Title: AXIAL FLUX ELECTRICAL MACHINES

Abstract: An axial flux electrical machine having a rotor rotatable about an axis and the machine comprising at least one metallic pole support unit (10) arranged to have mounted thereon a plurality of cores (34) of magnetisable material, such that the pole support unit (10) does not substantially electromagnetically link the cores; wherein the pole support unit (10) is provided in at least a region of the axis (14) and/or in a circumferential region of the machine radially displaced from the axis, wherein the material of the or each pole support unit (10) does not surround the cores; and wherein the force exerted by the or each pole support unit (10) on each core is generally in a radial plane of the machine and applied to the core within a length (L), in an axial direction of the machine, of each core (34).
AXIAL FLUX ELECTRICAL MACHINES

Field Of The Invention

The present invention relates to axial flux electrical machines. More particularly, the present invention relates to iron-cored axial flux electrical machines.

Background Of The Invention

Axial flux, or axial air gap, machines have been employed for many years. In principle, for any radial flux machine, which is the mainstay of electric machines, there is an axial flux equivalent. In fact, the axial flux version of all major radial flux electric machines, which include induction [US patent no. 4959578], brushless permanent magnet [US Patent No. 6037696], brushed DC [GB Patent No. 2184613], and switched reluctance [US Patent No. 5925965], have been documented in the prior art. Usually axial flux machines tend to be employed in more specific applications where large aspect ratio is an important design consideration. This is because axial flux machines can be conveniently manufactured in disc form or wheel form, where the axial length is small compared with the diameter of the machine. In addition, axial flux machines can also be conveniently assembled into dual rotor or dual stator configurations, or even in multi-nested configurations. This type of modular assembly/design does not appear often and is difficult in radial flux machines. On the other hand, radial flux machines tend to have longer axial length because a large fraction of the axial length is attributed to the end turns of the winding. Despite the apparent similarities between the two machine types and some distinct advantages of axial flux machines, the axial flux machines are much less popular than their radial flux
counterparts, and are not the preferred choice in general applications.

One reason that axial flux machines are not popular appears to be the difficulty of lamination of the stator and/or the rotor cores in axial flux machines. This leads to the common use of air-cored axial flux machines, in an attempt to avoid the issues of lamination of the stator and rotor cores. Air-cored machines use air rather than laminated iron for the stator and/or rotor cores. Air-cored machines, however, suffer from relatively low power density, or low volumetric efficiency, at normal speed range. In order to increase power density, some air-cored axial flux machines are designed to run at very high speed, for example over 50,000rpm ["Modular design of highspeed permanent-magnet axial-flux generators", T. El-Hasan, P.C.K. Luk, IEEE Transactions on Magnetics, Sep 2000, Volume: 36, Issue:5, Part 1, pp.3558-61]. Very high manufacture costs, however, are incurred for these high speed machines. Also, air-cored machines tend to use larger magnets in order to maintain sufficiently high flux levels in the air gap, resulting in increased costs in magnets. Thus, many axial flux machines are iron-cored and different lamination methods have been employed to reduce eddy currents.

The method used by Akse [US Patent No. 2469808] is an example of lamination designs commonly employed. The core of the motor made from this method is composed of a flat annular ring formed from a tight, spirally wound strip of electrical steel lamination. The teeth of the motor are formed by cutting slots in the steel from the cross-section surface of the laminated annular ring. Usually only straight teeth (or pole), in preference over the usual pole-shape teeth, are cut because of complexity of setting up the cutting process. The space for electrical winding is therefore reduced or compromised. Although the axial flux machine thus formed is a close equivalent of conventional radial flux machines in terms of machine's magnetic performance and machine's
eddy current loss model, it is very complex to manufacture. These machines cannot conveniently be mass produced.

The lamination design by Varga [US patent no. 4959578] uses a zigzag folded steel sheet to form the laminated pole. Although this method is radically different from that of Akye's, it is still very complex to manufacture. In addition, only straight teeth can be conveniently formed by this method, resulting in reduced space for electrical winding, similar to Akye's method. Besides, there would be significant eddy current losses on the non-magnetic plate holding the laminations if the plate is made of aluminium or other non-magnetic metals. Alternatively the plate can be made of non-metal, but the mechanical structure of the machine may be compromised, or it may incur complexity of manufacture and materials.

The lamination method by Carl [US Patent No. 2004/0119374] use both steel laminates and soft magnetic composite (SMC) materials. Although the composite materials can help to reduce eddy current losses, there is decreased in flux penetration in the machine cores due to its lower permeability. Also, soft magnetic composites require very high compression force to form the magnetic core, and thus increasing the difficulty and complexity of the manufacture process. They are also relatively brittle and therefore can present a risk for the machine's mechanical integrity. The continuous efforts over the years in axial flux machines have not so far resulted in wider acceptance of the machine, even in areas the axial flux machines have potentially distinct advantages over the radial flux machines, such as in traction and wheeled vehicles.

Figure 5 shows the prior-art of a 'closed-up' pole support 40, with closed slots 41 to receive laminated pole 42. That is, the material of the pole support 40 surrounds each of the slots 41. This 'closed-up' feature allows only laminations to be inserted or punched in the axial direction of the pole support; i.e. into or out of the page in the Figure. The laminated
pole 42 is made by zigzag folded laminates, and as such has a straight feature with no extra space for winding area. Also, since the laminated pole 42 is usually punched into the slots 41, this assembly method prevents the use of pole-shape teeth for extra winding areas.

Figure 6 also relates to the Prior Art and shows a problem of this 'closed-up' pole support 40 if a non-magnetic metal is used to fabricate the pole support 40. The equivalent circuit 50 of the machine can be used to explain how large eddy currents may be generated. \( R_{\text{CORE}}, R \) and \( R_{\text{CORE}} \) are the equivalent resistances for the laminated rotor pole and stator pole respectively. \( R_{\text{LOAD}} \) is the equivalent circuit for the resistance of the mechanical output. Thus \( R_{\text{LOAD}} \) is variable depending on load. \( R_{\text{SUPP}} \) is the effective resistance for the eddy currents for the pole support 40, which will be very low for this 'closed-up' version. This can be explained by the eddy current models 51 and 52. In 51, it resembles an alternate pole excitation (such as in Permanent Magnet machines), in which the dotted lines represent the path for the current loops 53. This type of excitation may happen in induction machine operation. In this case, there are also significant eddy currents induced on pole support 40. Both cases show the highly undesirable effects of high eddy current for this closed-up pole support 40. Alternatively, non-metallic material may be used to avoid eddy current losses. However, the machine structure may be compromised.

Summary Of The Invention

According to a first aspect of the invention there is provided an axial flux electrical machine having a rotor rotatable about an axis and the machine comprising at least one pole support unit arranged to have mounted thereon a plurality of cores of magnetiseable material, each core electromagnetically isolated from neighbouring cores,
wherein the pole support unit is provided in at least a region of the axis and/or in a circumferential region of the machine radially displaced from the axis,

and the material of the or each pole support unit does not surround the cores.

Such a machine is advantageous as it may reduce assembly time, tooling and jigs requirements, and require significant less assembler training, all of which may help to cut down manufacturing cycle times.

In such an arrangement, the pole support unit should not provide any significant flux linkage through the cores.

The pole support may exert a force on each core which is generally in a radial plane. Such an arrangement is convenient as is should be mechanically stronger than if moments or other forces are created on the pole support.

The force applied to each core may be applied to the core within a length, in an axial direction of the machine, of each core. Thus, the cores may be thought of as being mounted upon at least a circumferential face of the pole support unit.

The or each pole support unit may support each core along a length of the core in an axial direction of the machine. Supporting a core along its length is advantageous as it may be mechanically stronger than supporting a core by other means. The axial length of the machine may also be reduced.

In such an arrangement flux from the machine passes through the pole support unit which induces eddy currents therein. Arranging the pole
support unit so that it does not surround the core is advantageous as it can help to reduce the magnitude of such eddy currents thereby improving the performance of the machine. The skilled person will appreciate that eddy currents can lead to heating which can reduce efficiency.

The pole support unit may be positioned roughly at a central region, in an axial direction, of the core.

The pole support unit may support each core in a region in which coils are provided on the core.

The pole support unit may be thought of as partially encapsulating the cores in order to provide support thereto.

The cores may be provided by stacks of laminations. In other embodiments, the cores may be provided by Soft Magnetic Composite material (SMC).

Conveniently, each discrete lamination within the stack is insulated from neighbouring laminations which helps to reduce eddy currents flowing within the laminations.

In some embodiments, at least winding is wound around each of the stacks of laminations.

The pole support unit may comprise a plate having a plurality of substantially flat sides, with each flat side being transverse to a radius of the machine. Generally, the flat side is perpendicular to a radius of the machine.

In an assembled machine a core, which might be a stack of laminations, may be attached to one or more, and generally to each, of the flat sides.
At least some of and generally each of the flat sides may comprise an attachment means arranged to attach core, which might be a stack of laminations, to the support unit.

In some embodiments, the attachment means comprises a threaded bore. Such an arrangement provides a simple structure to attach the stacks of laminations, although other structures are equally possible.

Conveniently, the pole support unit is provided at a central region of the machine. However, in alternative, or additionally, the pole support unit may be provided at a circumferential region of the machine.

In some embodiments, the pole support unit comprises a plurality of slots. Such an arrangement can help to provide mechanical strength to the machine formed from the pole support unit.

In embodiments in which the pole support unit comprises a plurality of slots, each of the slots contains a stack of laminations.

In some embodiments the slots within the pole support unit are open at one end thereof. Such slots should help to prevent eddy current from flow in the pole support unit, and in so doing, should not compromise mechanical integrity of the lamination assembly or the machine.

The pole support unit may comprise a substantially circular plate.

An axis of the stack of laminations may be arranged to be substantially parallel with a radius of the plate.
More generally, an axis of a core may be arranged to be substantially parallel with a radius of pole support unit. In some embodiments, the axis of core may be co-incident with a radius of the pole support unit. In other embodiments, the axis of the core may lie between the radii of two or more pole support units.

In some embodiments the open end of the slots is provided at end thereof adjacent an outer circumference of the plate. Such an embodiment may be suitable for both a stator and a rotor but may find particular suitability for a rotor since a shaft may be conveniently attached to material remaining at a central region of the pole support unit.

In alternative or additional embodiments the plate comprises a hole therethrough at a central region thereof. The open end of the slots may be provided at an end thereof adjacent the hole through the central region of the plate. Such an embodiment may be suitable for both a stator and a rotor but may find particular suitability for a stator since there is more space at a central region thereof in which to accommodate a rotating shaft of a rotor when compared to having the open end of the slots at the other end.

Generally, each core is I shaped in plan. Such a shape is convenient as it can provide mechanical location of a coil wrapped around the lamination.

Conveniently, the height of each lamination within a stack is substantially equal. Such an arrangement is advantageous as it provides a stack having substantially planar top and bottom faces.

However, in some embodiments, the width of the laminations varies within the stack. Such an arrangement is convenient as it allows the shape of the stack formed by the laminations to be tailored to the shape of the
pole support unit. For example, in a substantially circular pole support unit the shape of the stack may be arranged to follow radius' of the pole support unit.

As such the width may vary linearly from a narrow end to a wider end. Therefore, the narrow end of the stack may be arranged adjacent a central region of the pole support unit.

In some embodiments the rotor may be fabricated with the pole support unit. In other embodiments the stator may be fabricated with the pole support unit. In some other embodiments both the rotor and the stator may be fabricated with a pole support unit.

Indeed, some machines may be fabricated from a plurality of rotors and/or stators. Should a plurality of rotors and/or stators be used it may be convenient to mount this on a common axis.

In some embodiments each stator or rotor may comprise a single pole support unit. In such embodiments, the stack of laminations may be arranged within the pole support unit such that the pole support unit is substantially at a central region of the stack.

In other embodiments any one stator or rotor may comprise a plurality of pole support units, such as for example 2 pole support units. In such an embodiment each stack of laminations may be arranged within the pole support units such that the one of the two pole support units is arranged at an end region of the stacks.

Providing two pole support units may be advantageous as it provides more space along the stack laminations along which to provide a winding. However, providing on a single pole support unit may be advantageous as
it uses less material and as such may be cheaper to manufacture and also weigh less.

In some embodiments, the pole support unit is fabricated from a metal, such as aluminium. Aluminium is advantageous as since it can dissipate heat readily.

Whilst metal can have eddy currents induced therein, it is advantageous as is generally stronger than other, non-metallic, materials.

Other suitable metals include Copper, Steel, Stainless Steel, Titanium, Magnesium or any alloy of these metals.

According to a further aspect of the invention there is provided an axial flux electrical machine having a rotor rotatable about an axis and the machine comprising at least one pole support unit fabricated from a metal and arranged to have mounted thereon a plurality of cores of magnetiseable material, each core electromagnetically isolated from neighbouring cores,

wherein the pole support unit is provided in at least a region of the axis and/or in a circumferential region of the machine radially displaced from the axis,

and in which the pole support unit does not provide an electrical path around the core.

Features of the invention will become apparent from the following detailed description, which taken in conjunction with the annexed drawings, discloses embodiments of the present invention which are provided by way of example only.

**Brief Description Of The Drawings**
Figure 1A is a cross sectional view of an 'open-out' pole support embodiment of the present invention;

Figure 1B is a cross sectional view of an Open-in' pole support embodiment of the present invention;

Figure 2A is the plan view of a lamination stampings embodiment of the present invention;

Figure 2B is cross sectional view of a laminated pole embodiment of the present invention;

Figure 2C is elevated view of the laminated pole embodiment of the present invention;

Figure 3A is cross sectional view of the machine's laminated core with an 'open-out' pole support embodiment of the present invention;

Figure 3B is cross sectional view of the machine's laminated core with an 'open-in' pole support embodiment of the present invention;

Figure 4A is an elevated view of a winding and teeth assembly with a single pole support embodiment of the current invention;

Figure 4B is elevated view of winding and teeth assembly with a double pole support embodiment of the current invention;

Figure 5 (Prior Art) is a cross sectional view of a prior art pole
support;

Figure 6 is the equivalent circuit of the machine and current loops for eddy currents of the present invention;

Figure 7 is a cross sectional view of a winding assembly;

Figure 8 is a cross sectional view of a permanent magnet (PM) rotor embodiment of the present invention;

Figure 9A is a side view of a rotor-stator-rotor permanent magnet (PM) machine embodiment of the present invention;

Figure 9B is a side view of a stator-rotor-stator permanent magnet (PM) machine embodiment of the present invention;

Figure 10A is a side view of a stator-rotor-stator induction machine embodiment of the present invention;

Figure 10B is a side view of a stator-rotor induction machine embodiment of the present invention;

Figure HA is a side view of a stator-rotor-stator switched reluctance machine embodiment of the present invention;

Figure HB is a side view of a stator-rotor switched reluctance machine embodiment of the present invention;

Figure 12 shows a further embodiment of the invention;

Figure 13 shows yet a further embodiment of the invention; and
Figure 14 shows an embodiment similar to Figure 13 but with a further support.

5 Detailed Description Of Embodiments

The following description provides specific details in order to provide a thorough understanding of the invention. Nonetheless, those skilled in the art would understand that the invention can be practiced without employing these specific details. Indeed, the present invention can be practiced by modifying the illustrated system and method and can be used in conjunction with systems and techniques conventionally used elsewhere in the electrical machine community.

Embodiments of the invention generally comprise an axial flux electrical machine with a housing, a laminated rotor (rotors) and a laminated stator (stators). The laminated stator and/or rotor cores are formed by a non-magnetic, generally metal, support to which stamped laminations are conveniently secured, in a manner comparable to those used in radial flux machines. It each convenient to describe the cores as being laminated but this might not be the case and cores may be fabricated from a Soft Magnetic Composite (SMC).

FIG. 1 illustrates a pole support unit 10 to which laminations are secured. The pole support unit 10 allows a new method of lamination manufacture and assembly to be practiced. The pole support unit 10 is generally made of non-magnetic metal such as aluminium to provide mechanical ruggedness.

Referring to FIG. IA, an 'open-out' pole support unit 10 is a disc-shape, single piece formation with a plurality of slots 11 positioned around its
periphery. In this embodiment the slots 11 are equispaced around the circumference of the periphery. It will be seen that a bottom face of a slot provides a substantially flat side such that there a plurality of substantially flat sides around the pole support unit.

The pole support unit 10 is substantially circular in shape with each of the slots 11 therein being open at one end thereof. In this embodiment, the open end of the slots 11 is adjacent an outer circumference of the pole support unit 10.

The pole support unit 10 can be conveniently formed by casting, and should also be thick enough to accommodate fixing screws used to secure laminations to thereto. Threaded holes 12 provide an attachment means and are for fixing screws to secure laminated poles to pole support unit 10, while threaded holes 13 are for fixing screws to secure optional containment ring structure (for rotor core), or optional housing case (for stator core), to 10. Attachment means other than threaded bores may be equally possible. Attachment could be provided by welding, soldering, use of adhesive, or the like.

The optional containment ring or the optional housing case should not provide conducting paths for eddy currents when fitted. A central hole 14 provided at a central region of the pole support unit 10 can be made to appropriate size to conveniently receive the shaft of the machine. As such, while the pole support unit 10 can be used for both a stator or rotor cores, the 'open-out' pole support 10 is particularly suitable for a rotor core and is usually the preferred option for the rotor core. Figure 3A shows the cross section of the Open-out' lamination assembly 37, which can be easily seen to be conducive to a rotor core (i.e. in which laminations as shown in Figure 2 have been fitted to the pole support unit 10).
The slots 11 are to provide space to house laminated poles 34 of the machine which are described further in Figure 2.

Looking at the equivalent circuits shown in Figure 6 it will appreciated that \( r_s U_p R_T \) will be infinite (open circuit) in the case of the 'open-out' pole support unit 10. Thus, there should be no (or at least significantly reduced) eddy current losses on the pole support unit 10.

However, when a core has been inserted into the slot of Figure IA it will be appreciated that the material of the pole support unit 10 does not surround the core and as such the path that eddy currents can take is reduced. This reduction in eddy current path should reduce heat generation within the machine.

An axis 15 of the machine is shown in the Figure. When the machine is assembled, a rotor of the machine would have its axis aligned with the axis 15. A circumferential region of the machine is shown by the reference numeral 16.

Thus, use of the pole support 10 of Figure Ia may provide an axial flux electrical machine having a rotor rotatable about an axis and the machine comprising at least one pole support unit arranged to have mounted thereon a plurality of cores of magnetiseable material, such that the pole support unit does not substantially electromagnetically link the cores; wherein the pole support unit is provided in at least a region of the axis wherein the material of the or each pole support unit supports each core on two sides which are substantially radii of the machine and a third side in a region of the axis.

Referring to Figure. IB, an 'open-in' pole support unit 20 is shown which
is an inside-out version of the 'open-out' pole support unit 10. Slots 21 are now providing pockets opened inwardly toward the centre of the pole support unit 20.

Conceptually the 'open-in' pole support unit 20 is very similar to the 'open-out' pole support unit 10.

The 'open-in' pole support unit 20 can be conveniently formed by casting. However, if it is not made by casting, then the pole support unit 20 could also be formed by a plurality of arced plates 22 joined together, rather than a single piece as in the case of 10, and other embodiments are also possible. This feature ensures that the laminated poles (i.e. stacks of laminations may be with pre-wound windings) to be conveniently assembled and fastened to the pole support unit 20, by fixing screws using the thread-holes 22. Otherwise, it is not possible for laminated poles to be assembled easily to the pole support unit 20. Additional threaded holes 23 protrude into the material between the slots 21 and are reserved for fixing screws to secure an optional containment ring structure (for rotor core), or an optional housing case (for stator core). The optional containment ring or the optional housing case should not provide conducting paths for eddy currents when fitted. As discussed above the poles need not be provided by stacks of laminations and may be provided by a core, perhaps of SMC. It is however, convenient to refer to the cores as stacks of laminations.

Again, when a core has been inserted into the slot of Figure 1B it will be appreciated that the material of the pole support unit 20 does not surround the core and as such the path that eddy currents can take is reduced. This reduction in eddy current path should reduce heat generation within the machine.
It is not necessary for the stacks of laminations to have windings thereon. For example, if the pole support unit is being used to provide a rotor then no windings are needed. However, if the pole support unit is being used to provide a stator then a winding would generally be provided around the stack of laminations.

At a central region of the pole support unit 20 there is a central hole 24 which serves as an open circuit, and can be made to appropriate size to conveniently allow a shaft to go through if the pole support unit 20 is used for a stator core.

In this embodiment, the pole support unit 10 is again substantially circular in shape with each of the slots 11 therein being open at one end thereof. In this embodiment, the open end of the slots 11 is adjacent the hole 24 through a central region of the pole support unit 20.

Alternatively, if the pole support unit 20 is used for a rotor core, then it is fixed to the shaft. The shaft should not create conducting path for eddy currents. As such, while the pole support unit 20 can be used for both for stator or rotor cores, the 'open-in' pole support 20 is particularly suitable for a stator core and is usually the preferred option for the stator core. Figure 3B shows the cross section of the Open-in' lamination assembly 39 (i.e. in which laminations as shown in Figure 2 have been fitted to the pole support unit 20), which can be easily seen to be conducive to a stator core.

Looking at the equivalent circuits shown in Figure 6 it will again be appreciated that $R_{\text{SUPPORT}}$ will be infinite (open circuit) in the case of the 'open-in' pole support unit 10. Thus, there should be no eddy current losses on the pole support unit 10.
Thus, use of a pole support unit 10 as shown in Figure 1b may provide an axial flux electrical machine having a rotor rotatable about an axis and the machine comprising at least one pole support unit arranged to have mounted thereon a plurality of cores of magnetiseable material, such that the pole support unit does not substantially electromagnetically link the cores; wherein in a circumferential region of the machine radially displaced from the axis, and wherein the pole support unit supports each core on two side which are substantially radii of the machine and a third side in a circumferential region of the machine.

In FIG2A-2C, it can be seen how laminated poles 34 are made. The pole support unit 10 of Figure IA provides a number (12 in this embodiment) of pockets, each one of which is provided by a slot 11, which opens outwardly to receive a laminated pole 34. Each lamination pole is fabricated from a plurality of discrete laminations arranged in a stack (i.e. a plurality of plates), with an insulator between each of the laminations. The insulation is not described further since the skilled person will readily appreciate how to insulate the laminations from one another.

The core, whether or not provided by a stack of laminations, is fabricated from a magnetiseable material; often referred to as a soft magnetic material.

This 'open-out' structure of the pole support unit 10 not only allows the laminated poles, possibly with pre-wound winding, to be conveniently assembled, but also results in a open-circuit for the eddy currents otherwise circulating on the surfaces of the pole support 10 when alternating flux is established during machine operation.

Referring to FIG. 2A-2C, which shows examples of a lamination 30a, b,
c used within a pole support unit 10, 20. It will be seen that that the laminations are of a common I-shape made of ferrite, iron or similar magnetic material, with a fastening hole 32 provided at a central region thereof. The narrower central part 31 allows space for the windings which will be provided around the lamination. In general, many laminations 30a-c are required for a single machine. The lamination 30 a-c can be easily made in high volume by conventional stamping methods.

The fastening hole need not be provided at a central region thereof and there may be more than one fastening hole provided.

As can be seen from Figure 2a the laminations 30a-c are of varying width but substantially the same height for any one machine and/or pole support unit. Thus for example, it will be seen that the lamination 30a is narrower than the lamination 30b which is narrower than the lamination 30c, Figure 2b and c show a completed stack of laminations which are built into a single unit to be received within each slot 11, 21. Thus, when the laminations are built together they form an iron core of a trapezoidal shape, laminated iron pole 34 such that the width of the stack so formed varies substantially linearly from a narrow end to a wider end. A screw, bolt or the like is passed through the holes 32 in order to hold the laminations together. Laminated pole 34 can also be called the tooth of the machine. Since the central part 31 of the laminated pole 34 can be readily manufactured to fit seamlessly into slots 11 of pole support unit 10, or slots 21 of pole support unit 20, a highly integrated and strong structure for the motor cores is readily achievable. At least one and generally a plurality of coils will be provided around each stack of laminations.

Looking at the Figures 3a and 3b it is seen that the narrow end of the stack of laminations is provided adjacent a central region 14, 24 of the
pole support unit. It will also be seen that the axis of each stack of laminations 34 lies substantially along a radius of the pole support unit 10, 20.

Figure 4 shows the elevated views of possible winding and pole assemblies. Figure 4A shows a single-pole support embodiment using the open-out type pole support unit 10 (it is noted that open-in type 20 can also be used), in which the electrical windings 36 can be conveniently split into upper 36a and lower 36b on either sides of the pole support unit 10. If the arrangement of Figure 4a were used in a rotor or stator then that rotor or stator would comprise a single pole support unit. In such an embodiment, the stack of laminations 34 is arranged such that the pole support unit 10 lies at a central region thereof.

The core, provided by the stack of laminations 34, has a length in an axial direction of the machine of L as shown in the Figure. It will be seen that the pole support unit 10 lies within this length L such that the axial length of the rotor/stator is given by the axial length of the core; i.e. the pole support unit supports each core along a length of the core.

It will be seen that each of the cores 34 (shown as a stack of laminations) is electromagnetically isolated from its neighbours.

Figure 4B shows a double-pole support embodiment, in which the windings 36 may fit within stator core without being split into two parts. While the embodiment, shown in Figure 4a, has the simplicity of using only one pole support unit 10, the latter (shown in Figure 4b) enjoys a simpler winding arrangement and stronger mechanical structure. A high winding factor (i.e. the percentage of space occupied by copper of the winding) can be readily achieved with both embodiments.
In the arrangement of Figure 4b the stack of laminations 34 is arranged such that one of the two pole support units is arranged at each end region of the stack of laminations 34.

As with the arrangement of Figure 4a the core, provided by the stack of laminations 34, has a length in an axial direction of the machine of L. It will be seen that despite there being two pole support units in this embodiment, each of them lies with the length L such that the length of the stator/rotor is still governed by the length L of the core; i.e. each pole support unit supports each core along a length of the core.

Figure 7 shows the cross sectional view of a complete laminated core 60 with winding assembly embodiment of the invention. It is the generic laminated core (which can be made of pole support unit 10 or 20) with winding assembly, showing the flexibility of this embodiment of the invention, which can be usefully practiced as either a rotor or a stator of an axial machine.

Only a notional one coil 36 per pole is shown, and the winding diagrams are not shown. The winding connections are specific for the type of machines. For example, distributed winding is common in induction machines and brushless DC machines, whereas concentrated windings are used in switched reluctance machines. Although winding assembly embodiment 60 is usually used in a stator core, it can also be used in a rotor. For example, when used in the rotor of the induction machine, each winding 36 in 60 will needed to be short circuited.

Figure 8 shows the cross-sectional view of a permanent magnet (PM) machine rotor embodiment 70. The corresponding stator core and winding assembly for this rotor may take the form of embodiment 60. The rotor magnets 72 are axially and alternately polarized. The magnet carrier 74
holds the magnets in position by adhesive or other mechanical means. A central hole 76 receives the shaft of the machine.

Figures 9 to 11 illustrate how embodiments of the current invention can be practiced in several major electric machines. They perhaps show the preferred embodiments of the invention used in axial flux PM machines, induction machines (IM), and switched reluctance (SR) machines. The use of soft magnetic composite (SMC) is also illustrated in some of these embodiments to show the invention is flexible enough to exploit the advantages offered, in particularly in use as back iron (which is used to complete a low reluctance path for the main magnetic circuit of the machine), by these new materials. The back iron may be referred to as a flux enhancing member, which need not be made from iron, but could be made from any soft magnetic material.

Figure 9A shows the side view of a rotor-stator-rotor PM machine embodiment 80 of the present invention; i.e. a machine in which there are a plurality of rotors, comprising two rotors 70 and one stator made from core 60. The rotors 70 are axially positioned on either side of stator 60, each separated by from the stator by an air-gap 99 respectively. The rotors 70 and also the stator are mounted upon a common axis. Rotor magnets 72 are magnetically connected by means of a back-iron plate 112 (i.e. a flux enhancing member) to compete a low reluctance path for the magnetic path. The back-iron plate 112 is usually of the shape of a circular disc or ring. The thickness of back-iron plate 112 may not be uniform. For example, it can be shaped thicker towards the centre and thinner towards the outer rim, to take advantage of the reduced inertia and material, without compromising the low reluctance magnetic path. The back-iron plate 112 can be made of SMC to gain some weight or inertia advantage, as it may not subject to any significant mechanical stress and there may not require a strong structure of a normal iron. Since
the flux is essentially constant in the back iron for a PM machine, non-
laminated iron can also be used to reduce manufacture and assembly
5 costs, although it may incur higher weight compared with SMC. It will be
seen that the stator 60 comprises a plurality of cores 95, each mounted
upon a pole support unit 96 and having a plurality of coils wound
therearound.

Figure 9B shows the side view of a stator-rotor-stator PM machine
embodiment 90 of the present invention; i.e. a machine in which there are
10 a plurality of stators. It is a mirror-image of the embodiment 80, and
comprises of two outer stators made from core 60 and a PM rotor 70, and
the two air-gaps 99. Each of the stators, and also the rotor are mounted
upon a common axis. The magnetic poles of each stator 90 are
15 magnetically connected by means of a back-iron plate 112 (i.e. a flux
enhancing member) respectively. Each of the poles is provided by a
plurality of cores each mounted upon a pole support 96 and having a
plurality of coils wound therearound. The design and make of the back-
iron plate 112 is similar to that of the back iron plate 112 in the
19 embodiment shown in Figure 9a. However, since the back-iron plate 112
in the embodiment of Figure 9b is not rotating, its design considerations
on inertia and weight may be different from that of back of the back-iron
plate 112 in Figure 9a. It must be noted that a variation to the PM
machine embodiments described above is a stator-rotor embodiment. The
rotor 97 comprises a plurality of permanent magnets.

Figure 10A shows the side view of an induction machine (IM) rotor-
25 stator-rotor embodiment 100 of the present invention, comprising two
rotors made from core 60, and a stator 6060, separated by two air-gaps
111 respectively. Stator 6060 is formed by two cores 60 connected back-
to-back by means of a central yoke 111A, which serves similar functions
is to that of the back-iron plate 112. It should be noted that embodiment
100 can be essentially viewed as a stator-rotor-stator configuration.

Each stator comprises a plurality of cores 95 mounted upon a pole support unit 96 and having a plurality of windings wound therearound. Each rotor also comprises a plurality of cores 95r mounted upon a pole support unit 96r and having a plurality of coils wound therearound.

Figure 10B is the side view of an induction stator-rotor embodiment 110 of the present invention, comprising a rotor and a stator, both made of core 60, and one airgap 99. Both are completed with a back-iron plate 112, which however, may take different make or shape, given the different inertia and weight considerations to rotor and stator. The stator comprises a plurality of cores 95s mounted upon a pole support unit 96s and having a plurality of coils wound therearound. The rotor also comprises a plurality of cores 95r mounted upon a pole support unit 96r and having a plurality of coils wound therearound.

Figure HA is a side view of a switched reluctance (SR) machine stator-rotor-stator embodiment 120 of the present invention, comprising two stators made from core 60, a rotor made from non-winding core 37 (shown in Figure 3a), and two air-gaps 99 on either side of the rotor. It is noted that it is also possible that the rotor can also be made by non-winding core 39 (shown in Figure 3b). The laminated poles of each stator are magnetically joined by a back-iron plate 112, as in previous embodiments.

Each stator comprises a plurality of cores 95s mounted upon a pole support unit 96s with a plurality of coils wound therearound. The rotor comprises a plurality of cores 95r mounted upon a pole support unit 96r.

Figure HB is a side view of a SR motor stator-rotor embodiment 130 of
the present invention, comprising one stator made from core 60, a rotor
made from non-winding core 37 (or 39), and an airgap 99 in between.
The laminated poles of both the stator and rotor are completed with a
back-iron plate 112, which however, may take different make or shape,
given the different inertia and weight considerations to rotor and stator,
as before.

The stator comprises a plurality of cores 95s mounted upon a pole support
unit 96s with a plurality of coils wound therearound. The rotor comprises
a plurality of cores 95r mounted upon a pole support unit 96r.

Figure 12 shows a further embodiment of a rotor or a stator in which a
pole support unit 1200 is provided in which the slots 1202 have a reduced
radial length when compared with the slots shown in previous
embodiments. Again, the bottom face of the slot, adjacent a central region
of the support unit 1200, comprises a substantially flat side. As an
example, one stack of laminations 1204 is shown in a working position
mounted against one of the flat sides of the pole support unit 1200 and it
can be seen that the walls 1206 extends roughly one third along the length
of the stack of laminations 1204. In other embodiments, the walls of the
slot 1206 extend for greater or less of the way along the walls of the slot.

As a further example, a second stack of laminations 1208 is shown
removed from its mounted position. To form a completed rotor or stator
each of the twelve slots 1202 is populated with a stack of
laminations 1206, 1208 which are secured to the pole support unit 1200
with a mounting means. In this embodiment a bottom face of each slot is
provided with a threaded bore 1210 (which may also be referred to as a
threaded hole) which allows the stack of laminations to be secured in
place.
It is believed that reducing the radial length of the slots 1202 can be advantageous to reduce the eddy currents flowing within the pole support unit.

Thus, use of the pole support 10 of Figure 12 may provide an axial flux electrical machine having a rotor rotatable about an axis and the machine comprising at least one pole support unit arranged to have mounted thereon a plurality of cores of magnetiseable material, such that the pole support unit does not substantially electromagnetically link the cores; wherein the pole support unit is provided in at least a region of the axis wherein the material of the or each pole support unit supports each core along portions of two sides which are substantially radii of the machine and a third side in a region of the axis.

Figure 13 shows a further embodiment of a rotor and/or stator of the present invention in which a pole support unit 1300 is provided. In this embodiment, the radial length of the slots has been reduced to zero so that a twelve sided regular polygon remains. It will be seen that the regular polygon again provides a plurality of substantially flat sides.

It should be appreciated that whilst all of the embodiments show twelve slots or a twelve sided polygon as the pole support unit this need not be the case and other embodiments may have other numbers. For example, other embodiments may comprise roughly 8, 9, 10, 11, 13, 14, 15, 20, 25 or more slots / side polygons as the pole support unit.

Each face of the polygonal providing the pole support unit 1300 is provided with a threaded bore 1310 which allows a stack of laminations to be attached to the support unit 1300.

For ease of reference, a single stack of laminations 1304 is shown
mounted on the pole support unit.

The pole support unit 1300 of Figure 13 is provided at a central region of a machine.

Thus, use of the pole support 10 of Figure 13 may provide an axial flux electrical machine having a rotor rotatable about an axis and the machine comprising at least one pole support unit arranged to have mounted thereon a plurality of cores of magnetiseable material, such that the pole support unit does not substantially electromagnetically link the cores; wherein the pole support unit is provided in a region of the axis wherein the pole support unit supports each core along a face which is transverse to a radius of the machine in a region of an axis of the machine.

Figure 14 shows a further example in which the pole support unit 1300 of Figure 13 is used to support a stack of laminations 1404 (again, only a single stack of laminations 1404 has been shown for ease of reference) in conjunction with an external pole support unit 1412. Such an external pole support unit 1412 can help to increase the mechanical strength of the rotor or stator so provided. It will be appreciated that the external pole support unit is provided at a circumferential region of a machine in which it is provided.

In other embodiments, the pole support unit may comprise the external pole support unit 1412, there being no pole support unit 1300 in such embodiments.

Such an embodiment may provide an axial flux electrical machine having a rotor rotatable about an axis and the machine comprising at least one pole support unit arranged to have mounted thereon a plurality of cores of magnetiseable material, such that the pole support unit does not
substantially electromagnetically link the cores; wherein the pole support unit is provided in a region of the axis wherein the pole support unit supports each core along a face which is transverse to a radius of the machine in a region of the circumference of the machine.

The foregoing discussion of the invention has been presented for purposes of illustration and discussion. In addition, the description is not intended to limit the invention of the form disclosed herein. Consequently, variations and modifications commensurate with the above teachings and with the skills and knowledge of the relevant art are within the scope of the present invention. The embodiments described herein above are further intended to explain the best forms presently known of practicing the invention and to enable others skilled in the art to use the invention as such, or in other embodiments, and with the various modifications required by their particular applications or uses of the invention.

Embodiments of the invention can therefore provide a manufacturing process for axial flux machines, in particular in the areas of lamination formation and assembly, and winding, similar in simplicity to those used for radial flux machines. The method also helps to ensure that the electromagnetic performance, space for electrical windings, volumetric efficiency, eddy current losses, and mechanical integrity of the machines are all compared favourably with their radial flux counterparts. This will allow the axial flux machine to compete favourably with their radial flux counterparts in virtually any application area, rather than just in very niche applications as in current situations.
CLAIMS

1. An axial flux electrical machine having a rotor rotatable about an axis and the machine comprising at least one metallic pole support unit arranged to have mounted thereon a plurality of cores of magnetiseable material, such that the pole support unit does not substantially electromagnetically link the cores;

   wherein the pole support unit is provided in at least a region of the axis and/or in a circumferential region of the machine radially displaced from the axis,

   wherein the material of the or each pole support unit does not surround the cores; and

   wherein the force exerted by the or each pole support unit on each core is generally in a radial plane of the machine and applied to the core within a length, in an axial direction of the machine, of each core.

2. A machine according to claim 1 in which each of the cores comprises a plurality of discrete laminations.

3. A machine according to claim 2 in which the height of each lamination within the core is substantially equal.

4. A machine according to claim 2 or 3 in which the width of the laminations varies within the core.

5. A machine according to claim 4 in which the width varies substantially linearly from a narrow end to a wider end.

6. A machine according to any of claims 2 to 5 in which the laminations are insulated from one another.
7. A machine according to claim 1 in which the cores are fabricated from a Soft Magnetic Composite (SMC).

8. A machine according to any of the preceding claims in which the cores are mounted on a face generally transverse to a radius of the machine on at least one of the pole support units.

9. A machine according to any preceding claim in which at least winding is wound around each of the cores.

10. A machine according to any preceding claim in which the pole support unit comprises a plate having a plurality of substantially flat faces each of which is transverse to a radius of the machine.

11. A machine according to claim 10 in which each of the flat faces comprises an attachment means arranged to attach a core to the pole support unit.

12. A machine according to claim 11 in which the attachment means comprises a threaded bore.

13. A machine according to any preceding claim in which the cores are bolted to the pole support unit.

14. A machine according to any preceding claim in which a further pole support unit is provided in either the region of the axis or in the circumferential region which is not occupied by the first pole support unit.
15. A machine according to any preceding claim in which the pole support unit comprises a plurality of slots each comprising a face in an end region thereof on which a core is mounted.

16. A machine according to claim 15 in which the slots within the pole support unit are open at one end thereof.

17. A machine according to claim 16 in which the open end of the slots is provided at end thereof adjacent an outer circumference of the pole support unit.

18. A machine according to claim 16 in which the open end of the slots is provided at an end thereof adjacent the axis of the machine.

19. A machine according to any preceding claim in which each core is I shaped in plan.

20. A machine according to any preceding claim in which cores have connected thereto a magnetic flux enhancing member.

21. A machine according to claim 20 in which the magnetic flux enhancing member is fabricated from any of the following: iron, Soft Magnetic Composite (SMC).

22. A machine according to any preceding claim in which the rotor comprises the pole support unit.

23. A machine according to claim 22 as it depends from claim 20 in which each of the cores on the rotor is connected to the magnetic flux enhancing member.
24. A machine according to any preceding claim in which the stator comprises the pole support unit.

25. A machine according to claim 24 as it depends from claim 20 in which each of the cores on the stator is connected to the magnetic flux enhancing member.

26. A machine according to any preceding claim which comprises a plurality of rotors.

27. A machine according to claim 26 in which the rotors are all arranged about the axis.

28. A machine according to any preceding claim which comprises a plurality of stators.

29. A machine according to claim 28 in which the stators are all arranged about the axis.

30. A machine according to any preceding claim in which any one stator or rotor comprises a single pole support unit.

31. A machine according to claim 30 in which each core is arranged within the pole support unit such that the pole support unit lies along substantially a central region of the core.

32. A machine according to any preceding claim in which at least one stator and/or rotor comprises a plurality of pole support units.

33. A machine according to claim 32 in which at least one stator and/or rotor comprises two pole support units.
34. A machine according to claim 33 in which each core is arranged within the pole support units such that each of the two pole support units is arranged at end region of the cores.

35. A machine according to any preceding claim which is any one of the following: a permanent magnet machine; an induction motor machine; a switched reluctance motor machine.

36. A machine according to any of claims 1 to 35 which comprises two rotors arranged on either side of a stator.

37. A machine according to claim 36 which is a permanent magnet machine.

38. A machine according to claim 36 or 37 which comprises a first and a second flux enhancing member each having a plurality of magnets mounted thereon and being arranged about the axis such that the faces of the flux enhancing members on which the magnets are mounted face toward one another, the flux enhancing members and the magnets each providing a rotor, between the two flux enhancing members there is provided a stator comprising the pole support unit, and at least one coil being wound around each of the cores within the pole support unit.

39. A machine according to any of claims 1 to 35 which comprises two stators arranged either side of a rotor.

40. A machine according to claim 39 which comprises two pole support units and a first and second flux enhancing member each having a plurality of cores connected thereto and being arranged about the axis, each of the cores having at least one coil wound therearound and being
mounted upon one of the pole support units, between the two flux enhancing members there is provided a rotor arranged to rotate about the axis and comprising a plurality of magnets.

41. A machine according to claim 39 or 40 which comprises a permanent magnet machine.

42. A machine according to claim 39 which comprises four pole support units and a first and a second flux enhancing member each having a plurality of cores connected thereto and being arranged about the axis, each of the cores having at least one coil wound therearound and being mounted upon one of the pole support units, between the two flux enhancing members there is provided a rotor comprising a flux enhancing member at a central region thereof having mounted on either side thereof a plurality of cores, each mounted upon one of the pole support units and having at least one coil wound therearound.

43. A machine according to claim 42 which comprises an induction machine.

44. A machine according to claims 1 to 35 which comprises a single stator and a single rotor.

45. A machine according to claim 44 in which comprises two pole support units and in which the stator comprises a flux enhancing member having mounted thereon a plurality of cores, each core having wound therearound at least one coil and being mounted on one of the pole support units and in which the rotor also comprises a flux enhancing member having mounted thereon a plurality of cores, each core having at least one coil wound therearound and being mounted upon the other of the
pole support units, wherein the rotor and the stator are arranged such that
the cores of the rotor and the stator are adjacent one another.

46. A machine according to claim 45 which is an induction machine.

47. A machine according to claim 39 which comprises three pole
support units and in which each stator comprises a flux enhancing
member having mounted thereon a plurality of cores, each core having at
least one coil wound therearound and being mounted upon one of the pole
support units, the stators being arranged on the axis such that the cores
face on another, the rotor being mounted between the stators and
comprising the third pole support unit having mounted thereon a plurality
of cores.

48. A machine according to claim 47 which is a switched reluctance
machine.

49. A machine according to claim 44 which comprises two pole support
units and in which the stator comprises a flux enhancing member having
mounted thereon a plurality of cores, each core having wound
therearound at least one coil and being mounted on one of the pole
support units and in which the rotor also comprises a flux enhancing
member having mounted thereon a plurality of cores, each core being
mounted on the second of the pole support units, wherein the rotor and
the stator are arranged such that the cores of the rotor and the stator are
adjacent one another.
Cross-section view of 'open-out' lamination base embodiment

FIG. 1A

Cross-section view of 'open-in' lamination base embodiment

FIG. 1B
Lamination stampings of varying widths

FIG. 2A

Cross section view of a laminated pole

FIG. 2B

Elevated view of a laminated pole

FIG. 2C
Cross sectional view of a machine's laminated core with an 'open-out' lamination base

FIG. 3A

Cross sectional view of a machine's laminated core with an 'open-out' lamination base

FIG. 3B
Winding and teeth assembly with single-lamination base embodiment

FIG. 4A

Winding and teeth assembly with double-lamination base embodiment

FIG. 4B
Cross-sectional view of prior art lamination base

FIG. 5 (Prior Art)
Equivalent circuit of the machine and current loops for eddy currents

FIG. 6 (Prior Art)
Cross section view of winding assembly

FIG. 7
Cross sectional view of a permanent magnet (PM) axial rotor

FIG. 8
Side view of a rotor-stator-rotor permanent magnet (PM) machine embodiment

FIG. 9A

Side view of a stator-rotor-stator permanent magnet (PM) machine embodiment

FIG. 9B
Side view of a stator-rotor-stator induction machine (IM) embodiment

FIG. 10A

Side view of a stator-rotor induction machine (IM) embodiment

FIG. 10B
Side view of a stator-rotor-stator switched reluctance (SR) machine embodiment

FIG. 11A

Side view of a stator-rotor switched reluctance (SR) machine embodiment

FIG. 11B