of pairs of active sections per coil can be scaled
with the radius of machine and/or by choosing the span (pitch) between the active sections
forming each pair. Each additional pair of active sections per coil therefore increases the
number of slots per pole per phase by one, so higher efficiencies are attainable, especially
as the size of the machine is increased.

According to this seventh aspect, each active section may optionally comprise a plurality of
winding turn portions stacked parallel to the axis of rotation such that a cross-section
perpendicular to the radial direction of each active section is elongate with a major
dimension parallel to the axis of rotation. Axially stacking insulated winding turns mitigates
the skin and proximity effects in the active sections. This reduces heating, since the current
is better spread through the conductor cross-section, and improves flux linkage.

According to the seventh aspect, each pair of active sections may optionally be axially
offset from each other. Axially offsetting the active sections facilitates stacking of the coils
in the axial and circumferential direction, which provides for flexibility in the span (pitch)
between each pair of active sections and also improves the structural rigidity of the
complete winding owing to the interlocking nature of the coils. It also increases the flux
linkage in the core and therefore increases torque generation.

The following optional features may also apply to the conductive coil of the sixth aspect and
to the conductive coil of the seventh aspect.

In use, current flows in opposite radially directions along the active sections that form the
pair of active sections (that is, current flows along the second active section in a opposite
direction to the current that flows along the first active section).

Each active section may be only a single winding turn wide. Alternatively, each active
section may be a plurality of winding turns wide. That is, each active section may comprise
a plurality of circumferentially stacked winding turn portions. If each active section does
comprise a plurality of circumferentially stacking winding turn portions, the number of
circumferentially stacked winding turn portions is preferably less than the number of axially
stacked winding turn portions, such that the major dimension of the cross-section of the coil
that is perpendicular to the radially extending direction of the active section is parallel to the
axis of rotation. For example, the active sections may be only two winding turn portions
wide but comprise more than two winding turn portions in the axial direction. For example,
the ratio of the number of axially stacked winding turn portions to the number of circumferentially stacked winding turn portions may be greater or equal to three, preferably greater or equal than five, more preferably greater or equal to seven. A coil that is more than one winding turn portion wide increases the overall length of conductor, which in turn increases the impedance of the coil. A higher impedance may allow the use of a controller with a lower switching rate, which may in some cases reduce costs.

The winding turn portions of the first and second generally radially extending active sections of a pair of active sections may have proximal ends located at an inner radius and distal ends located at an outer radius. The proximal ends of the winding turn portions may be connected by inner loop sections and the distal ends are connected by outer loop sections such that, in use, current flows in opposite radial directions along the pair of radially extending active sections.

The outer loop sections may be configured to form an outer part of the coil that is substantially parallel to the axis of rotation. An axially parallel part of the coil can be axially inserted into an aperture in a stator housing, which improves ease of stator manufacture. Further, the extended nature of the outer part of the coil provides a greater surface area for mechanical locking of the coils and cooling at the outside circumference of the stator.

Each outer loop section may have any shape but may preferably be substantially semi-circular or rectangular such that the outer part of the coil is a half-disk or rectangular surface. The surface of the outer part may also be curved, for example involute-shaped. These surfaces create a large surface area yet also require a relatively limited length of conductor, which reduces material costs.

Additionally or alternatively, the outer loop sections may be configured to form a substantially involute part of the coil. Involute parts, which maintain a substantially constant gap between adjacent conductive elements, provide for a radially-interlocking arrangement of circumferentially-distributed coils. There may be two substantially involute outer parts of the coil, connecting the outer part of the coil to the two active sections.

The inner loop sections may be configured to form an inner part of the coil that is substantially parallel to the axis of rotation. Being substantially parallel to the axis of rotation, the inner part takes up as little circumferential space as possible. This is significant as physical space it as a premium at the inner radius of the stator.
Each inner loop section may have any shape but may preferably be substantially semi-circular or rectangular such that the inner part of the coil is a half-disk or rectangular surface. The surface of the inner part may also be curved, for example involute-shaped. These shapes require a relatively limited length of conductor to implement, which reduces material costs.

The inner loop sections may be configured to form a substantially involute part. Involute parts, which maintain a substantially constant gap between adjacent conductive elements, provide for a radially-interlocking arrangement of circumferentially-distributed coils. There may be two substantially involute inner parts of the coil, connecting the inner part of the coil to the two active sections.

The number of pairs of active sections may be an integer multiple of two. Using an integer multiple of two pairs of active sections readily allows each coil to be made from a plurality of identical conductive elements, which reduces manufacturing costs.

The conductive coil may be configured so that, in use, current flows in the same direction along adjacent active sections of the coil separated by one of the spaces for a flux guide. This avoids the current flowing in these adjacent active sections being counter-productive to torque production.

The plurality of pairs of active sections that make up one coil may be integrally formed or formed by connecting, in series, a plurality of separate elements which each comprise one pair of active sections. The connection may be made using a ferrule, by brazing or by welding, for example. Separate elements may be formed by winding, bonding and forming conductors, which can be performed using techniques that are relatively cheap to implement. Integrally forming elements may be expensive, but may also allow for more complex coil topologies that cannot be achieved or are difficult to achieve by usual winding techniques. Furthermore, with integrally-formed elements, the number of constituent parts of the stator is reduced.

The conductive coil may comprise first and second connection portions for connecting the conductive coil to a power supply. The first and second connection portions may extend parallel to the axis of rotation. The connection portions may extend in the same parallel direction or in opposite parallel directions. Parallel extending connecting portions allow for very simple connection of the coils to the power supply.
The first and second connection portions of the coil may be provided proximate to a radially outer end of the coil. In this way, connections can be made proximate to the outer radius of the stator assembly, where there is more circumferential space than, for example, at the inner radius of the stator assembly. This means that connections are less densely packed, which provides for ease of manufacture and more reliable electrical connections.

A stator for an axial flux electrical machine, the stator comprising a plurality of conductive coils according to the sixth aspect is also provided. A stator for an axial flux electrical machine, the stator comprising a plurality of conductive coils according to the seventh aspect is also provided. In either case, the plurality of conductive coils may be circumferentially distributed around the stator.

The plurality of conductive coils may be provided in a plurality of groups, each group corresponding to one pole of the stator.

Each conductive coil may be configured to be connected to a phase of a multi-phase power supply.

Circumferentially adjacent conductive coils may be configured to be connected to different phases of the multi-phase supply such that, for an N-phase power supply, the stator comprises a plurality of groups of N conductive coils, each group of N conductive coils comprising one coil for each phase of the N-phase supply, each group corresponding to one pole of the stator.

For each phase of the multi-phase power supply, every second coil of the stator that is connected to said phase may be connected to a common busbar. In this way, the winding may be divided into two interleaved portions that connect half of the total number of coils per phase to one of two phase busbars.

Circumferentially adjacent conductive coils may circumferentially overlap to define spaces of a first type for receiving flux guides. Each space of the first type may be a circumferential space between two adjacent active sections of two different coils. Like the active sections defining them, the spaces of the first type extend in the radial direction and may be elongate in the radial direction. Since the coils of the stator naturally form a structure for receiving flux guides, the stator to be manufactured quickly, and also with a high degree of accuracy which improves the efficiency of the electrical machine.
The stator may further comprise flux guides positioned in the spaces of the first and/or second type.

The stator may further comprise a stator housing. The stator housing may comprise circumferentially distributed and axially extending apertures for receiving the outer parts of the conductive coils that are substantially parallel to the axis of rotation. As noted above, this provides for easier and more accurate manufacture and heat transfer from the conductive components of the stator through the stator housing.

Axial flux electrical machines comprising such stators are also provided. The axial flux machines may comprise a pair of opposed rotors disposed on opposite sides of the stator. Each rotor may be dedicated solely to one stator, or one or more rotors may be shared between two axially aligned stators.

A method of manufacturing a stator of an axial flux electrical machine is also provided. The method comprises positioning a plurality of conductive coils in a stator housing so that the plurality of coils are circumferentially distributed around the stator housing. Each conductive coil comprises a first active section and a second active section, each active section extending in a generally radial direction substantially perpendicular to an axis of rotation of the electrical machine and comprising a plurality of winding turn portions stacked parallel to the axis of rotation such that a cross-section perpendicular to the radial direction of each active section is elongate with a major dimension parallel to the axis of rotation. The second active section is pitched apart in a circumferential direction and axially offset from the first active section.

The stator housing may comprise a plurality of circumferentially distributed and axially extending apertures. In this case, positioning the plurality of conductive coils in the stator housing may comprise, for each respective conductive coil, positioning an axially extending part of the respective coil into one of the axially extending apertures. This increases ease of assembly, accuracy of assembly, mechanical locking and, in use, cooling and efficiency.

Each conductive coil may comprise a plurality of pairs of active sections connected to each other in series, wherein adjacent pairs of active sections circumferentially overlap so as to define a space of a second type for receiving a flux guide. The space of the second type may be a circumferential space between two adjacent active sections of the same coil but different pairs of active sections of the coil. The method further comprises positioning flux guides in the spaces. As noted above, advantageously, each additional pair of active
sections per coil increases the number of slots per pole per phase by one, which can reduce losses and therefore improve efficiency. Further, the number of active sections per coil can be scaled with the radius of machine, so higher efficiencies are possible with larger machines.

Another method of manufacturing a stator of an axial flux electrical machine is provided. The method comprises positioning a plurality of conductive coils in a stator housing so that the plurality of coils are circumferentially distributed around the stator housing. Each conductive coil comprises two pairs of active sections, each active section extending in a generally radial direction substantially perpendicular to an axis of rotation of the electrical machine. The generally radially extending active sections of each pair are pitched apart in a circumferential direction. The two pairs of active sections of each partially circumferentially overlap so as to define a space of a second type for receiving a flux guide. The space of the second type is a circumferential space between two adjacent active sections of different pairs of active sections of the same coil. The method further comprises positioning flux guides in the spaces.

In this second method, each active section may comprise a plurality of winding turn portions stacked parallel to the axis of rotation such that a cross-section perpendicular to the radial direction of each active section is elongate with a major dimension parallel to the axis of rotation. This reduces heating, since the current is more evenly spread through the conductive cross-section. The active sections of each pair may be axially offset from each other. Axially offsetting the active sections facilitates stacking of the coils in the axial and circumferential direction, provides for flexibility in the span (pitch) between each pair of active sections and also improves the structural rigidity of the complete winding owing to the interlocking nature of the coils.

In both methods, the conductive coils may be positioned so that circumferentially adjacent conductive coils circumferentially overlap and thereby define spaces of a first type for receiving flux guides. Each space of the first type may be a space between two adjacent active sections of two different coils. Both methods may further comprise positioning flux guides in the spaces of the first type.

Both methods may further comprise impregnating at least part of the stator in a bonding compound, such as a resin. This strengthens the stator assembly, protecting it against mechanical and electromagnetic forces it experiences during use. Means for connecting
the coils to the power supply may not be impregnated with the bonding compound, advantageously allowing access to the connections after impregnation.

According to a further aspect of the claimed disclosure, there is provided a stator for an axial flux electrical machine. The stator comprises a plurality of circumferentially distributed conductive coils. Each of the plurality of conductive coils is configured to be connected to a phase of a multi-phase power supply and comprises at least one pair of active sections. Each active section extends in a generally radial direction substantially perpendicular to an axis of rotation of the electrical machine. The generally radially extending active sections of each pair are pitched apart in a circumferential direction. Circumferentially adjacent conductive coils circumferentially overlap to define spaces of a first type for receiving a flux guide. Each space of the first type is a circumferential space between two adjacent active sections of two different coils.

The circumferential spaces are, like the active sections, substantially radially extending, and may be elongate in the radial direction.

The conductive coils of such a stator form a structure into which flux guides, such as lamination packs, can be placed. This allows for the stator to be manufactured quickly, and also with a high degree of accuracy which improves the efficiency of the electrical machine. Additionally, the number of flux guides and, correspondingly, slots per pole per phase of the stator can be readily increased and readily scales with the radius of the electric machine. Increasing the number of slots per pole per phase can make the circumferential, spatial magnetic flux density within the stator and the two machine airgaps more sinusoidal, with lower harmonic distortion. For sinusoidally varying phase currents, the average torque that is produced by the electrical machine results more from the interaction of the fundamental magnetic field components and not from the harmonic components. This is advantageous because harmonic components in the circumferential spatial magnetic flux density result in larger eddy currents in the permanent magnets of the rotors, which causes higher losses and increased heating. Furthermore, any additional harmonic components in the winding magnetomotive force distribution can cause increased losses in the flux guides.

In use, current flows in opposite radial directions along the active sections that form a pair of active sections of a coil.

Each conductive coil may comprise a plurality of pairs of active sections connected to each other in series. Adjacent pairs of active sections may circumferentially overlap so as to
define a space of a second type for receiving a flux guide. The space of the second type may be a circumferential space between two adjacent active sections of the same coil but different pairs of active sections of the coil. The circumferential space is, like the active sections defining, substantially radially extending and may be elongate in the radial direction. Each additional pair of active sections per coil increases the number of slots per pole per phase by one, which can reduce losses and therefore improve efficiency. Advantageously, the number of active sections per coil can be scaled with the radius of machine.

The number of pairs of active sections may be an integer multiple of two. Using an integer multiple of two pairs of active sections readily allows each coil to be made from a plurality of identical conductive elements, which reduces manufacturing costs.

The plurality of pairs of active sections that make up one coil may be integrally formed or formed by connecting, in series, a plurality of separate elements which each comprise one pair of active sections. The connection may be made using a ferrule, by brazing or by welding, for example. Separate elements may be formed by winding, bonding and forming conductors which can be performed using known winding techniques that are relatively cheap to implement. Integrally forming elements may be expensive but may also allow for more complex coil topologies that cannot be achieved or are difficult to achieve by usual winding techniques. Furthermore, with integrally-formed elements, the number of constituent parts of the stator is reduced.

The stator may further comprise flux guides, such as electric steel laminations, positioned in the first and/or second types of spaces. Flux guides channel the flux axially between corresponding magnetic poles on opposing rotors. These flux guides may have high magnetic permeability in at least the axial direction and thus, for a specific arrangement of permanent magnets, increases the magnetic flux density in the stator.

The plurality of conductive coils may be provided in a plurality of groups, each group corresponding to one pole of the stator. Circumferentially adjacent conductive coils may be configured to be connected to different phases of the multi-phase supply such that, for an N-phase power supply, the stator comprises a plurality of groups of N conductive coils, each group of N conductive coils comprising one coil for each phase of the N-phase supply, each group corresponding to one pole of the stator.
The stator may be configured so that, in use, current flows in the same direction along adjacent active sections separated by one of the second type of spaces for a flux guide. This avoids the current flowing in these adjacent active sections being counter-productive to torque production.

The active sections of each pair of active sections may be axially offset from each other. Axially offsetting the active sections facilitates stacking of the coils in the axial and circumferential direction, which provides for flexibility in the span (pitch) between each pair of active sections and also improves the structural rigidity of the complete winding owing to the interlocking nature of the coils.

Each active section may comprise a plurality of winding turn portions stacked parallel to the axis of rotation such that a cross-section perpendicular to the radial direction of each active section is elongate with a major dimension parallel to the axis of rotation. Axially stacking insulated winding turns mitigates skin and proximity effects in the active sections. This is because the cross-section of each winding turn is smaller and, given that the winding turns are series connected, the current is deterministically governed to flow over the full axial extent of each active section. This reduces heating, since the current is spread more evenly through the conductive cross-section and improves flux linkage.

Each active section may be only a single winding turn wide. Alternatively, each active section may be a plurality of winding turns wide. That is, each active section may comprise a plurality of circumferentially stacked winding turn portions. If each active section does comprise a plurality of circumferentially stacking winding turn portions, the number of circumferentially stacked winding turn portions is preferably less than the number of axially stacked winding turn portions, such that the major dimension of the cross-section of the coil that is perpendicular to the radially extending direction of the active section is parallel to the axis of rotation. For example, the active sections may be only two winding turn portions wide but comprise more than two winding turn portions in the axial direction. For example, the ratio of the number of axially stacked winding turn portions to the number of circumferentially stacked winding turn portions may be greater or equal to three, preferably greater or equal than five, more preferably greater or equal to seven. A coil that is more than one winding turn portion wide increases the overall length of conductor, which in turn increases the impedance of the coil. A higher impedance may allow the use of a controller with a lower switching rate, which may in some cases reduce costs.
The winding turn portions of the first and second generally radially extending active sections may have proximal ends located at an inner radius and distal ends located at an outer radius. The proximal ends of the winding turn portions may be connected by inner loop sections and the distal ends may be connected by outer loop sections such that, in use, current flows in opposite radial directions along the pair of radially extending active sections.

The outer loop sections may be configured to form an outer part of the coil that is substantially parallel to the axis of rotation. An axially parallel part of the coil can be axially inserted into an aperture in a stator housing, which improves ease of stator manufacture. Further, the extended nature of the part of the coil provides a greater surface area for mechanical locking of the coils and cooling at the outside circumference of the stator.

The stator may further comprise a stator housing that comprises circumferentially distributed and axially extending apertures for receiving the outer parts of the conductive coils that are substantially parallel to the axis of rotation. As noted above, this provides for easier and more accurate manufacture and improved heat transfer from the conductive components of the stator through the stator housing.

Each outer loop section may have any shape but may preferably be substantially semi-circular or rectangular such that the outer part of the coil is a half-disk or rectangular surface. The surface may also be curved, for example involute-shaped. These surfaces create a large surface area yet also require a relatively limited length of conductor for a given axial extent of the coil, which reduces material costs.

The outer loop sections may be configured to form substantially involute parts of the coil. Involute parts, which maintain a substantially constant gap between adjacent conductive elements, provide for a radially-interlocking arrangement of circumferentially-distributed coils. There may be two substantially involute outer parts of the coil, connecting the outer part of the coil to the two active sections.

The inner loop sections may be configured to form an inner part of the coil that is substantially parallel to the axis of rotation. Being substantially parallel to the axis of rotation, the inner part takes up as little as circumferential space as possible. This is significant as physical space is at a premium at the inner radius of the stator.
The inner loop sections may have any shape but may preferably be substantially semi-circular or rectangular such that the inner part is a half-disk or rectangular surface. The surface may also be curved, for example involute-shaped. These shapes require a relatively limited length of conductor to implement, which reduces material costs.

The inner loop sections may be configured to form a substantially involute part of the coil. Involute parts provide a radially-interlocking arrangement for circumferentially-distributed coils. There may be two substantially involute inner parts of the coil, connecting the inner part of the coil to the two active sections.

The stator may further comprise connecting means for connecting the conductive coils to the multi-phase power supply. The connecting means may be provided axially above a plane that is perpendicular to the axis of rotation and axially above the conductive coils and/or may be provided below a plane that is perpendicular to the axis of rotation and axially below the conductive coils. Positioning the connecting means above and/or below the coils allows for easy connection of the coils to the connecting means, and also means that the connections may be accessible even after impregnation of the stator assembly. This prevents a faulty connection from rendering the entire stator unusable.

Each of the plurality of conductive coils may comprise a pair of connection portions that extend substantially parallel to the axis of rotation for connecting the conductive coils to the connecting means. The connection portions may extend in the same parallel direction or in opposite parallel directions. Parallel extending connection portions allow for very simple connection of the coils to the connecting means.

The connecting means may comprise a plurality of busbars, which may be annular, or a plurality of busbar sections.

For each phase of the multi-phase power supply, every second coil of the stator that is connected to said phase may be connected to a common busbar. In this way, the winding may be divided into two interleaved portions that connect half of the total number of coils per phase to one of two phase busbars.

A yokeless axial flux electrical machine comprising any of the stators described above is also provided.

The yokeless axial flux electrical machine may further comprise a pair of opposed rotors disposed on opposite sides of the stator, each rotor comprising a plurality of
circumferentially distributed permanent magnets defining a pole pitch of the electrical
machine. The angle by which each pair of active sections is pitched apart may be different
than the pole pitch of the electrical machine defined by the permanent magnets. While the
angle by which each pair of active sections is pitched apart may be the same as the pole
pitch, using a different angle facilitates long-chording or short-chording of the winding.

The angle by which each pair of active sections may be pitched apart is less than the pole
pitch. Using a smaller angle allows short-chording, which can be used to further reduce
harmonics in the stator field.

One of the pair of opposed rotors may be shared between the stator and a second, axially
aligned, stator.

According to a yet further aspect of the claimed disclosure, there is provided a method of
manufacturing a stator of an axial flux electrical machine. The method comprises
positioning a plurality of conductive coils in a stator housing so that the plurality of coils are
circumferentially distributed around the stator housing. The conductive coils are positioned
so that circumferentially adjacent conductive coils circumferentially overlap and thereby
define spaces of a first type receiving a flux guide. Each space of the first type is a
circumferential space in the region where two coils overlap. The method further comprises
positioning flux guides in the spaces of the first type.

The conductive coils of such a stator form a structure into which flux guides, such as
lamination packs, can be placed. This allows for the stator to be manufactured quickly, and
also with a high degree of accuracy which improves the efficiency of the electrical machine.

Each conductive coil may comprise a plurality of pairs of active sections connected to each
other in series. Adjacent pairs of active sections may circumferentially overlap so as to
define a space of a second type for receiving a flux guide. The space of the second type
may be a circumferential space between two adjacent active sections of the same coil but
different pairs of active sections of the coil. In this case, the method may further comprise
positioning flux guides in the spaces of the second type. Not only does this provide
additional structure for placing flux guides, but it allows for the manufacture of machines
with a higher number of slots per pole per phase. As explained above, this can reduce
harmonics in the stator field and improve machine efficiency.
The stator housing may comprise a plurality of circumferentially distributed and axially extending apertures. In this case, positioning the plurality of conductive coils in the stator housing may comprise, for each respective conductive coil, positioning an axially extending part of the respective coil into one of the axially extending apertures. This increases ease of assembly, accuracy of assembly, mechanical locking and, in use, cooling and efficiency.

The method may further comprise impregnating at least part of the stator in a bonding compound, such as a resin. This strengthens the stator assembly, protecting it against mechanical and electromagnetic forces it experiences during use. Means for connecting the coils to the power supply may not be impregnated with the bonding compound, advantageously allowing access to the connections after impregnation.

Any feature in one aspect of the disclosure may be applied to other aspects of the disclosure, in any appropriate combination. In particular, method aspects may be applied to apparatus aspects, and vice versa. Furthermore, any, some and/or all features in one aspect can be applied to any, some and/or all features in any other aspect, in any appropriate combination.

It should also be appreciated that particular combinations of the various features described and defined in any aspects of the disclosure can be implemented and/or supplied and/or used independently.

**Brief Description of the Drawings**

Embodiments of the disclosure will now be further described by way of example only and with reference to the accompanying figures in which:

Figure 1A is a side view of an axial flux machine showing a stator assembly, rotors and a shaft;

Figure 1B is a perspective view of the axial flux machine of Figure 1A;

Figure 2A is a perspective view of the rotors and shaft of the axial flux machine of Figures 1A-1B;

Figure 2B is a plan view of one rotor of the axial flux machine of Figures 1A-B and 2A, more clearly showing the permanent magnets of the rotor;
Figure 3 is a cross-sectional side view of an axial flux machine, showing additional detail not visible in Figures 1A-1 B and 2A-2B;

Figure 4A is a perspective view of the conductive components of a stator assembly of an axial flux machine that includes 48 conductive coils;

Figure 4B is a side view of the conductive components of the stator assembly of Figure 4A;

Figure 4C is a plan view of the conductive components of the stator assembly of Figures 4A and 4B;

Figure 5A shows plan and underneath views of a single conductive coil element having a single pair of radially extending active sections;

Figure 5B shows two perspective views of the conductive coil element of Figure 5A;

Figure 5C shows two side views of the conductive coil element of Figures 5A and 5B;

Figure 5D shows front-on and rear-on views of the conductive coil element of Figures 5A-5C;

Figure 5E is a plan view of part of a stator that includes a plurality of the conductive elements of Figures 5A-5D circumferentially distributed around the stator, showing spaces resulting from their overlap;

Figure 5F is a plan view showing the stator of Figure 5E;

Figure 5G is a plan view of a conductive element illustrating how the conductive element may be wound in a flat plane;

Figure 5H is a side view of the conductive element illustrated in Figure 5G;

Figure 5I is a perspective view of the conductive element illustrated in Figures 5G and 5H;

Figure 5J is a plan view of an alternative conductive coil element;

Figure 5K is a plan view of a stator which utilizes a plurality of the conductive coil elements of Figure 5J;
Figure 6A shows plan and underneath views of a conductive coil that includes two pairs of circumferentially overlapping radially extending active sections connected in series;

Figure 6B shows two perspective views of the conductive coil of Figure 6A;

Figure 6C shows two side views of the pair of the conductive coil of Figures 6A and 6B;

Figure 6D shows front-on and rear-on views of the conductive coil of Figures 6A-6C;

Figure 7A is a front-on view showing the conductive coil of Figures 6A-6D connected to a pair of busbars;

Figure 7B is a perspective view of the conductive coil of Figures 6A-6D connected to the pair of busbars;

Figure 7C is a plan view of the pair of the conductive coil of Figures 6A-6D connected to the pair of busbars;

Figure 8A is a perspective view of eight conductive coils connected to the same pair of busbars;

Figure 8B is a plan view of the eight conductive coils connected to the same pair of busbars;

Figure 9A is a front-on view of two circumferentially adjacent conductive coils connected to respective pairs of busbars;

Figure 9B is a perspective view of the two circumferentially adjacent conductive coils connected to respective pairs of busbars;

Figure 9C is a plan view of the two circumferentially adjacent conductive coils connected to respective pairs of busbars;

Figure 10 is a perspective view of six adjacent conductive coils illustrating an alternative way of connecting the conductive coils to a 3-phase power supply;

Figure 11A is a plan view of half of the conductive components of a sixteen-pole, three-phase stator assembly that includes 24 conductive coils each having two pairs of radially extending active sections;
Figure 11B is a perspective view of the stator assembly of Figure 11A;

Figure 12A is a perspective view of a stator assembly, including a stator housing that houses the conductive coils of the stator assembly;

Figure 12B is a plan view of the stator assembly of Figure 12A, showing how the conductive coils are received within the stator housing apertures;

Figure 12C is a perspective view of the stator assembly of Figures 12A and 12B, showing the busbars and phase connections;

Figure 13 is a flowchart illustrating a method of manufacturing a stator;

Figure 14 is an efficiency map showing the efficiency of an axial flux machine comprising the stator assembly of Figures 12A-12C for a range of torque and speed values;

Figure 15 is a perspective view of a rotor plate for an axial flux electrical machine as described herein;

Figure 16A is a perspective view of an alternative rotor for an axial flux electrical machine as described herein;

Figure 16B is a perspective view of a further alternative rotor for an axial flux electrical machine as described herein;

Figure 17A is a perspective view of an extruded housing for an axial flux electrical machine as described herein;

Figure 17B is a plan view of an extruded housing for an axial flux electrical machine as described herein;

Figure 18 is a perspective view of a housing comprising a cooling system for an axial flux electrical machine as described herein;

Figure 19 is a perspective view of two stacked axial flux electrical machines as described herein;

Figure 20 is a schematic view of an alternative axial flux electrical machine comprising a shared rotor;
Figures 21A, 21B, and 21C show views of a flux guide for an axial flux electrical machine as described herein;

Figure 22 is a plan view of a multi-part extruded housing for an axial flux electrical machine; and

Figure 23 is a plan view of a portion of an alternative multi-part extruded housing for an axial flux electrical machine.

Like reference numbers are used for like elements throughout the description and figures.

Detailed Description

An embodiment of the disclosure will now be described with reference to an axial flux motor 100. While a motor 100 is described, it should be appreciated that the disclosure could equally be implemented in other types of axial flux electrical machines such as generators.

Overview of an Axial Flux Machine

Figure 1A and Figure 1B illustrate the main components of an axial flux motor 100. The axial flux motor 100 includes a stator assembly 1, two rotors 2a, 2b disposed on opposite sides of the stator assembly 1, and a shaft 3. The shaft includes a drive end 3a and non-drive end 3b. The rotors 2a, 2b are fixedly mounted to the shaft 3. In use, the stator 1 of the axial flux motor 100 remains stationary and the rotors 2a, 2b and shaft 3 rotate together relative to the stator 1. It should be appreciated that various components typically present in a motor 100, such as rotor cover plates and means for connecting the stator to a source of power, have been omitted from Figures 1A and 1B for clarity.

While Figures 1A-1B show two rotors 2a, 2b and a single stator 1, it will be appreciated that other configurations are possible. For example, one of the rotors 2a, 2b could be shared between two axially-aligned stators. That is, there may be two stators and three rotors, with one of the three rotors shared between the two stators.

Figures 2A and Figure 2B illustrate the rotors 2a, 2b and the shaft 3 of the motor 100 without the stator assembly 1. As is particularly clear from Figure 2B, each rotor 2a, 2b includes a plurality of circumferentially distributed permanent magnets 21, 22, 23, 24. The magnets 21, 22, 23, 24 are, for example, rare-earth magnets such as NdFeB magnets. Circumferentially adjacent magnets, such as permanent magnets 21 and 22 have opposite
polarity. That is, each north pole 23 is circumferentially adjacent to two south poles 22, 24, and each south pole 22 is circumferentially adjacent to two north poles 21, 23.

Although it cannot be seen in Figures 2A and 2B, the rotors 2a, 2b are mounted such that opposing permanent magnets have opposite poles. That is, a north pole on rotor 2a faces a south pole on rotor 2b and vice versa. Consequently, the magnets of the two rotors 2a, 2b generate a magnetic field with axial lines of magnetic flux between the two rotors 2a, 2b.

As will be understood by those skilled in the art, the stator assemblies 1 described herein are yokeless, but not ironless. A yoke is an additional structural element present in some stators for guiding lines of magnet flux between opposite poles of the rotor magnetic field. That is, the yoke completes the magnetic circuits within the stator. Since the axial flux machines 100 described herein utilize a pair of opposed rotors 2a, 2b whose opposed permanent magnets have opposite polarity, there is no need for a yoke to complete the magnetic circuits because the flux is unidirectional. Having a yokeless stator reduces the overall weight of the axial flux machine, which is greatly beneficial in many practical applications. In addition, it improves efficiency since there are no losses attributed to a varying flux density in a yoke region.

The circumferential (angular) separation $\alpha$ of the centres of two adjacent permanent magnets 21, 22 of the rotor 2a, 2b defines the pole pitch of the axial flux motor 100. It is noted that the average span of the permanent magnets $\beta$ may be the same as or less than the pole pitch $\alpha$ of the motor 100. In Figures 2A-2B, adjacent magnets are separated by a non-magnetic spacer and so the average span $\beta$ of the permanent magnets 21-24 is less than the pole pitch $\alpha$ of the motor 100. In an example, $\beta$ is approximately $3/4$ of $\alpha$. The ratio of $\beta$ to $\alpha$ can be chosen to reduce the circumferential, spatial harmonic distortion of the permanent magnet flux density in the stator 1. As will be appreciated, it is not essential to provide non-magnetic spacers to enable the span $\beta$ of the permanent magnets 21-24 to be less than the pole pitch $\alpha$ of the motor 100. For example, the permanent magnets 21-24 can be affixed to the rotor using adhesive, or the like, in their required spaced apart positions.

The rotors 2a, 2b illustrated in Figures 2A-2B have sixteen circumferentially distributed permanent magnets 21-24 and therefore have sixteen poles. However, this is merely an example and in practice there may be greater or fewer than sixteen poles, partly depending on the intended application. For example, the poles typically exist in pairs (so there is typically an even number of poles) and the number of poles is to some extent limited by the
radius of the rotors 2a, 2b, which will depend on the size of motor suitable for the intended application. The rotor 2a, 2b could, for example, have eight or thirty-two poles.

Turning to Figure 3, this shows a cross-sectional view of the axial flux motor 100 of Figures 1-2 with additional detail. As the embodiments described herein principally concern the conductive components 10 of the stator assembly 1, which will be described in more detail below with reference to Figures 4-12, only a brief overview of the components of Figure 3 will be provided. Those skilled in the art will be familiar with the components of an axial flux machine such as an axial flux motor 100, and will also appreciate that not all of the features shown in Figure 3 are essential to an axial flux machine, and that features which are present can be implemented in a variety of different ways.

In addition to the stator 1, drive-end rotor 2a, non-drive-end rotor 2b and shaft 3, Figure 3 shows the drive-end and non-drive-end rotor cover plates 4a, 4b which enclose the rotors 2a, 2b and generally seal the motor 100 to prevent the ingress of outside material. Rotor spacer ring 4c spaces apart the rotors 2a, 2b. O-ring seals 8a, 8b and dynamic seal 9 further seal the internals of the motor 100. Rotation of the rotors 2a, 2b is assisted by the drive-end and non-drive end bearings 6a, 6b, which maintain the airgaps 5 between the permanent magnets of the rotors 2a, 2b and the stator 1. An encoder assembly 7 that includes an encoder mount 71, an on-axis position encoder 72 and an associated encoder sensor magnet 73 is also shown.

Conductive Coils and Stator

The conductive components 10, including the conductive coils 12, of a stator assembly 1 will now be described with reference to Figures 4-12. It should be appreciated that although specific examples are described, with specific numbers of stator poles 11, conductive coils 12 and current phases, this is not intended to limit the scope of the claims.

Briefly turning to Figures 12A-12C, there is illustrated a stator assembly 1 which can be seen to include an annular or ring-shaped stator housing 20 which houses the conductive components 10 of the stator 1. The core of the stator assembly 1, where the axial flux provided by the rotor magnets interacts with the radially flowing current flowing through the conductive components 10 to generate the torque that causes the rotors 2a, 2b to rotate, includes radially extending active sections of the conductive components 10 of the stator and flux guides 30 in the form of lamination packs. The flux guides 30, in the form of lamination packs, which may comprise grain-oriented electrical steel sheets surrounded by
electrical insulation, are positioned in spaces between the radially extending active sections
of the conductive components 10 of the core. The flux guides 30, in the form of lamination
packs, act to channel the magnetic flux produced by the permanent magnets 21-24
between the current carrying conductors.

Now turning to Figures 4A-4C, the conductive components 10 (which from now on will be
simply referred to as the “stator 10”) are shown without the stator housing 20 or the flux
guides 30, in the form of lamination packs. As is best appreciated from the top-down view
of Figure 4C, the stator 10 has distributed windings and comprises a plurality (in this case
sixteen) of circumferentially distributed stator poles 11a, 11b, ..., 11p, each of which
comprises a plurality of conductive coils 12. Each conductive coil 12 is connected to one
phase of a multi-phase power supply via connection means 15, 16 which in this example
take the form of busbars. In this specific example, the stator 10 is configured for use with a
three-phase power supply so there are three conductive coils 12 per pole 11a-1 1p of the
stator.

It will be appreciated that with sixteen poles 11a-1 1p and three conductive coils 12 per
pole, the stator 10 of Figures 4A-C has a total of 48 circumferentially distributed conductive
coils 12. However, it can be seen from the top-down view of Figure 4C that this stator 10
actually has 96 radially extending active sections. Further, it can be seen from the side-on
view of Figure 4B that there are two axially offset layers of radially extending active
sections, giving a total of 192 radially extending active sections. The reasons for this will
become apparent from the description of Figures 5-9. In summary, each conductive coil 12
includes one or more conductive elements 120, each of which includes a pair of axially
offset radially extending active sections. Each conductive coil 12 of the stator 10 of Figures
4A-4B includes two such conductive elements 120, and since each conductive element 120
includes a pair of axially offset radially extending sections, the total of 192 radially
extending active sections is accounted for.

The conductive components of stator 10 may be made of any combination of one or more
conductive materials. However, the conductive components 10 are preferably made from
copper.

Figures 5A-5D are various views of a single conductive element 120. As noted above and
as will be explained in more detail below, each conductive coil 12 is made up of one or
more conductive elements 120. It will be appreciated that in the case of one conductive
element 120 per conductive coil 12, a conductive coil 12 and a conductive element 120 are
equivalent. Figures 6A-6D illustrate a conductive coil 12 which is made up of two conductive elements 120 and 120', and will be described below.

Returning to Figures 5A-5D, as is best appreciated from the top-down views of Figure 5A in which the axis of rotation is perpendicular to the plane of the page, a conductive element 120 includes a pair of circumferentially pitched apart, radially extending active conducting sections 121a, 121b. These radially extending active sections 121a, 121b are referred to as “active” sections because, when the conductive coils 12 are positioned in the stator, they are disposed within the stator core and so interact with the magnetic field provided by the magnets of the rotors 2a, 2b. It will be appreciated that since the active sections extend in a generally radial direction, which is approximately perpendicular to the axial flux in the core, the flux linkage is at least close to maximized.

The angle γ by which the two active sections 121a, 121b are pitched apart will be referred to as the coil span. The coil span can be the same as or different (less or more) than the pole pitch a (defined by the angle between the centres of the permanent magnets of the rotor). Preferably the coil span γ is less than the pole pitch a. For example, γ may be approximately 5/6 of a. By making γ less than a, short-chording of the winding can be implemented, which reduces the spatial harmonic content of the winding magnetomotive force (mmf).

Turning to Figures 5E and 5F, these show a sixteen-pole, three-phase stator 10' which is similar to the stator 10 of Figures 4A-4C, but differs in that each coil 12 of stator 10' has only one conductive element 120 (one pair of active sections 121a, 121b). That is, in Figures 5E and 5F, a coil 12 and a conductive element 120 are equivalent. Like stator 10, conductive coils 120a, 120b, 120c of stator 10' are circumferentially distributed around the stator and circumferentially adjacent coils circumferentially overlap.

As is particularly clear from Figure 5E, the circumferential overlap of the coils 120a, 120b, 120c defines circumferential spaces between active sections of the coils. These circumferential spaces, which are elongated in the radial direction, can receive flux guides. Spaces such as the labelled spaces 141a, 141b, 141c will be referred to as spaces of the first type. As can be seen, spaces of the first type 141a, 141b, 141c are defined between active sections of different coils. For example, space 141b is between one of the two active sections of coil 120a and one of two active sections of coil 120c. However, it is to be appreciated that the two coils that define a particular space of the first type 141a,
141b, 141c can depend on various factors, including the number of phases per stator pole, the number of poles and the selected coil span $\gamma$.

Now returning to Figures 5A-5D, as can be seen from Figures 5B and 5D, the two active sections 121a, 121b are axially offset from each other. This facilitates stacking of the conductive coils 12 in the circumferential direction, and also facilitates the circumferential stacking of conductive elements 120 where there are multiple conductive elements 120 per conductive coil 12. As will be discussed in more detail with reference to Figure 14, this allows for more stator poles and more slots per pole per phase, both of which can provide for greater efficiency. Furthermore, the winding may be readily short chorded.

As can be seen in each of Figures 5B, 5C and 5D, each conductive element 120 is formed from a continuous length of wound conductor. The outermost winding of the length of conductor terminates at a first connection portion 128, which will be referred to as the outer tail 128. The outer tail 128 extends substantially parallel to the axial direction. As will be described in more detail below, this facilitates convenient connection of the coils 12 to the multi-phase power supply. The innermost winding turn portion terminates at a second connection portion 129, which will be referred to as the inner tail 129.

As can also be seen in each of Figures 5B, 5C and 5D, the length of conductor that forms the conductive element 120 is wound such that there are a plurality of winding turn portions 131a, 131b stacked parallel to the axis of rotation of the electrical machine. The resulting cross-section of the conductive element 120 that is perpendicular to the radial direction of each active section 121a, 121b is elongate with a major dimension parallel to the axis of rotation. In the example of Figures 5A-5D, there are fourteen axially stacked winding turn portions 131a, 131b, though this is not intended to limit the disclosure as other numbers are equally possible.

Figures 5G, 5H and 5I illustrate how the conductive element 120 may be formed by winding a length of conductor. As illustrated in Figure 5G, the conductor is wound around a pair of support elements 301, 302 (which protrude perpendicularly out of the plane of page) in a single plane so as to form a flat, planar winding with a number (in this case fourteen) of turns or layers. That the winding is flat is best appreciated from Figures 5H and 5I. The innermost winding terminates at the inner tail 129 and the outermost winding terminates at the outer tail 128.
Having formed the flat winding shown in Figures 5G-5I, the three-dimensional shape of the conductive element 120 is formed by bending or deforming the flat winding into the shape shown in Figures 5A-5D. The bending can be performed using a bending tool, as is known in the art. For example, a bending tool with axially offset inner male profile blocks may push against outer female forms to bend the flat winding so that the active sections are axially offset from each other. The outer tail 128 and inner tail 129 may be separately bent as desired.

To make the bending process easier, the flat winding may first be imparted with additional strength so that the winding maintains its shape during the bending. In one example, the conductor has a heat- or solvent-activated outer bond layer so that after winding, the turns/layers can be bonded together to maintain the shape.

It should be appreciated, particularly from Figures 5G-5I, that the conductive element 120 can be wound in a variety of different ways, and the particular winding that is illustrated is not intended to limit the disclosure. Some alternatives include:

- While the winding in Figure 5G has been wound around the support elements 301, 302 in an anti-clockwise sense, the length of conductor could equally be wound in the clockwise sense.

- While the outermost turn of the winding terminates such that that outer tail 128 leads into an active section 121a, 121b of the conductive element 120, this need not be the case. The outer turn could terminate at any point of the turn, for example so that the outer tail 128 leads into a loop section of the turn rather than an active section.

- While fourteen axially stacked winding turns are illustrated in Figure 5, there could be more than or fewer than fourteen turns.

- While the winding is one turn/layer thick (see Figure 5H in particular), it could be more than one turn/layer thick. In this case, each conductive element 120 will comprise a plurality of circumferentially stacked winding turn portions. While any number of circumferentially stacked winding turn portions is possible, the number will preferably be less than the number of winding turn portions in the axial direction, such that the cross-section of the conductive element 120 that is perpendicular to the radial direction of each active section 121a, 121b still has a major dimension
that is parallel to the axis of rotation. For example, the ratio of the number of axially stacked turns to the number of circumferentially stacked turns may be greater than three, and may preferably be greater than five.

As will be appreciated from the above, in use, current will flow along the two active sections 121a, 121b of the conductive element 120 in opposite directions (that is, inward and outward parallel to the radially extending direction). The reversal of the current direction is provided by outer loop sections 122 of the winding turn portions 131a, 131b and by inner loop sections 125 of the winding turn portions 131a, 131b. Each of the outer loop sections 122 includes a first portion 123 and a pair of second portions 124a, 124b (one for each of the pair of active sections 121a, 121b) which connect the active sections 121a, 121b to the first portion 123. Similarly, each of the inner loop sections 125 includes a first portion 126 and a pair of second portions 127a, 127b (one for each of the pair of active sections 121a, 121b) which connect the active sections 121a, 121b to the first portion 126.

As can be seen from Figures 5B, 5C and 5D, the outer first portions 123 together form an outer part 133 of the coil element 120 with a surface that is substantially parallel to the axis of rotation. In the specific example of Figures 5A-5D, the outer first portions 123 are substantially semi-circular and so the outer part 133 is a substantially flat half-disk 133, but other shapes are possible. For example, each of the outer first portions 123 may have a shape corresponding to three sides of a rectangle, such that they together form an outer part 133 which has a flat rectangular surface. As another example, the outer part 133 of the conductive element 120 formed by the outer first portions 123 need not be flat or planar: this is illustrated in Figure 5J, which shows a conductive element 120" with an outer part 133" with a curved profile and therefore curved surface. Figure 5K illustrates a plan view of a stator 10" comprising such conductive elements, which can be compared to Figure 4C (though note that stator 10" does not show any connecting means 15, 16).

The surface 133 formed by the outer first portions 123 can be used to facilitate cooling due to its relatively large surface area. Further, since the outer part 133 of the coil 120 is substantially parallel to the axis of rotation, a stator housing 20 may be provided with axially extending apertures 25 which axially receive the outer part 133 of the coil element 120", 120" to provide mechanical locking and improved cooling. This will be explained in more detail below.

The inner first portions 126 together form an inner part 136 of the coil element 120. The inner part 136 illustrated in Figures 5B-5D is substantially the same as the outer part 133
described above, and like the outer part 133 described above may be parallel to the axis of rotation and may be of various shapes and profiles. However, the inner part 136 will generally play less of a role in cooling and stacking of the coils 12, and so the inner portions 126 may be configured so as to reduce the overall quantity of conductor per conductive element 120 to reduce costs.

With regards to the outer second portions 124a, 124b and the inner second portions 127a, 127b, while they appear substantially straight in Figures 5A-5D, they are in fact slightly curved. Specifically, the shape of each of the outer first portions 124a, 124b is a section of a first involute, and so the first portions 124a, 124b together form outer substantially involute parts 134a, 134b of the coil element 120. Similarly, the shape of each of the inner second portions 127a, 127b is a section of a second involute, and so the first portions 127a, 127b together form inner substantially involute parts 137a, 137b of the coil element 120. The significance of the involutes will be described with reference to Figures 6A-6D.

While it has been described above that the conductive element 120 is formed by winding a length of conductor, this is not essential. The conductive element 120 could be manufactured in other ways, including by being formed integrally.

Further, while the illustrated elements 120 are wound from a length of conductor and comprise a stack of winding turn portions 131a, 131b, this is preferred but not essential. For example, rather than axially extending stack of winding turn portions 131a, 131b, each conductive element 120 could be formed by a single axially extending conductive strip. In some cases a single axially extending conductive strip may be preferable to a plurality of axially stacked winding turn portions 131a, 131b but, as will be described below, the use of stacked winding turn portions 131a, 131b advantageously helps mitigate the skin and proximity effects which can otherwise lead to increased losses.

As noted above, each conductive coil 12 may include only one conductive element 120. However, for reasons which will be explained in more detail below, each conductive element preferably includes two or more circumferentially overlapping conductive elements. An example of a conductive coil that includes two circumferentially overlapping conductive elements 120, 120' will now be described with reference to Figures 6A-6D.

Figure 6A shows above and below views of a conductive coil 12 which includes two conductive elements 120, 120'. The features of each of the two conductive elements 120,
120' are the same as those of the single conductive element 120 described above with
reference to Figures 5A-5D, and so their features will not be described again.

To form the conductive coil 12, two identical conductive elements 120, 120' are electrically
connected together in series at their inner tails 129, 129'. In the examples illustrated herein,
the inner tails 129, 129' are connected using a ferrule 130. However, there are other ways
of connecting the inner tails 129, 129', such as brazing or welding. To connect the two
elements 120, 120', one of the two conductive elements 120, 120' is rotated 180° about the
axis running vertically in the plane of the page in Figure 6A so that the outer tails 128, 128'
of the two conductive elements 120, 120' are in opposite directions and the inner tails 129,
129' are adjacent and therefore readily connected by a ferrule 130. Alternatively, the
conductive coil 12 comprising two conductive elements could be integrally formed as a
single piece.

The resulting conductive coil 12 has two pairs of circumferentially overlapping, pitched
apart pairs of active sections 121a, 121b; 121a', 121b'. Notably, the overlap of the two
pairs of active sections defines two spaces 142a, 142b. The first space 142a is defined
between one (a first) active section 121a of a first of the conductive elements 120 of the
coil 12 and between one (a first) active section 121a' of the second of the conductive
elements 120' of the coil 12. The second space 142b is defined between the other (the
second) active section 121b of the first conductive element 120 of the coil 12 and between
the other (the second) active section 121b' of the second conductive element 120' of the
coil 12. That is, the two spaces 142a, 142b are circumferential spaces between adjacent
active sections 121a, 121a'; 121b, 121b' of two different pairs of active sections 121a,
121b; 121a', 121b' of the same coil 12. Spaces of this type will be referred to as spaces of
the second type. Like the spaces of the first type, spaces of the second type 142a, 142b
provide spaces for flux guides 30, in the form of lamination packs. This makes it easier to
construct the stator assembly 1, and also increases the number of slots per pole per phase
of the stator assembly 1, which can increase the motor's efficiency.

Having now described spaces 141a-c of the first type (that is, spaces defined between
active sections of different coils) and spaces 142a-b of the second type (that is, spaces
defined between active sections of the same coil but different pairs), it is noted that when a
plurality of coils 12 which define spaces of the second type are provided in a stator 10 so
as to define spaces of the first type, the spaces of the first and second types may coincide.
This can be seen most clearly in Figure 11A, which illustrates a sixteen-pole, three-phase
stator in which each coil 12 comprises two conductive elements 120, 120'. Only half of the
conductive coils 12 are shown in Figures 11A-B so that the spaces can be clearly seen. Whether spaces of the first and second type coincide may depend on a number of factors, including the selected coil span \( \gamma \), the number of stator poles and the number of phases.

Returning to Figures 6A-6D, it can also be seen from Figures 6A and 6B that there is a gap 143a between the second portions 124a, 124a' of the outer loop sections 122, 122' which form one pair of outer involute parts 134a, 134a' of the two conductive elements 120, 120'. Likewise, there is a gap 143b between the second portions 124b, 124b' of the outer loop sections 122, 122' which form the other pair of outer involute parts 134b, 134b'. There is also a gap 144a between the second portions 127a, 127a' of the inner loop sections 125, 125' which form one pair of inner involute parts 137a, 137a'. Finally, there is also a gap 144b between the second portions 127b, 127b' of the inner loop sections 125, 125' which form the other pair of outer involute parts 137b, 137b'. Due to the geometric properties of involutes, the width of these gaps 143a, 143b, 144a, 144b remains substantially constant along the length of the involute sections of the conductive elements 120, 120'. This advantageously reduces the resulting diameter of the motor for a given rating and losses in the coils.

While a conductive coil 12 with two conductive elements 120, 120' has been described, it should be appreciated that a conductive coil 12 could have any integer number of conductive elements 120, including more than two. Increasing the number of conductive elements per conductive coil 12 will increase the number of spaces of the second type defined by the circumferentially adjacent active sections of the conductive elements 120, which in turn increases the number of slots per pole per phase in the stator 1. This can lead to the generation of a stator magnetic field with a more accurately sinusoidal magnetic flux density, with less significant harmonic distortion. This advantageously reduces the development of eddy currents in the permanent magnets of the rotors 2a, 2b, which in turn reduces heating losses and therefore provides a higher motor efficiency. However, it will be appreciated that the number of conductive elements 120 per conductive coil 12 will generally be limited by size constraints. For example, for a given cross-section of conductor (that is, the cross-section of the wire from which the windings are wound) and a given radius of the stator, the number of conductors which can be circumferentially fit into a single coil span \( \gamma \) is limited.

If a coil 12 is to have more than two conductive elements, there may be several further considerations. For example:
If the coils are to be formed by connecting multiple conductive elements 120 (by ferrules 130, for example), it may be preferable to provide several types of conductive elements to facilitate simpler connection of adjacent conductive elements. For instance, the conductive elements 120 described above may be used for the two circumferentially outer conductive elements, since their outer tails 128 will be connected to the power-supply. However, the one or more inner conductive elements that are between the outer conductive elements will be connected to conductive elements at both their inner tails 129 and outer tails 128, so a second type of conductive element with outer tails 128 adapted in a similar fashion to the inner tails 129 may be provided for ease of connection. Alternatively, each coil 12 may be formed as an integral unit, rather than by the connection of three or more separate conductive elements.

- Integer multiples of two conductive elements 120 per coil 12 may be preferable to an odd number of conductive elements 120 per coil 12. If an integer multiple of two elements 120 are used, the outer tails 128 of the two circumferentially outermost elements 120 will be directed in opposite parallel directions, as in Figure 6A-6D. While this is not essential, it provides for a more straightforward connection of the coils 12 using the connection means which will be described below with reference to Figures 7-10.

While a stator 10 with a single axial layer of circumferentially distributed coils 12 (the single layer having coils 12 with axially offset active sections) has been described, it will be appreciated that there may be multiple axially-stacked layers of coils per stator. In this case, the spaces of the first type and/or the spaces of the second type of each layer may advantageously substantially circumferentially coincide. This would advantageously allow for the insertion of axially-longer flux guides 30 which could extend through the axial length of the multiple axially-stacked layers, providing further gains in terms of ease and speed of assembly.

**Connecting the Coils to a Multi-Phase Power Supply**

Ways of connecting a plurality of circumferentially distributed conductive coils 12 to a multi-phase power supply will now be described. It should be appreciated that in practice there are many different ways which this could be accomplished, and many different ways will occur to one skilled in the art. The disclosure is therefore not limited to any particular connection arrangement. However, the described ways of connecting the conductive coils
12, which utilize connection means 15, 16 which are provided axially above/below a plane that is perpendicular to the axis of rotation and axially above/below the conductive coils, provides a particularly neat and well-organized set of connections. Further, the connections are easy to make, which reduces the likelihood of a poor connection, and the stator may be resin impregnated without impregnating the connection means, which allows connections to be checked and fixed even after impregnation of the stator assembly.

First referring to Figure 4B, there is a first connection means 15 that is provided axially above a plane that is perpendicular to the axis of rotation of the motor 100 and that is axially above the conductive coils 12. There is also a second connection means 16 that is provided axially below a plane that is perpendicular to the axis of rotation of the motor 100 and that is axially below the conductive coils 12. In the case of the stator 10, which is configured for use with a 3-phase power supply, the connection means 15 and 16 include provision for each of the 3-phases. However, this could be extended to a multi-phase power supply with any number of phases.

In the particular connection arrangement of Figures 4A-4C, which will be referred to as a parallel connection arrangement, each of the connection means 15, 16 includes three phase-connections and one star-connection. That is, the first connection means 15 includes a first phase connection 151 for a first phase of the power supply, a second phase connection 152 for a second phase of the power supply, a third phase connection 153 for a third phase of the power supply, and a star connection 154. Similarly, the second connection means 16 includes a first phase connection 161 for the first phase of the power supply, a second phase connection 162 for the second phase of the power supply, a third phase connection 163 for the third phase of the power supply, and a star connection 164.

In the described examples, the phase connections 151-153, 161-163 and star connections 154, 164 are in the form of annular busbars whose outer circumference (though equally this could be the inner circumference) substantially coincides with the axially extending outer tails 128, 128' of the conductive coils. The phase connection busbars 151-153, 161-163 are themselves connected to the power supply via inputs 1510-1530, 1610-1630.

In the illustrated parallel connection arrangement, each conductive coil 12 is connected to one phase of the power supply by connecting the coil 12 to one of the phase connections of one of the connection means 15, 16 (as an example, phase connection 151) and to the star connection of the other of the connection means 15, 16 (in the example, star connection 164). The connection of one conductive coil 12 to one phase connection 151
and one star ring 164 is illustrated in and will now be described with reference to Figures 7A-7C.

Figures 7A-7C show one conductive coil 12 that has two conductive elements 120, 120' connected to a first phase connection 151 from the first connection means 15, and to the star connection 164 from the second connection means 16. Since the outer tails 128, 128' of the conductive coil 12 extend axially and in opposite directions, and since the circumference of the busbars 151, 164 coincides with the axial extending outer tails 128, 128', the outer tails 128, 128' are easily connected to the connections 151, 164.

In order to make the connection even easier, the annular busbars 151, 164 are provided with circumferentially spaced apart receiving means 151a-h, 164a-x for receiving the axially extending outer tails 128, 128' of the coils 12. In the 3-phase parallel connection arrangement shown, each star connection 154, 164 will be connected to half of all coils 12, whereas each phase connection 151-153, 161-163 will only be connected to one in six coils 12. Consequently, in this example, the star connection 164 has three times as many equally spaced receiving means 164a-x than the first phase connection 151.

Returning to Figures 4A-4C, each pole 11a-1p of the stator 10 consists of one conductive coil 12 for each phase (Le., three conductive coils 12 per pole 11a-p because the stator is configured for use with a 3-phase supply), and circumferentially adjacent conductive coils 12 are connected to different phases. This is illustrated in Figures 11A and 11B for a sixteen pole stator 10 which is connected to a 3-phase power supply but for which only half of the conductors are shown, and so has only 24 circumferentially distributed conductive coils 12 can be seen.

In view of this, in the 3-phase parallel connection arrangement illustrated in Figures 4, 7-9 and 11-12, every sixth conductive coil 12 will be connected to the connection means 15, 16 in the same way. This is illustrated in Figures 8A and 8B. It can be that there are eight equally spaced conductive coils 12a-g connected to the same phase connection 151 and the same star ring 164. Although not shown in Figures 8A-8B, it will be appreciated that halfway between each of the coils will be another coil 12 connected to the same phase of the power-supply, but by the complimentary set of bus bars. That is, to the phase connection 161 and the star connection 154.

The conductive coils 12 corresponding to the other phases of the power-supply will be connected in essentially the same way as described above for one phase. To illustrate this,
Figures 9A-9C show how two circumferentially adjacent conductive coils 12 are connected in the parallel connection arrangement.

Figures 9A-9C show two circumferentially adjacent conductive coils 12a, 12b. Conductive coil 12a is connected in a similar way as conductive coil 12 in Figures 7A-7C. That is, coil 12a is connected to the second phase connection 152 and the star connection 164. Coil 12b, being circumferentially adjacent to coil 12a, is connected to a different phase of the power supply and is therefore connected to a different pair of busbars. Specifically, but without loss of generality, circumferentially adjacent coil 12b is connected to the third phase connection 163 of the second connection means 16 and to the star connection 154 of the first connection means.

The connections of the conductive coils 12 have been described above with reference to a parallel connection arrangement. However, other connection arrangements are possible. To illustrate this, Figure 10 shows an alternative arrangement, which will be referred to as a series connection arrangement.

In the series connection arrangement of Figure 10, the first connection means 15' which is above the conductive coils 12 differs from the connection means 15 of Figures 4, 7-9 and 11-12 in that it does not include a star connection: it only includes a first phase connection 15T, a second phase connection 152' and a third phase connection 153'. However, the second connection means 16' is the same as the second connection means 16 of Figures 4, 7-9 and 11-12 in that it has three phase connections 16T, 162', 163' and a star connection 164'. To compensate for the lack of star connection in the first connection means 15', the conductive coils 12 are connected in a different way. The phase connections 15T-153' of the first connection means 15' also serve twice as many conductive coils 12, and therefore have additional receiving means compared to the receiving means of the second connection means 16' and the first and second connection means 15, 16 of the parallel connection arrangement.

Figure 10 illustrates the series connection arrangement for two circumferentially adjacent stator poles 11 and 11'. Like the parallel connection arrangement, each pole 11, 11' includes one conductive coil per pole, giving three coils per pole: pole 11 consists of conductive coils 12a, 12b and 12c, and pole 11' consists of conductive coils 12a', 12b' and 12c'. Also like with the parallel connection arrangement, circumferentially adjacent coils are connected to different phases. However, while the coils of the same phase but adjacent poles (12a and 12a', for example) in the parallel connection arrangement are essentially
independently connected and form separate current paths, in the series connection arrangement their connections are related and they are part of the same current path.

Considering only coils 12a, 12a' which are connected to the same phase, the coil 12a of the first pole 11 is connected by its outer tails to the phase connection 153' of the first connection means and to the phase connection 163' of the second connection means. The coil 12a' of the second, adjacent pole 11' is connected to the phase connection 153' of the first connection means 15' and to the star connection 164' of the second connection means. The current path can therefore be considered to run from the phase connection 163' through the coil 12a, then along phase connection 153' and then through coil 12a' to the star connection 164'.

Different connection arrangements may be used for different practical applications. For example, the series connection arrangement described above theoretically provides a machine Torque Constant (measured in Nm/A) that is twice as high as that provided by the parallel connection arrangement described above. This will be better for some, though certainly not all, practical applications.

While the connection means 15, 15' have been described as being above the coils 12 and the connection means 16, 16' have been described as being below the coils, it should be appreciated that both pairs 15, 16; 15', 16' may be above the coils or both pairs 15, 16; 15', 16' may be below the coils. In this case, it may be preferable to produce coils 12 whose outer tails 128, 128' extend in the same axial direction rather than opposite axial directions.

Further, while the connection means 15, 16, 15' and 16' have been described as continuous, annular busbars, this is merely one way of implementing the connection means. For example, the connection means may not be continuous or annular, and may instead take the form of a series of two or more circumferentially distributed busbar sections. Many other kinds of connection means will occur to those skilled in the art.

**Stator Manufacture**

The features and construction of the conductive coils 12 described above provide for particularly efficient and effective manufacture of a stator that includes a plurality of circumferentially distributed coils 12. Of particular significance is the fact that the coils 12 themselves provide a structure into which flux guides 30, for example in the form of lamination packs, can be provided. This makes placing of the flux guides 30 in the stator
assembly 1 a comparatively straightforward and precise exercise, especially compared to many known manufacturing techniques which may involve winding coils around bobbin-like structures which house lamination packs, and then separately securing (using glue, for example) the wound bobbin-like structures into a stator housing. Various other advantages will be described.

Figure 13 is a flow-chart illustrating a method 500 for manufacturing a stator.

The method 500 includes providing 510 a plurality of conductive coils, such as the conductive coils 12 described above. Preferably the conductive coils 12 have a plurality of circumferentially overlapping pairs of circumferentially pitched apart radially extending active sections (as in the coil 12 of Figures 6A-6D) such that each coil 12 provides spaces of the second type. However, the coils 12 may only have one pitched apart pair of active sections (as in the coil of Figures 5A-5D). The conductive coils 12 may have been formed as a single integral piece, by connecting multiple conductive elements 120 in series, or in any other way.

At 520, the method 500 includes positioning a plurality of the conductive coils 12 in a stator housing so that the plurality of coils are circumferentially distributed around the stator housing. Preferably the conductive coils are positioned so that circumferentially adjacent conductive coils circumferentially overlap and thereby define spaces of the first type for receiving flux guides. The circumferential overlap of circumferentially adjacent coils 12 can be ensured by providing an appropriate number of coils 12 of an appropriate coil span $\gamma$ within the housing. As noted above, where the coils 12 have multiple pairs of active sections such that the coils each define spaces of the second type, the spaces of the first and second types may coincide with each other.

The stator housing 20 may be provided with a plurality of circumferentially spaced apart axially extending apertures 25 for receiving the coils 12. This makes the positioning of the coils 12 in the stator housing easier and more precise. Advantageously, if the coils 12 are formed so as to have an axially extending outer part 133, the axially extending outer part 133 can be received within the axially extending apertures 25. Since the axially extending outer part 133 have a large surface area, they provide good mechanically locking of the coils 12 in the stator housing for assembly without the need for glue (for example) and also provide a source of cooling of the stator. Circumferentially distributed apertures 25 for receiving the coils 12 can most clearly be seen in Figures 12A-12C.
Optionally, at 530, the method 500 includes positioning flux guides 30, such as lamination packs, in the spaces (of the first and/or second type) defined by the coils 12. As explained above, the overlap of adjacent coils creates spaces of the first type 141a, 141b, 141c between active sections of different coils. If the coils 12 each comprise more than one pair of radially extending active sections (as in Figures 6A-6D), pairs of spaces 142a, 142a’ of the second type will also be defined within each conductive coil 12. In either case, flux guides can also be positioned within the spaces. Since the coils 12 themselves provide a structure with defined spaces, positioning the lamination packs into the structure is straightforward, fast and precise. In combination with the provision of apertures 25 in the stator housing 20 for receiving the coils 12, this means that both the components of the stator core (the active sections of the coils 12 and the flux guides 30) can be quickly and very accurately positioned compared to many known techniques. It will be appreciated that accurately positioned core components reduces losses and therefore improves machine efficiency.

Optionally, at 540, the method 500 includes connecting the plurality of coils 12 to connecting means 15, 16 so that the coils can be connected to the multi-phase power supply. This may be done in any desired way, for example as described above using busbars in the parallel or series connection arrangements.

Optionally, at 550, the method 500 includes impregnating at least part of the stator assembly 1 in a bonding compound such as a resin. This strengthens the stator structure and therefore protects the stator assembly 1 against the electromagnet and mechanical forces it experiences in use. Furthermore, it can improve the conduction of heat between the stator constituents if the bonding compound has a heat transfer coefficient significantly higher than air.

If the connecting means 15, 16 are provided axially above and/or below the coils 12 as described above, the impregnation of the stator can take place before or after the coils are connected to the connecting means. Further, and advantageously, if the connecting means 15, 16 themselves are not impregnated, the connections can be tested, altered, and if necessary replaced after impregnation. This is highly desirable because a faulty connection in a resin-impregnated stator may otherwise render the entire stator unusable and unfixable.

**Machine Efficiency**
Axial flux machines 100 comprising the stator assembly 1 described herein have been found to provide not only a high peak efficiency, but a high efficiency over a broad range of operating parameters. While high peak efficiencies are often quoted, they are in practice rarely achieved, especially in applications where the machine is required to perform over a range of operating parameters. Efficiency over a broad range of parameters is therefore a more practically meaningful measure for many applications.

To illustrate this, Figure 14 is an efficiency map showing the measured efficiency of an axial flux machine comprising the stator assembly of Figures 12A-12C for a range of torque and speed values that are commonly-used in many applications. Contours of constant efficiency are included on the efficiency map. As can be seen, as well as a high peak efficiency (93%), the efficiency remains very high for almost all of the area of the efficiency map and high (over 80%) even at a relatively low speed of 500 rpm up to a torque of 30 Nm.

There may be a number of different reasons for the high efficiencies which the stator assembly 1 is able to achieve. Some of these will now be described.

First, as explained above, the almost self-forming structure of the conductive components of the stator 10 that is provided by the geometry of the coils 12 allows for the very accurate placement of components of the stator core. The accurate placement of the components of the core means that there is better coupling of the stator and rotor fields, and a high degree of symmetry around the circumference of the stator which improves the generation or torque.

Another significant advantage is the generation of a stator field with a more accurately sinusoidal magnetic flux density. As will be understood by those skilled in the art, the higher the number of slots per pole per phase in the stator, the more sinusoidal the magnetic flux density can be. The coils 12 and stator 10 described above can provide an increased number of slots per pole per phase by increasing the number of conductive elements 120 per conductive coil 12, and this number can easily be scaled up (if, for example, the radius of the stator can be increased for a particular application). An advantage of a highly sinusoidal magnetic flux density is that the flux density has a relatively low harmonic content. With a low harmonic content, more of the coupling the rotor and stator fields involves the fundamental components of the flux density, and less involves the interaction with the harmonic components. This reduces the generation of eddy currents in the rotor magnets, which in turn reduced losses due to heating. In contrast, many known axial flux
motors utilize a concentrated winding arrangement which only provides for a limited number (e.g. fractional) slot per pole per phase, which generates a much more trapezoidal flux density with more significant harmonic components.

While the coils 12 can be implemented using axially extending strips, they are preferably implemented using axially stacked winding arrangement illustrated in Figures 5A-5D and 6A-6D. While many motor manufacturers may consider this a disadvantage because it may be considered to reduce the fill factor in the stator core, the inventors have found this disadvantage is compensated for by the reduction in the skin and proximity effects which causes currents to flow around the outside of the conductor cross-section and predominantly the axially-outer portions of the active sections. The number of windings in the axial direction may be selected to balance these two considerations.

Rotor

As discussed above, the axial flux electrical machine includes two rotors 2a and 2b, disposed on opposite sides of the stator assembly 1, and attached to the shaft 3. One of the rotors 2a may be affixed to the drive end 3a of the shaft 3, and the other may be affixed to the non-drive end 3b of the shaft.

The rotors 2a, 2b are mounted on the shaft 3 such that opposing permanent magnets have opposite poles, such that a north pole on rotor 2a faces a south pole on rotor 2b and vice versa. Consequently, the magnets of the two rotors 2a, 2b generate a magnetic field with axial lines of magnetic flux between the two rotors 2a, 2b.

The rotors 2a, 2b, shown in Figures 2A-2B and discussed above include sixteen circumferentially distributed permanent magnets 21-24, and therefore include sixteen poles. The construction rotors 2a, 2b, may be such that the rotors 2a, 2b, are formed of a rotor plate 1500, such as that shown in Figure 15, which comprises planar face 1502 (a flat plate) for receiving the permanent magnets. It will of course be understood that the rotor plate 1500 is the same for both rotors 2a and 2b.

The rotor plate 1500 includes a lip 1504 on the outermost edge, which protrudes from the face 1502, and may be operable to improve the retention of the permanent magnets 21-24. This may have the advantageous effect that under rotation of the rotors 2a, 2b, the permanent magnets 21-24 are less likely to become dislodged from the rotor 2a, 2b, thus improving the longevity of the axial flux machine.
The improved affixing of the permanent magnets 21-24 on the rotor plate 1500, may also reduce the likelihood of the rotors 2a, 2b of the axial flux machine from becoming unbalanced, which may also increase the longevity and performance of the axial flux machine.

According to the present disclosure, the permanent magnets 21-24 may be unsegmented, that is to say that each permanent magnet 21-24 is formed of a single permanent magnet, and is not formed of multiple permanent magnets. This reduces the complexity of construction of the axial flux machine and in turn may improve the ease of manufacture, the longevity, and the overall simplicity of the axial flux machine.

The unsegmented permanent magnets 21-24 may be used in the axial flux machine according to the present disclosure because of the limited presence of eddy currents in the permanent magnets 21-24. The limited presence of eddy currents in the permanent magnets 21-24 may be attributed to the axial flux machine being driven from the fundamental magnetic field components and less from the harmonic components. This reduces the eddy currents generated in the permanent magnets, which in turn reduces losses due to heating.

The permanent magnets 21-24 may be affixed to the rotor plate 1500 by way of adhesive. Alternatively, where the rotor plate 1500 is formed of ferrous metal, the permanent magnets may simply be retained in position by magnetic forces generated by the permanent magnets themselves.

As discussed above, in relation to Figures 2A-2B, adjacent magnets are separated by a non-magnetic spacer. Each spacer may be retained by a fastener, such as a threaded fastener. In an alternative shown in Figure 16A, such spacers are not required. In this alternative, the rotor 1600 which comprises a rotor plate 1500 as discussed above and a plurality of permanent magnets. The permanent magnets in this example are affixed to the rotor plate by bonding them using adhesive. It has been found that this is sufficient, in combination with the magnetic forces between the permanent magnets and the rotor plate, to retain the permanent magnets in position, and maintain the spaces 1602 between adjacent magnets.

Again as discussed above in relation to Figures 2A-2B, in the examples shown in Figures 2A-2B and 16A, each permanent magnet is non-segmented and therefore has a single, monolithic, body. An alternative example is shown in Figure 16B, where the rotor 1604,
which again comprises a rotor plate 1500 as well as a plurality of substantially identical permanent magnets 1606. In the example of Figure 16B each permanent magnet 1606 is formed of a plurality of permanent magnet segments 1608a, 1608b, 1608c and 1608d. The permanent magnet segments 1608a - 1608d are arc shaped segments radially stacked adjacent each other such that the north poles are oriented in the same direction. A further alternative (not shown) forms each segmented permanent magnet from a plurality of elongate permanent magnet segments circumferentially stacked adjacent each other such that the north poles are oriented in the same direction.

In a further alternative example (not shown) to the rotors 2a, 2b, a rotor may be provided where the spacers are integrally formed with the rotor plate. In this example, the height of each spacer extending in an axial direction from the rotor plate is less than the thickness of the permanent magnet. In this way, excessive flux leakage between adjacent permanent magnets may be prevented. For example, the height of each spacer may be less than 50% of the thickness of the permanent magnet, more preferably less than 20%.

**Stator Housing**

The axial flux electrical machine described herein may comprise an extruded stator housing, such that the conductive coils 12 of the stator assembly 1 are provided within the housing. As can be seen in Figures 17A and 17B, the housing 1700 is generally tubular and cylindrical in shape, with an inner face 1702 and an outer face 1704.

The outer face may be shaped so as to increase the overall surface area of the outer face of the extruded housing, such as including cooling fins 1706 or a heatsink formed therein.

In increasing the surface area of the outer surface of the axial flux electrical machine, the extruded housing 1700 of the axial flux electrical machine may increase the rate at which heat energy may be dissipated from the axial flux electrical machine. Cooling of the axial flux electrical machine will be discussed in more detail below.

Previously-proposed axial flux electrical machine housings have employed stacked, stamped plates, in order to reduce eddy currents in the housing. As discussed above, the presence of eddy currents in an axial flux electrical machine in accordance with the present disclosure is limited, and as stated above, this may be an effect of the axial flux machine being driven from the fundamental magnetic field components and less from the harmonic components.
The limited presence of eddy currents may enable the housing 1700 of the axial flux electrical machine in accordance with the present disclosure to be formed of an extruded section as opposed to stacked, stamped plates. In turn, this may result in improved manufacturability and/or cost savings; for example the assembly complexity may be reduced, and therefore the assembly time may be reduced.

Forming the housing 1700 of the axial flux electrical machine as a single extruded section may also improve the structural rigidity of the axial flux electrical machine. It may also reduce the weight.

Additionally, the extruded housing of the axial flux electrical machine comprises, on the inner face 1702 thereof, a series of recesses which accommodate the outer sections of the coils 12 of the stator assembly 1, to improve the heat dissipation from the coils 12. This will be discussed in more detail later.

**Cooling**

The extruded housing described above may be used to improve the cooling performance of axial flux electrical machines in accordance with the present disclosure, as briefly described above.

As stated above, the outer face of the extruded housing of the axial flux machine may be shaped so as to increase the overall surface area of the outer face of the extruded housing, such as including cooling fins or a heatsink formed therein. It may therefore be advantageous to maximise the heat transfer from the stator assembly 1 of the axial flux electrical machine into the extruded housing.

Efficient cooling of the axial flux electrical machine in accordance with the present disclosure may also be promoted by the shape and orientation of the coils within the axial flux machine, and particularly the shape and orientation of the outer portion of the coils 12 which are at the outer edge of the stator 1. The cooling performance of the axial flux electrical machine may be improved by increasing the rate at which heat energy may be dissipated from the coils 12 of the stator 1.

To increase the rate at which heat energy may be dissipated from the stator 1, the heat energy may advantageously be transferred into the extruded housing of the axial flux electrical machine. To this end, the inner face of the extruded housing of the axial flux machine may include a lip, recess, or face which is shaped such as to make thermal
contact with the outer portions of the coils 12 of the stator 1, and therefore to enable heat transfer from the coils 12 of the stator into the extruded housing of the axial flux machine. As discussed above, the outer portion of each of the coils 12 have a surface that is substantially parallel to the axis of rotation, with the inner face of the housing including a complementary recess for the outer portion of each of the coils.

The coils 12 of the stator are encased within a potting compound which has a high heat transfer capacity, to promote efficient heat energy transfer from the coils 12 of the stator. In addition, a thermal paste or heat transfer compound may be placed between the flat section of each of the coils 12 and the inner face of the extruded housing to increase the heat transfer capacity further.

The heat energy may then be dissipated into the air, through the cooling fins or heat sink of the outer face of the extruded housing.

The extruded housing may also include a recess, channel, or similar in which to accommodate a liquid cooling arrangement. This liquid cooling arrangement may be used to increase the rate at which heat energy may be dissipated from the axial flux electrical machine, and therefore to improve the cooling performance of the axial flux machine. Advantageously, the recess, or channel, may be provided such that it is immediately adjacent the curved portion of the outer sections of the coils.

Liquid cooling, for example water cooling, may deliver more effective cooling performance than air cooling. This is because water has a greater specific heat capacity than air, and the specific heat capacity of water is over four times greater than that of air.

Such a liquid cooling arrangement is shown in Figure 18. The liquid cooling arrangement within the extruded housing 1800 may, for example, comprise a pipe 1802 formed of a material with high heat conductivity properties, such as copper, and may be in contact with the extruded housing directly, or additionally, via a thermal paste or putty to improve the heat transfer between the extruded housing and the pipe 1802. The pipe 1802 forming the liquid cooling arrangement provides an inlet 1804 and outlet 1806 on the outer face of the extruded housing 1800. A further pipe (not shown) is provided on the opposite face of the extruded housing 1800, and provides a similar inlet 1808 and outlet 1810.

Cooling water is fed into the inlets 1804, 1808 of each pipe, and removed from the outlets 1806, 1810 of the pipe. The cooling water is supplied into the inlet of the pipe at a reduced
temperature, and may be fed out of the outlet into a radiator, heat exchanger, phase-change cooler or similar, before returning to the inlet. This may be considered a cooling ‘circuit’. If the axial flux electrical machine is to be used, for example, in a vehicle, the heat energy transferred from the axial flux electrical machine into the cooling water may be used to heat the cabin of the vehicle, or to maintain the temperature of the battery packs of the vehicle, by way of a heat exchanger.

The cooling fins and/or heatsink may be employed in combination with a liquid cooling arrangement in order to maximise the rate at which the heat energy may be dissipated from the axial flux electrical machine.

The cooling circuit may be a closed loop system, such that the cooling liquid, for example water, is passed into the inlet of the cooling arrangement within the extruded housing, around the cooling channel which may form the cooling arrangement, and out of the outlet of the cooling arrangement, into a radiator, heat exchanger or similar (to transfer the heat energy from the cooling liquid into the air, or to another cooling or heating system, likely through a pump, and then back in to the inlet of the cooling arrangement.

In the case that the cooling circuit is a closed loop system, and the loop includes a radiator, the radiator may include forced cooling in the form of a fan or fans, to promote airflow through the radiator and to improve the cooling performance of the cooling circuit.

As mentioned above, in the case of a vehicle, the heat may be transferred from the axial flux electrical machine cooling circuit and into, for example, the heating circuit of the vehicle, or a heater to maintain the temperature of the battery pack of the vehicle. Maintaining the temperature of a battery pack in a vehicle may increase the performance of the battery pack; a low temperature may reduce the performance of the battery pack, thus reducing the range of the vehicle.

If the axial flux electrical machine is installed in a large vehicle, for example a bus or coach, the available space for cooling the axial flux machine may be large. The cooling circuit may therefore include a large radiator or heat exchanger, and may provide heat energy to a circuit which provides heating for the passengers of the vehicle. Alternatively, if the cooling circuit is a closed loop, it may utilise the space for cooling by using a large radiator.

The liquid cooling arrangement may also be advantageous in the case of mechanically stacked axial flux electrical machines described below. Air cooling may not be sufficient for
a plurality of axial flux electrical machines stacked together, and so for example, the liquid cooling arrangement of a first axial flux electrical machine in the stack may be connected to the liquid cooling arrangement of a second axial flux electrical machine in the stack, and so on. In an example, the outlet of the liquid cooling arrangement of the first axial flux electrical machine is connected to the inlet of the liquid cooling arrangement of the second axial flux electrical machine in the stack.

Liquid may then be passed through the cooling arrangement of both the first and second axial flux electrical machines. In an alternative example, a radiator or heat exchanger may be placed between the outlet of the cooling arrangement of the first axial flux electrical machine and the inlet of the second axial flux electrical machine in the stack. This may increase the cooling capacity.

In a further example, an axial flux electrical machine is mechanically affixed to a controller such that the controller and axial flux electrical machine form a single unit, and the cooling arrangement in the axial flux machine is configured to cool both the axial flux machine and the controller. In this example, a cooling plate may be provided between the axial flux electrical machine and the controller, the cooling plate being hollow and having an inlet and outlet for connection to a cooling circuit, or the like.

In a yet further example, an axial flux electrical machine is electrically attached, but not mechanically affixed to a controller. A further cooling channel may be provided in the controller, and the cooling circuit which cools the axial flux electrical machine may be extended in order to pass coolant through the cooling channel in the controller, thus also cooling the controller.

**Mechanical Stacking**

An advantage of the modular and yokeless nature of the axial flux electrical machine described above is that multiple instances of the axial flux electrical machine may be stacked on a single shaft (or mechanically coupled shafts to the effect of providing a single shaft) to form a stacked axial flux electrical machine assembly 1900. An example of this arrangement is shown in Figure 19. In this example, two substantially identical axial flux electrical machines as described herein are mechanically stacked together, and mechanically coupled such that the combined torque output of both axial flux electrical machines is provided at a single output shaft.
It will be appreciated that the stacked axial flux electrical machine assembly may comprise any number of axial flux electrical machines - i.e. any number of axial flux electrical machines may be stacked to provide a combined output at a single output shaft.

Each axial flux electrical machine of the stacked axial flux machine assembly may be controlled by its own separately provided controller. Alternatively, each axial flux machine may have its own integrated controller.

Figure 20 shows a schematic view of an alternative “stacked” axial flux electrical machine 2000. In this example, the assembly 2000 comprises two stators 2002, 2004, and three rotors 2006, 2008 and 2010. The stators 2002 and 2004 are as described herein. The rotors 2006 and 2010 are also as described herein. However, the rotor 2008 is provided with permanent magnets on opposed faces and is thus “shared” by both stator 2002 and stator 2004. The rotors 2006, 2008 and 2010 are provided on a single shaft (not shown).

Laminated Flux Guide

As described above, the stator of the axial flux machine utilises a number of flux guides that are circumferentially distributed around the stator, each flux guide being positioned in a radially-elongated space defined by circumferentially adjacent conductive coils. The purpose of the flux guide, in broad terms, is to increase the flux density produced by the coils and permanent magnets.

The flux guide according to the present embodiment will now be described in relation to Figure 21A, 21B and 21C.

The flux guide 2100 according to the present embodiment is made from a metal configured to increase the axial flux density produced by the permanent magnets and the coils of the stator. Here, the flux guide is made from laminated sheets of grain oriented electrical steel, for example cold-rolled grain-oriented (C.R.G.O) steel. These sheets are cut to form rectangular laminations. A first set 2102 of laminations are cut to substantially the same size in all three dimensions - they each have the same thickness and have the same surface height and surface width. A second set 2104 of laminations are each cut to have the same thickness and the same size in one of the two surface dimensions. This thickness and size is the same as that for the first set 2102. However, the laminations of the second set 2104 have incrementally decreasing size in the other surface dimension compared to the size of the first set of laminations in this dimension.
The laminations are then stacked in order of size, with the largest laminates - the laminates of the first set - forming the base of the stack and the smallest laminate at the top of the stack. The laminations are also arranged so that each lamination aligns with its adjacent lamination along at least three edges, resulting in the stack tapering in the direction in which the surface dimension of the second set incrementally increases. This results in one surface of the whole laminate stack having a stepped appearance.

In the present embodiment, the stack of laminations are then wrapped in an insulating material, such as a meta-aramid polymer wrapping, to form a lamination pack with a tapered shape as shown most clearly in Figure 21B. Electrically insulating the stack after lamination is preferred, as it provides optimal performance when the flux guides are provided in the stator. However, it will be appreciated that the laminate stack may not be insulated after stacking, providing a flux guide 2106 - in this case the stack of laminates may be directly provided in the stator.

The grains of the electrical steel are orientated in a substantially certain, single, direction. The individual laminations are stacked so that the grains of every lamination in the pack have the same grain direction. The lamination packs are then arranged between adjacent coils of the stator so that the grain orientation of the pack is substantially parallel to the axis of rotation. As such, the grain direction aligns with the axial flux lines produced by the stator in operation. This alignment of the grains of the steel acts to guide the flux produced by the circumferentially distributed conductive coils and the flux produced by the permanent magnets on the rotors. The effect of this is an increase in the magnetic flux density compared to the density of flux produced by the coils and permanent magnets when the flux guides are not present.

As has been described above, the separation between adjacent coils increases in the radial direction. As a result, the space defined by adjacent coils tapers towards to centre of the stator. Thus, the lamination pack (the flux guide) is provided with a tapered shape in the manner described above. In particular, the taper of the flux guide substantially matches the change in separation of adjacent coils. This is done to maximise the amount of flux guide material between adjacent coils, and thus maximise the effect of the flux guide on the flux density when the stator is in use.

*Further features of the Stator Housing*
Further examples of a stator housing for use with the axial flux electrical machine described herein are shown in Figures 22 and 23. As described above, the conductive coils 12 of the stator assembly 1 are provided within the stator housing 2200. Similarly to the stator housing shown in Figures 17A and 17B, the housing 2200 is generally tubular and cylindrical in shape, with an inner surface 2202 and an outer surface 2204.

Again, similarly to the stator housing of Figures 17A and 17B, a series of recesses 2206 are provided in the inner surface of the stator housing which accommodate the outer sections of the coils 12 of the stator assembly 1, to improve the heat dissipation from the coils 12. As discussed above, the outer portion of each of the coils 12 have a surface that is substantially parallel to the axis of rotation. The recesses 2206 form a complementary feature for receiving this outer portion of the coils. In this way, the heat transfer between the coils 12 and the stator housing 2200 is improved. In addition, the torque transfer and rigidity of the connection between the coils 12 and the stator is improved.

The coils 12 of the stator are encased within a potting compound which has a high heat transfer capacity, to promote efficient heat energy transfer from the coils 12 of the stator. In addition, a thermal paste or heat transfer compound may be placed between the flat section of each of the coils 12 and the inner face of the extruded housing to increase the heat transfer capacity further.

As can be seen, the cross-section of each recess, perpendicular to the axis of rotation of the axial flux electrical machine, is elongate, the major dimension of each elongate recess extending substantially in the radial direction of the axial flux electrical machine. In this example, each elongate recess has an aspect ratio of about 8.

The stator housing 2200 also comprises an annular ring 2208 configured to form an annular channel 2210 adjacent the circumferential outer surface of stator housing. The stator housing 2200 comprises a spacer 2212 configured to divide annular channel. The spacer 2212 extends from a first axial end of said stator housing to a second axial end of said stator housing. The spacer 2212 positions the annular ring 2208 relative to the stator housing outer surface to form the annular channel 2210, and divides the annular channel such that it forms a C-shape.

The spacer 2212 comprises a slot formed in the outer surface of the tubular body and a key formed on the inner surface of the annular ring 2208. The slot and key engage to mechanically couple the stator housing to the annular ring. The annular ring comprises a
cooling fluid inlet (not shown) disposed adjacent a first side of said spacer, and a cooling fluid outlet (not shown) disposed adjacent a second side of said spacer, the inlet and the outlet being in fluid communication with the annular channel.

The axial ends of the stator housing 2200, the annular ring 2208, and the annular channel 2210, are sealed and mechanically coupled by end plates (not shown) which also house bearings for receiving the electrical machine shaft. Recesses may be provided in the end plates to receive the end faces of the stator housing and the annular ring. The end plates are coupled to the stator housing using fixings, such as bolts, which engage, for example, with the threaded holes 2211.

As can be seen, the tubular body of the stator housing comprises protrusions within which the threaded holes 2211 are formed. As such, the annular ring 2208 is shaped such that the annular channel 2210 is substantially the same width along its circumferential length. However, the width decreases adjacent the protrusions comprising the threaded holes, which may improve fluid flow through the channel. The shape of the annular ring 2208 is therefore wavy, or rise-like.

This example of the stator housing can be coupled to a cooling system as described above, and as will now be appreciated, the spacer divides the annular channel such that cooling fluid flow proceeds circumferentially around the annular channel.

In the example shown in Figure 22, the stator housing 2200 is formed by extrusion. In order to improve the extrusion tool life, the minimum thickness of any feature of the tools is maximised by forming the recesses 2206 in two stages. A first set of protrusions 2214, or fingers, are formed integrally with the main tubular body of the stator housing. A second set of fingers 2216 are formed separately, also by extrusion, and then mechanically coupled to the stator housing 2200. The fingers 2216 comprise a slot 2218 configured to engage with a corresponding key 2220 formed integrally on the inner surface 2202 of the stator housing 2200.

As can be seen, the wall thickness of the tubular body of the stator housing is similar to the wall thickness of the fingers 2214 which also improves the manufacturability of the stator housing by extrusion.
An alternative stator housing 2300 is shown in Figure 23. The features of the stator housing 2300 are the same as the stator housing 2200, except that the recesses 2302 are formed in a different manner.

In this example, the recesses 2302 are again formed by a first set of protrusions 2304, fingers, integrally formed with the tubular body 2306 of the stator housing. Again, a second set of protrusions 2308, fingers, are formed separately and subsequently mechanically coupled to the stator housing. In this example, the fingers 2308 comprise a key 2310 configured to engage with a corresponding slot 2312 provided in the inner surface of the stator housing.

In an alternative to the use of extrusion, the stator housing may be formed by stacking a plurality of stamped plates. The stamped plates may be mechanically coupled together, or may be welded or brazed together, or a combination thereof.

Described above are a number of embodiments with various optional features. It should be appreciated that, with the exception of any mutually exclusive features, any combination of one or more of the optional features are possible.
1. A stator housing for an axial flux electrical machine, the housing being tubular and substantially cylindrical in shape, the inner surface of the housing comprising a plurality of recesses, each recess configured to receive an outer part of a conductive coil of a stator of an axial flux electrical machine.

2. A stator housing according to Claim 1, wherein the cross-section of each recess, perpendicular to the axis of rotation of the axial flux electrical machine, is elongate, the major dimension of each elongate recess extending substantially in the radial direction of the axial flux electrical machine.

3. A stator housing according to Claim 2, wherein each elongate recess has an aspect ratio of between about 5 and about 15.

4. A stator housing according to Claim 1, 2 or 3, wherein the side walls of each recess are substantially parallel to the rotational axis of the axial flux electrical machine.

5. A stator housing according to any of Claims 1 to 4, wherein the circumferential distance between adjacent recesses is between about 1 times and about 3 times the width of each recess.

6. A stator housing according to any of the preceding claims, further comprising an annular ring configured to form an annular channel adjacent the circumferential outer surface of said stator housing.

7. A stator housing according to Claim 6, further comprising a spacer configured to divide said annular channel, the spacer extending from a first axial end of said stator housing to a second axial end of said stator housing.

8. A stator housing according to Claim 7, wherein said spacer mechanically couples said stator housing to said annular ring.

9. A stator housing according to Claim 7 or 8, wherein said annular ring comprises a cooling fluid inlet disposed adjacent a first side of said spacer, and a cooling fluid outlet disposed adjacent a second side of said spacer, the inlet and the outlet being in fluid communication with the annular channel.
10. A stator housing according to any of the preceding claims, wherein said housing is formed by extrusion.

11. A stator housing according to Claim 10, wherein the plurality of recesses are formed from a first set of protrusions extending from the inner surface of the stator housing and a second set of protrusions extending from the inner surface of the stator housing, wherein the first set of protrusions are formed integrally with said stator housing, and the second set of protrusions are formed separately and positioned within said stator housing.

12. A stator housing according to Claim 11, wherein said second set of protrusions are mechanically attached to said stator housing.

13. A stator housing according to Claim 11 or 12, wherein said first set of protrusions are interlaced with said second set of protrusions.

14. A stator housing according to Claim 13, wherein said first set of protrusions are interlaced with said second set of protrusions such that each protrusion from the first set of protrusions is adjacent a protrusion from the second set of protrusions.

15. A stator housing according to any of Claims 11 to 14, wherein each of the second set of protrusions comprises a key configured to engage with a corresponding slot formed in the inner surface of the extruded stator housing to mechanically attach each protrusion thereto.

16. A stator housing according to any of Claims 11 to 14, wherein each of the second set of protrusions comprises a slot configured to engage with a corresponding key formed on the inner surface of the extruded stator housing to mechanically attach each protrusion thereto.

17. A stator housing according to any of claims 10 to 16, wherein the stator housing is extruded as a single part.

18. A stator housing according to any of claims 10 to 16, wherein the stator housing is formed of a plurality of circumferentially-interlocking extruded segments.

19. A stator housing according to any of claims 10 to 18, when dependent on any of claims 6 to 9, wherein said annular ring is formed by extrusion.
20. A stator housing according to Claim 19, when dependent on any of claims 7 to 9,
wherein said spacer is formed of a slot and key, the slot being formed on one of an inner surface of said annular ring and the outer surface of said stator housing, the key being formed on the other of the inner surface of said annular ring and the outer surface of said stator housing.
500

510
Provide a plurality of conductive coils

520
Position the coils in a stator housing so that they are circumferentially distributed around the stator

530
Position lamination packs in the spaces defined by the coils

540
Connect the coils to means for connecting the stator to a power supply

550
Impregnate at least part of the stator assembly with a bonding compound

FIG. 13
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02K1/12  H02K1/18  H02K3/04  H02K3/46  H02K21/24
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>WO 2010/122404 A1 (ANSALDO ENERGIA SPA [IT]; GHELARDI GIAN PAOLO [IT] ET AL.) 28 October 2010 (2010-10-28) abstract; figure 6</td>
<td>1-20</td>
</tr>
</tbody>
</table>

See patent family annex.

Date of the actual completion of the international search
17 April 2020

Date of mailing of the international search report
28/04/2020

Name and mailing address of the ISA/
European Patent Office, P.B. 5818 Patentlaan 2
NL-2280 HJ Fijswijk
Tel. (+31-70) 340-5040,
Fax. (+31-70) 340-3016

Authorized officer
Espinós Iglesias, E
<table>
<thead>
<tr>
<th>Patent document cited in search report</th>
<th>Publication date</th>
<th>Patent family member(s)</th>
<th>Publication date</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP 3048699</td>
<td>A1 27-07-2016</td>
<td>NONE</td>
<td></td>
</tr>
<tr>
<td>US 2011259659</td>
<td>A1 27-10-2011</td>
<td>CN 102227862 A</td>
<td>26-10-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CN 102257708 A</td>
<td>23-11-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CN 102257709 A</td>
<td>23-11-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EP 2342800 A2</td>
<td>13-07-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EP 2342802 A2</td>
<td>13-07-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EP 2342803 A2</td>
<td>13-07-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 2012507983 A</td>
<td>29-03-2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 2012508549 A</td>
<td>05-04-2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 2012508555 A</td>
<td>05-04-2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KR 20110084902 A</td>
<td>26-07-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KR 20110086063 A</td>
<td>27-07-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KR 20110093803 A</td>
<td>18-08-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2010109452 A1</td>
<td>06-05-2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2010109453 A1</td>
<td>06-05-2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2010109462 A1</td>
<td>06-05-2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2011050010 A1</td>
<td>03-03-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2011062723 A1</td>
<td>17-03-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2011148225 A1</td>
<td>23-06-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2011259659 A1</td>
<td>27-10-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2011273035 A1</td>
<td>10-11-2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2012001501 A1</td>
<td>05-01-2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WO 2010062764 A2</td>
<td>03-06-2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WO 2010062765 A2</td>
<td>03-06-2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WO 2010062766 A2</td>
<td>03-06-2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WO 2018015293 A1</td>
<td>25-01-2018</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BR 112019000128 A2</td>
<td>09-04-2019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CN 109478808 A</td>
<td>15-03-2019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DK 3485558 T3</td>
<td>23-03-2020</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EP 3485558 A1</td>
<td>22-05-2019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2019288584 A1</td>
<td>19-09-2019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WO 2018015293 A1</td>
<td>25-01-2018</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WO 2010122404 A1</td>
<td>28-10-2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EP 2422093 A1</td>
<td>29-02-2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IT 1393872 B1</td>
<td>11-05-2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2012161554 A1</td>
<td>28-06-2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WO 2010122404 A1</td>
<td>28-10-2010</td>
</tr>
</tbody>
</table>