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(57) **ABSTRACT**

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An apparatus for converting between mechanical and electrical energy, particularly suited for use as a compact high power alternator for automotive use and “remove and replace” retrofitting of existing vehicles. The apparatus comprises a rotor with permanent magnets, a stator with a winding, and a cooling system. Mechanisms to prevent the rotor magnets from clashing with the stator by minimizing rotor displacement, and absorbing unacceptable rotor displacement are disclosed. The cooling system directs coolant flow into thermal contact with at least one of the winding and magnets, and includes at least one passageway through the stator core. Various open and closed cooling systems are described. Cooling is facilitated by, for example, loosely wrapping the winding end turns, use of an asynchronous airflow source, and/or directing coolant through conduits extending through the stator into thermal contact with the windings.

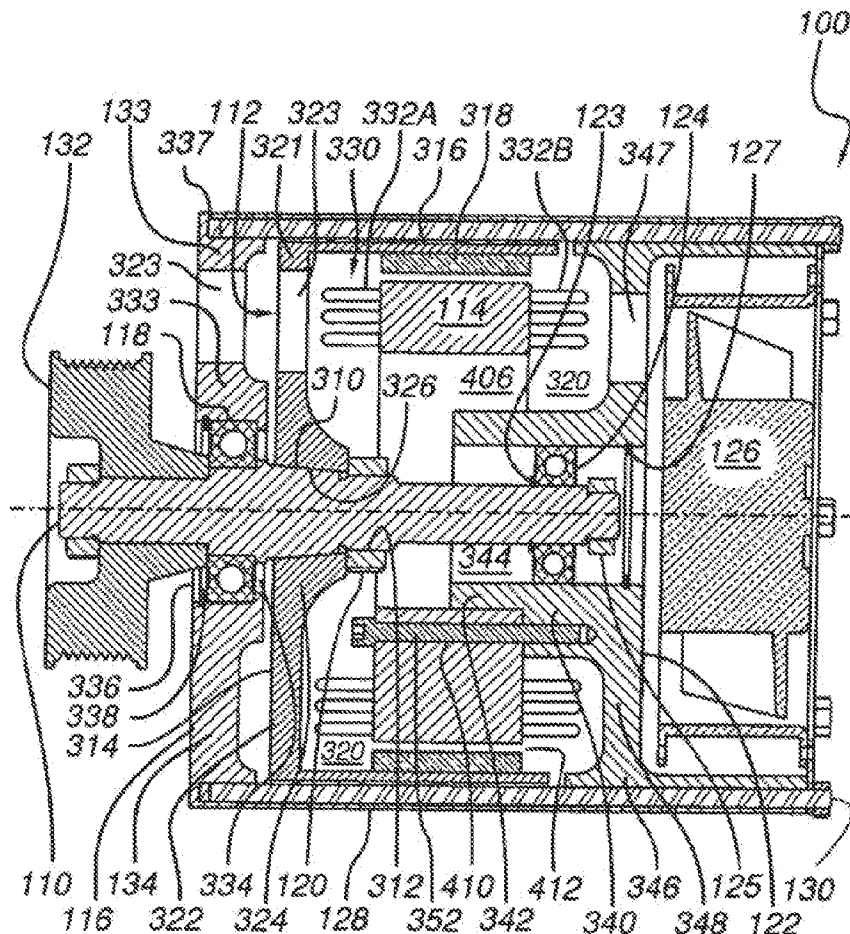


FIG. 1

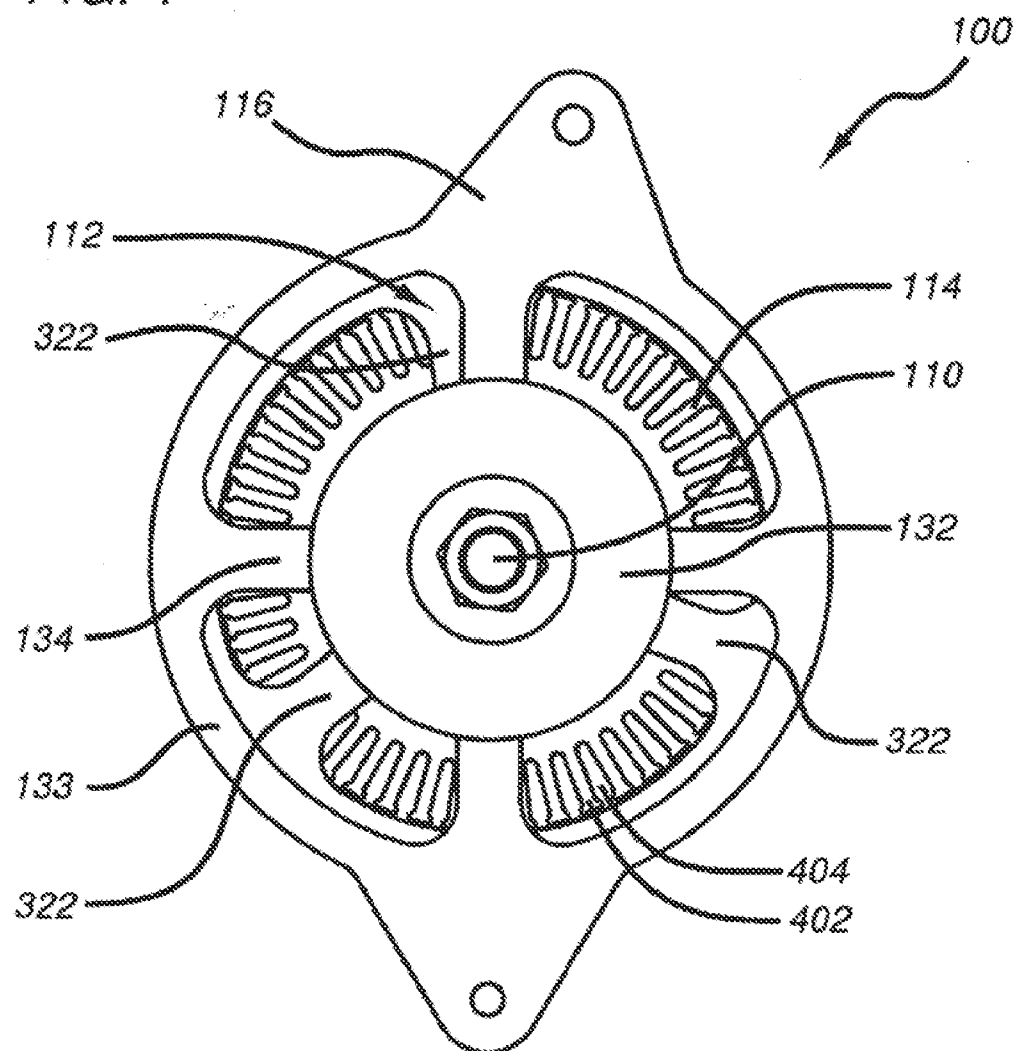


FIG. 2

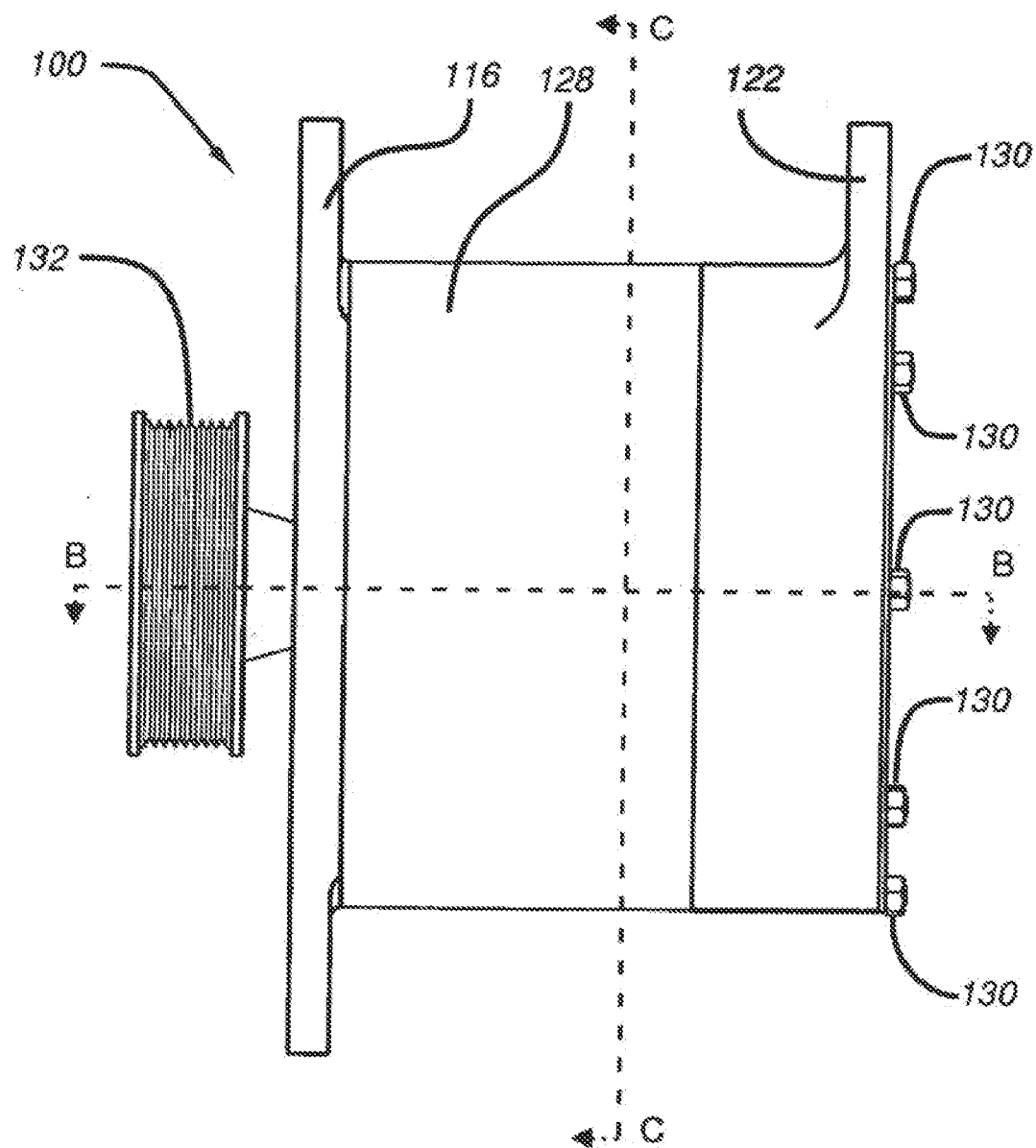
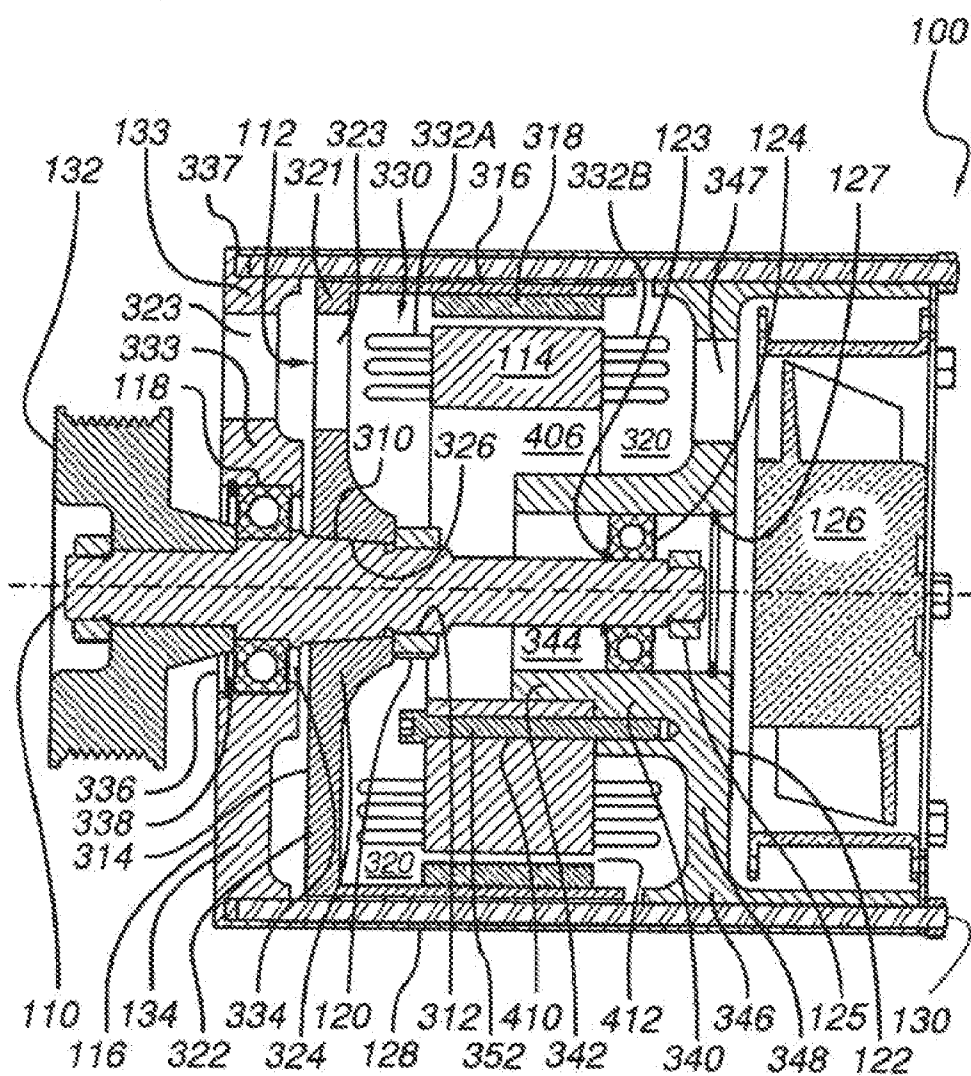
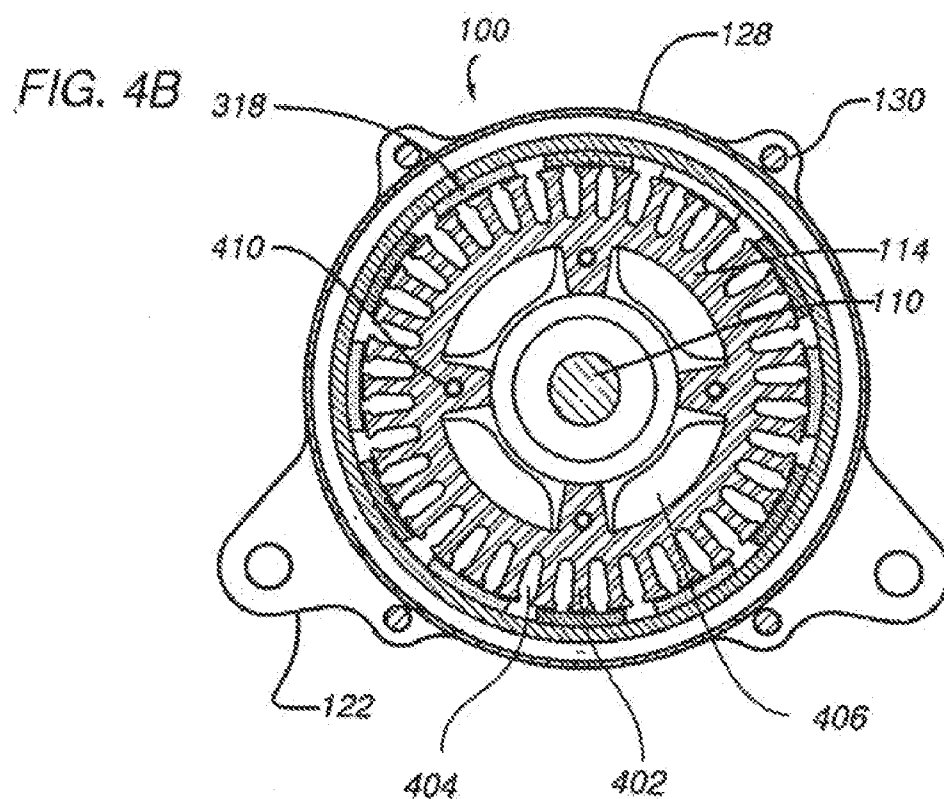
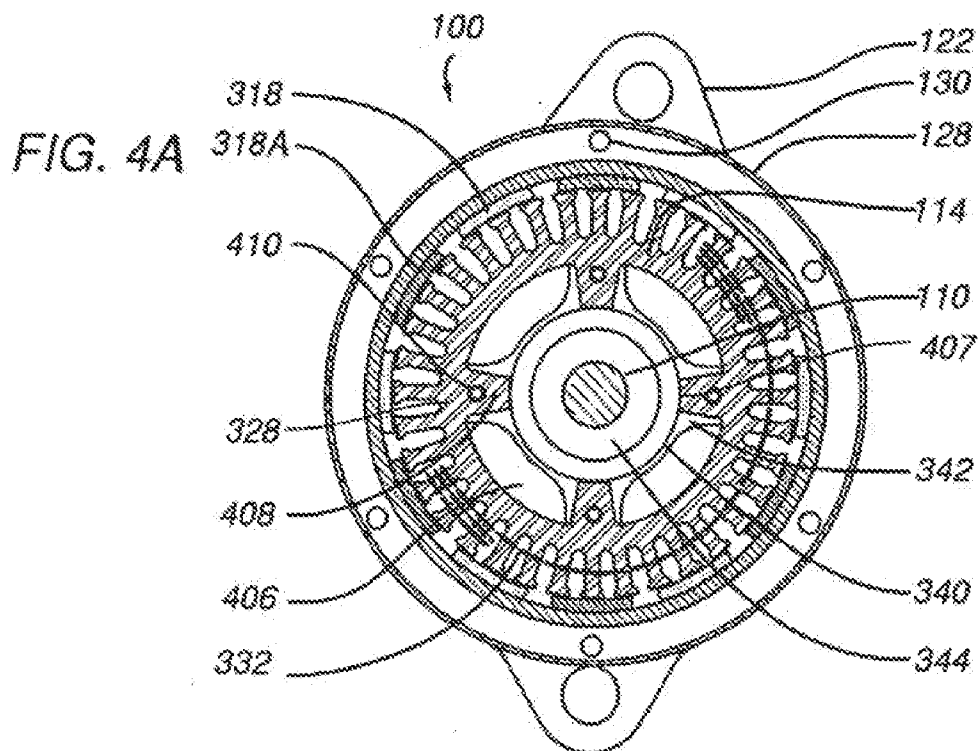
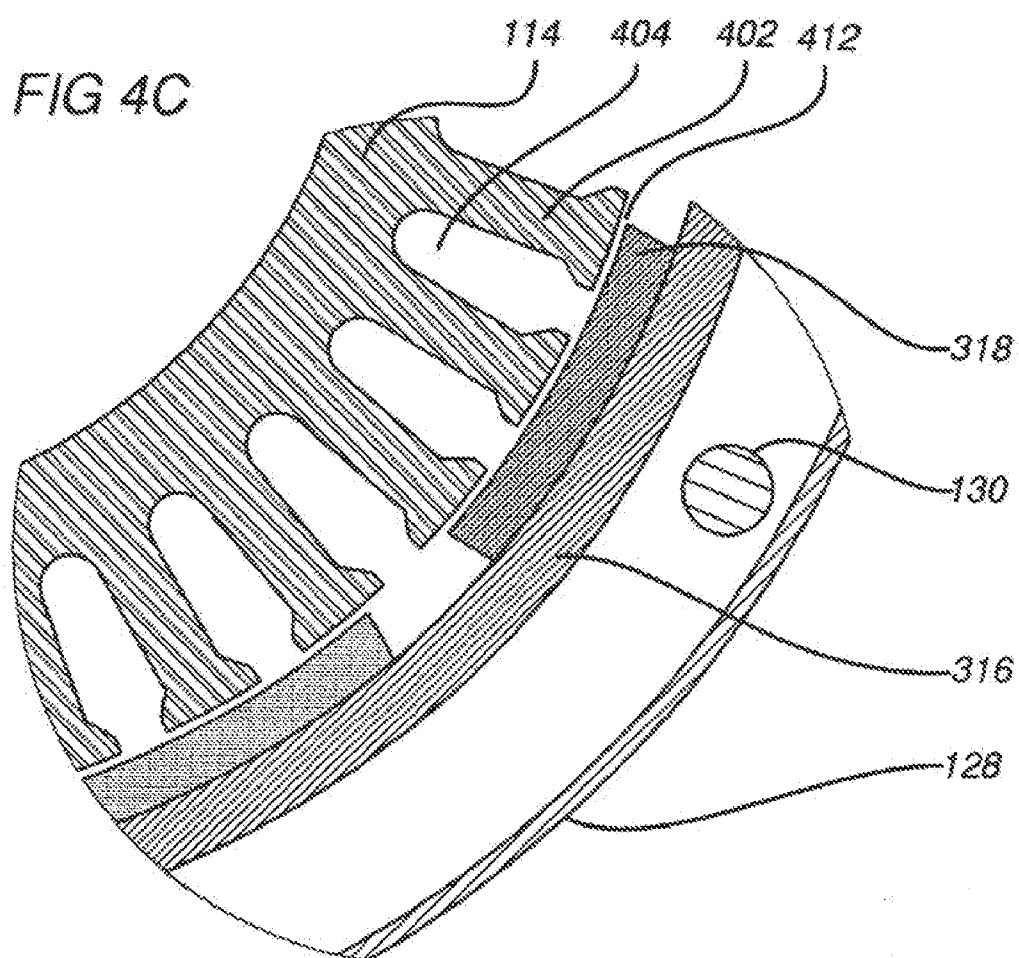


FIG. 3







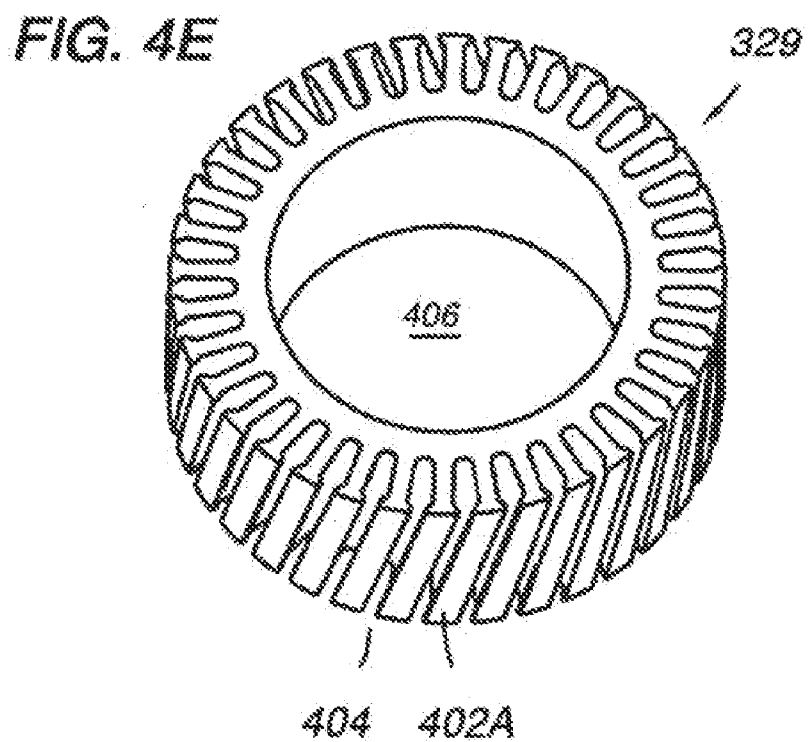
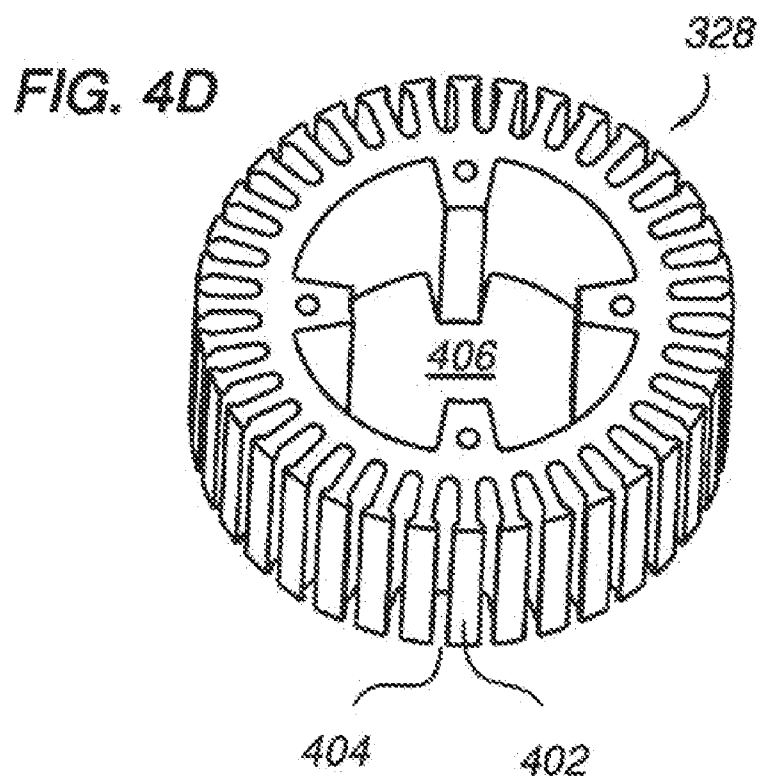


FIG. 4F

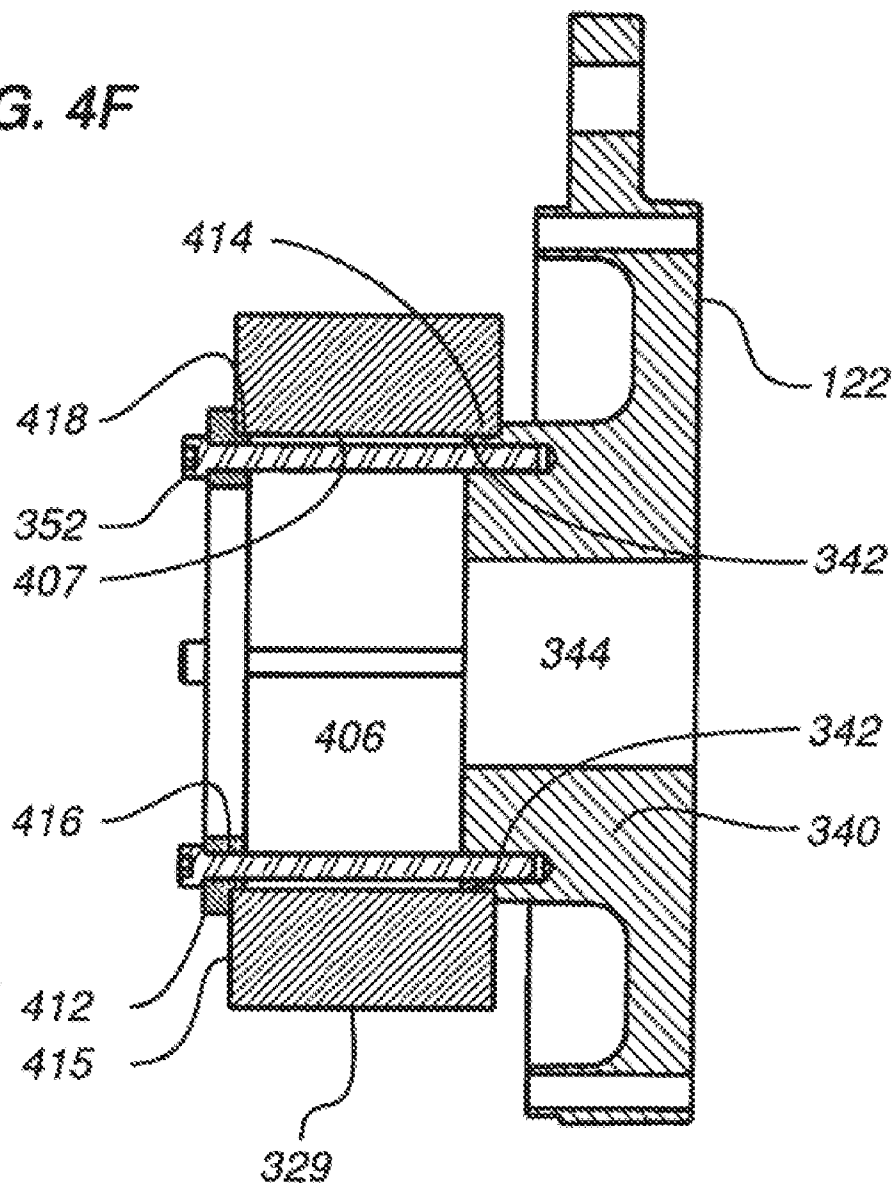


FIG. 4G

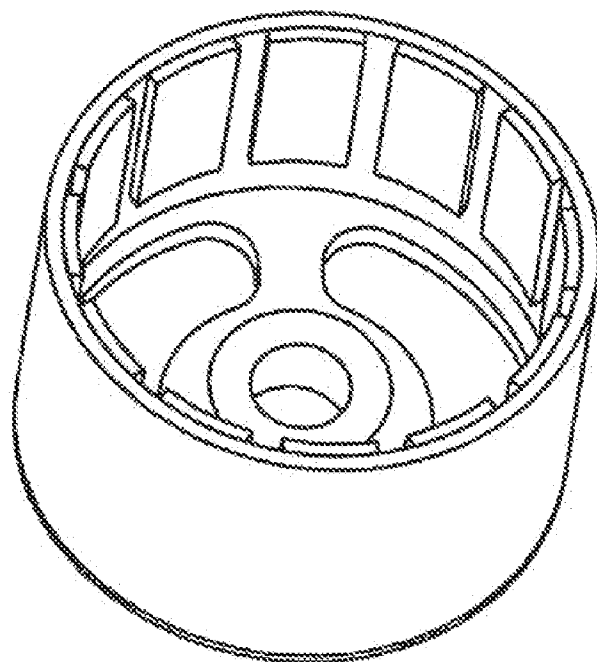


FIG. 4H

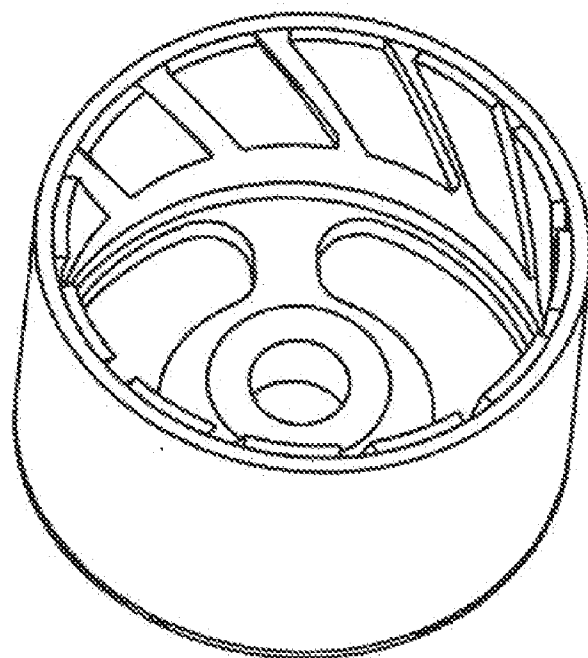
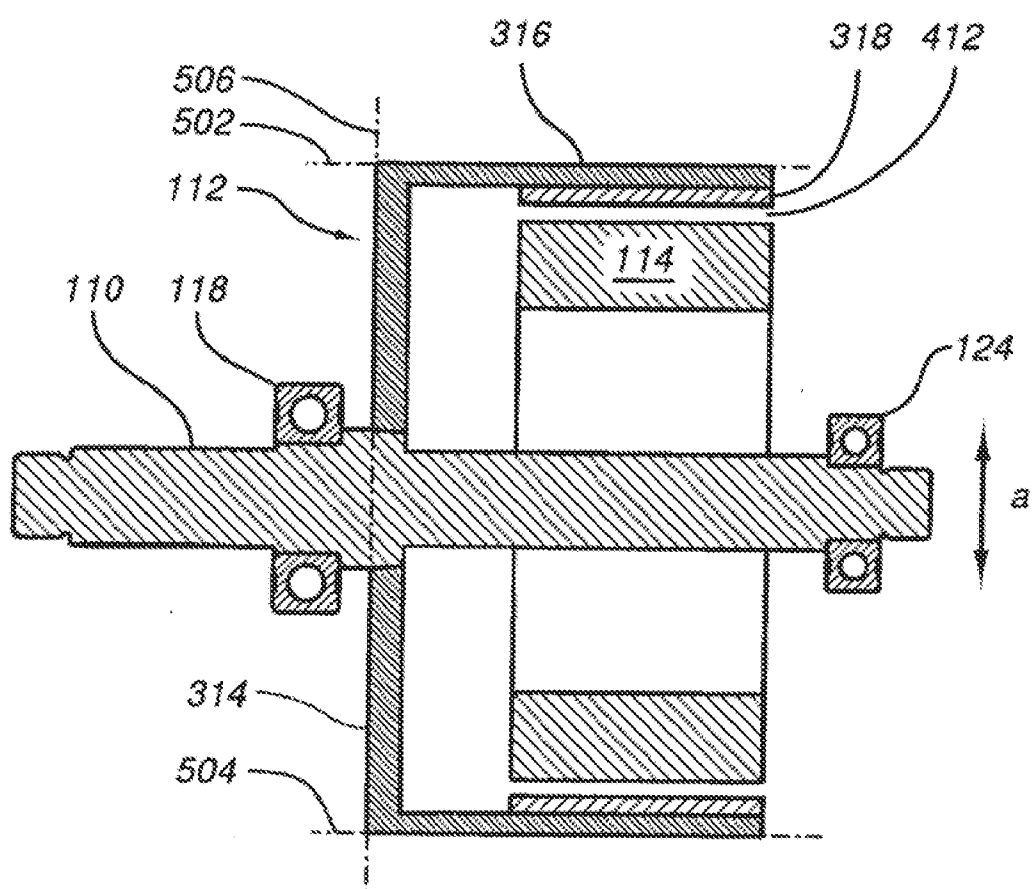
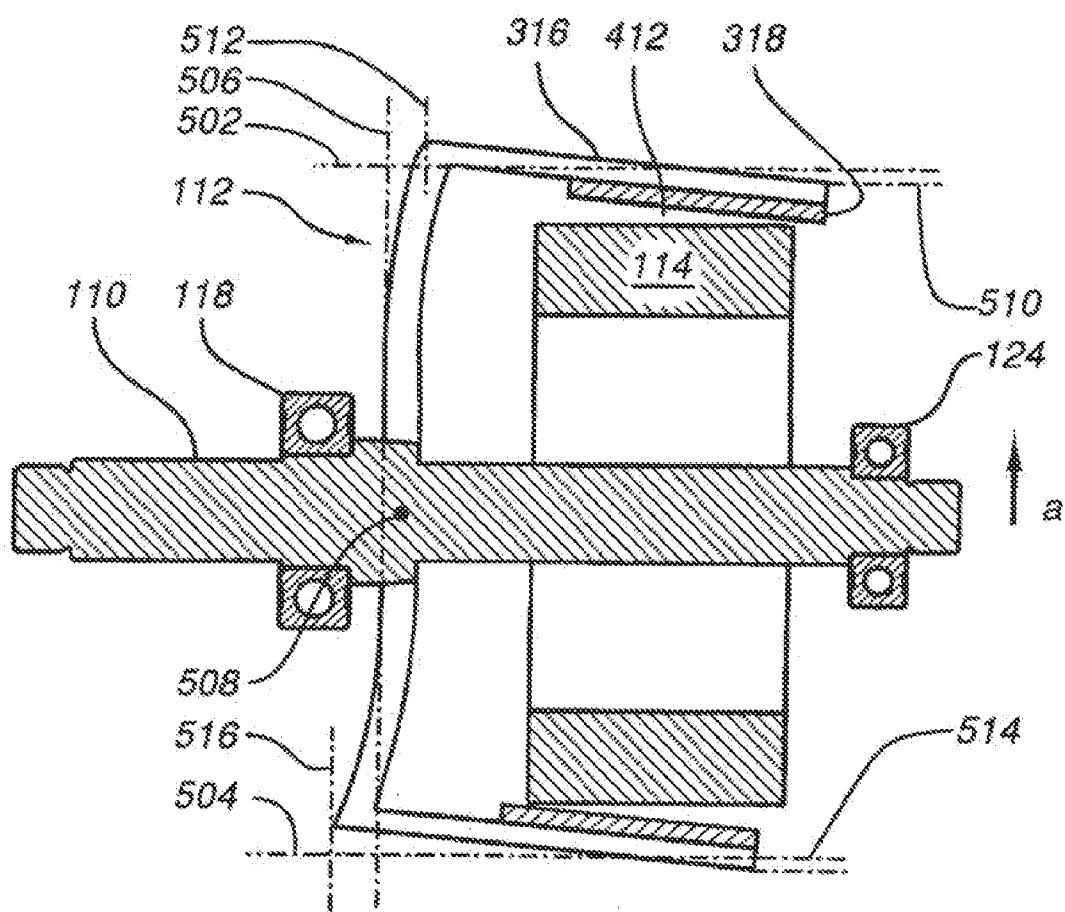


FIG 5A





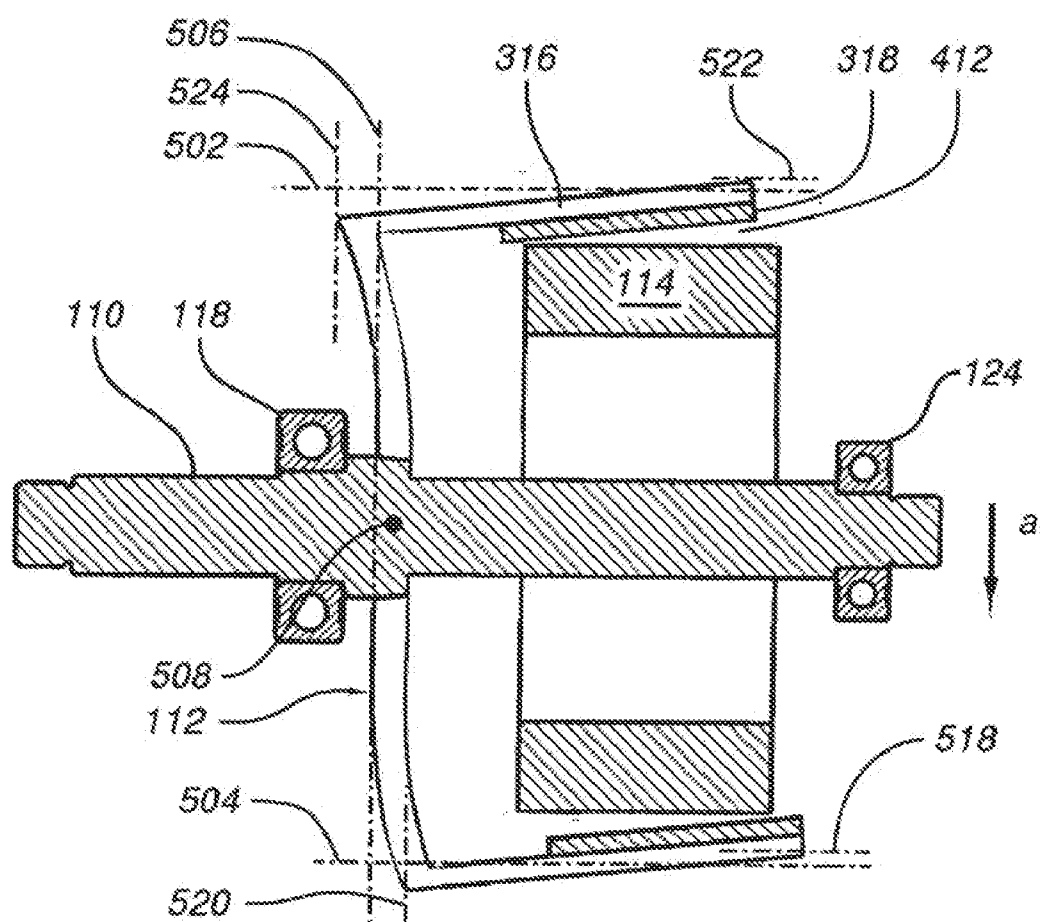


FIG 6A

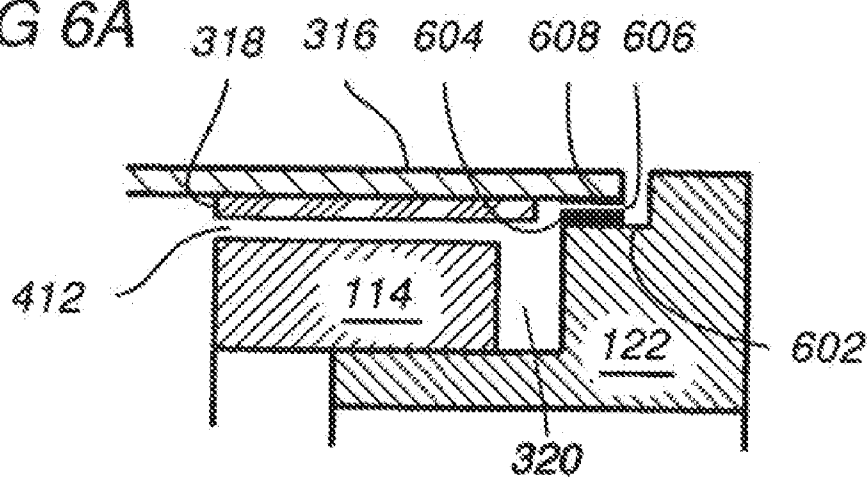


FIG 6B

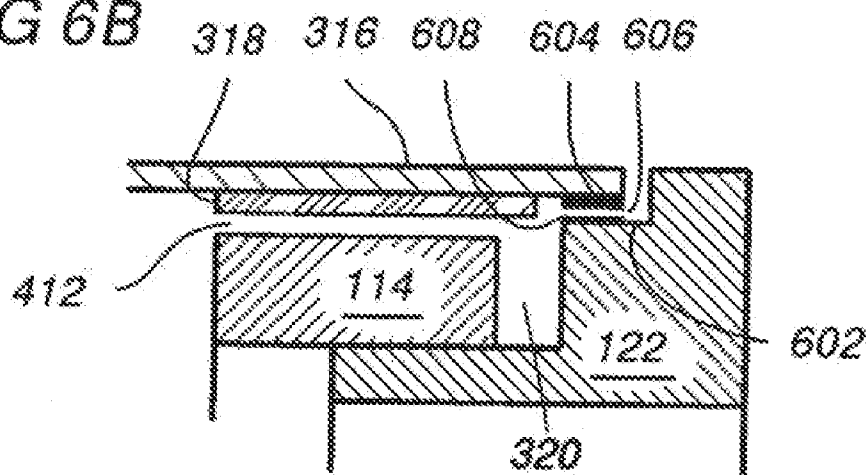


FIG 6C

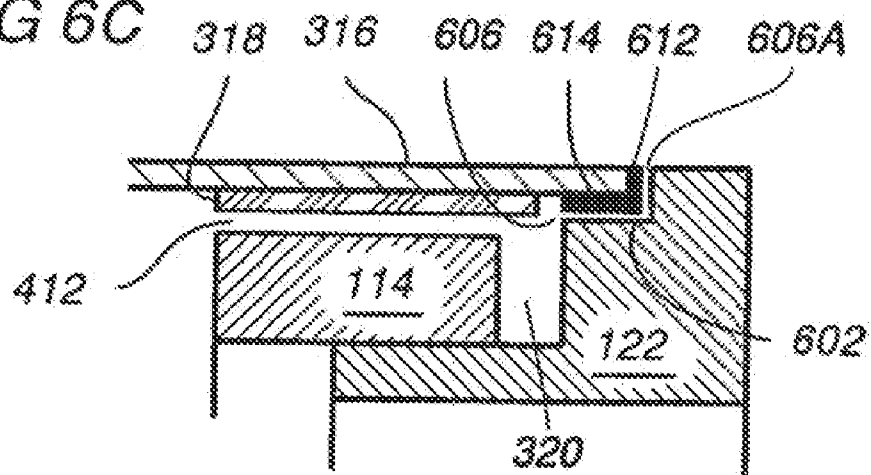


FIG 6D

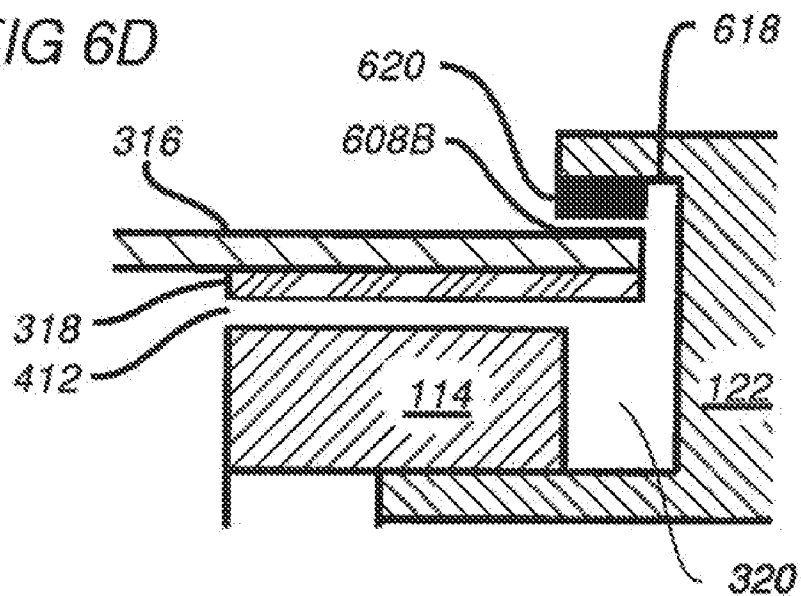


FIG 6E

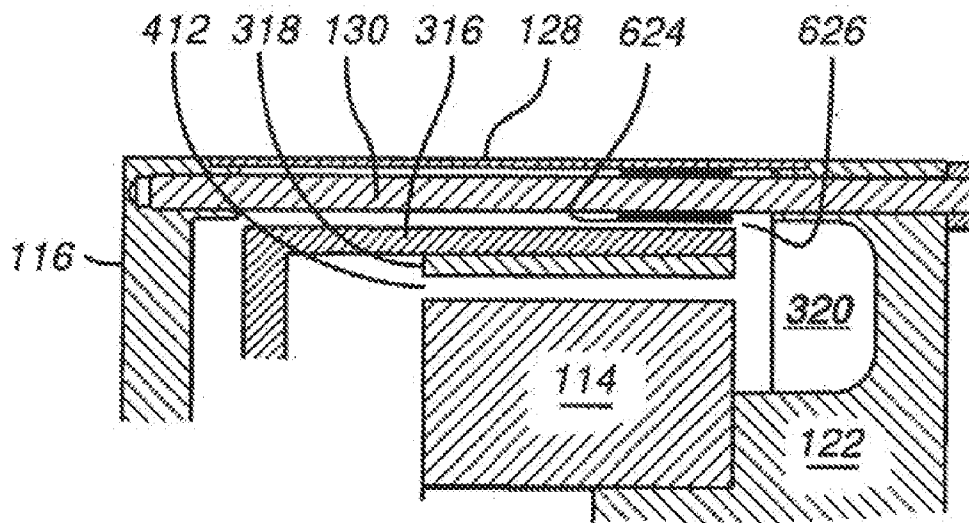


FIG 6F

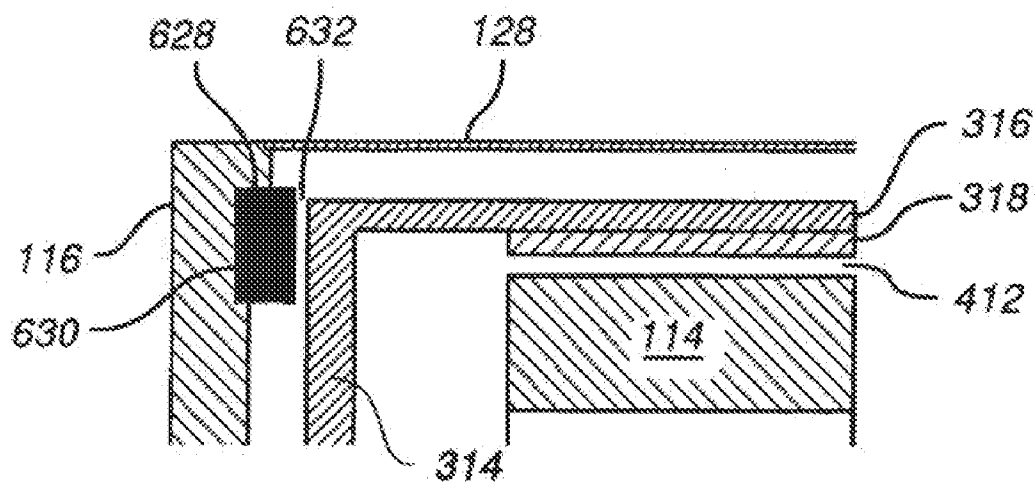


FIG 6G

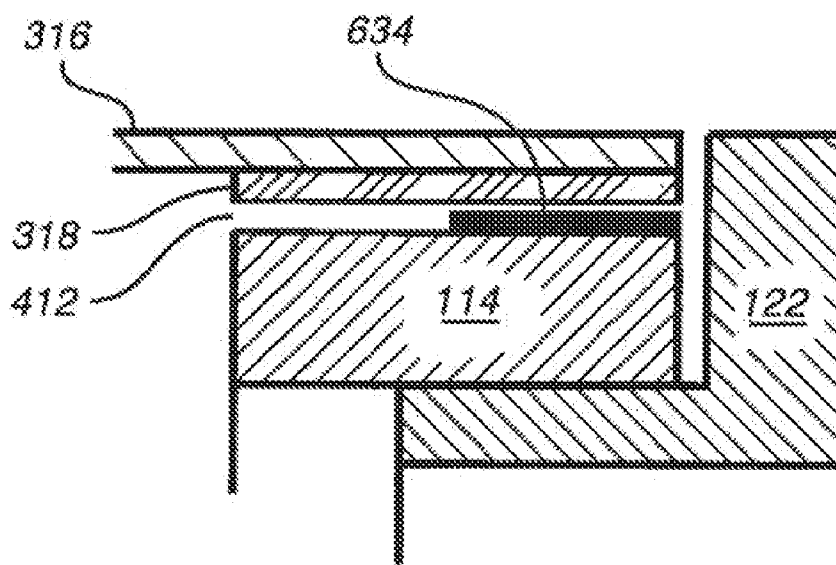


FIG 7A

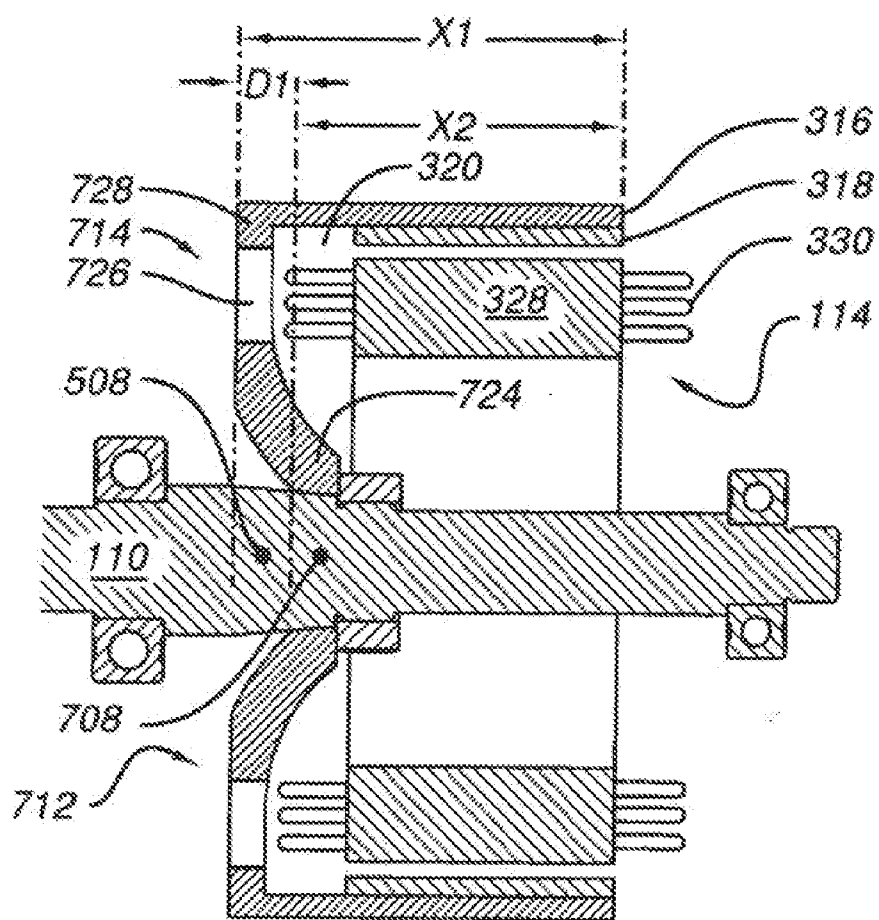


FIG. 7B

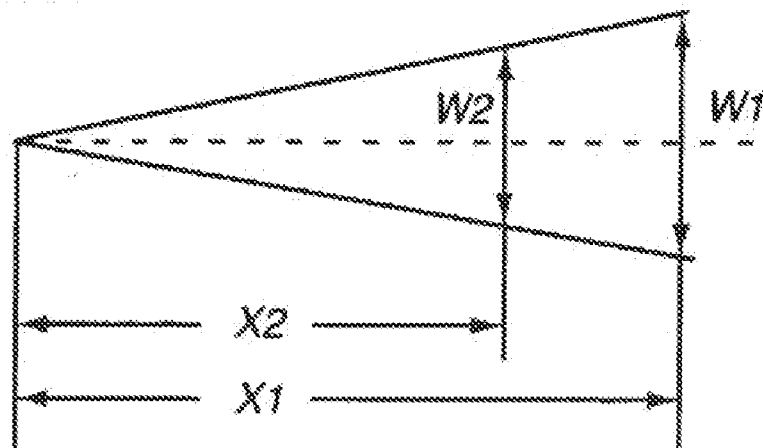
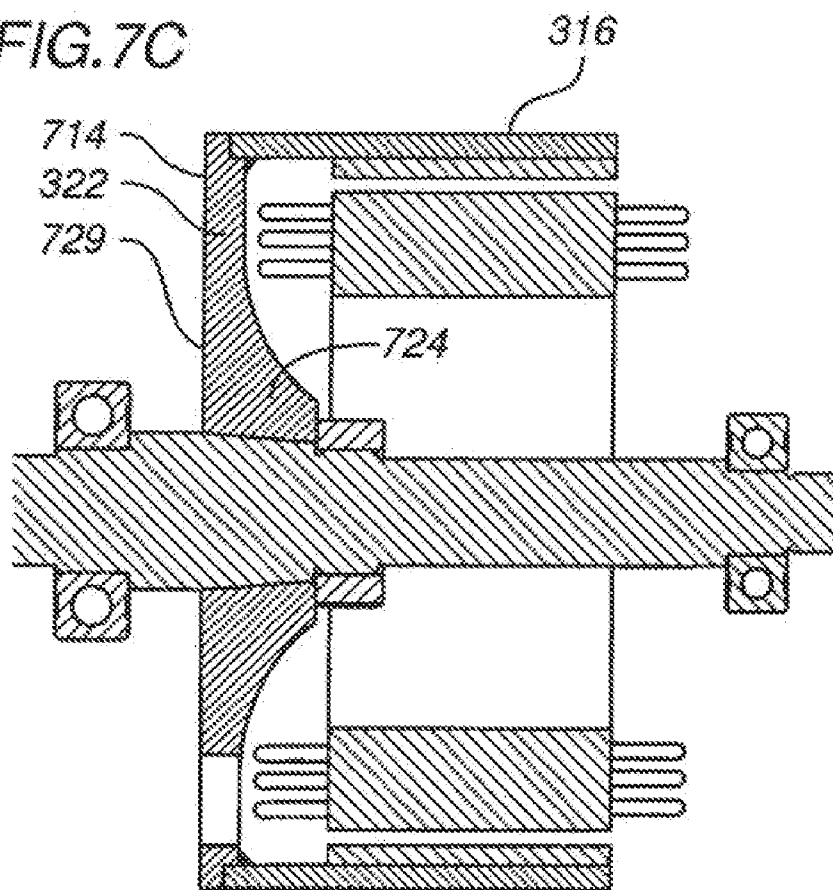


FIG. 7C



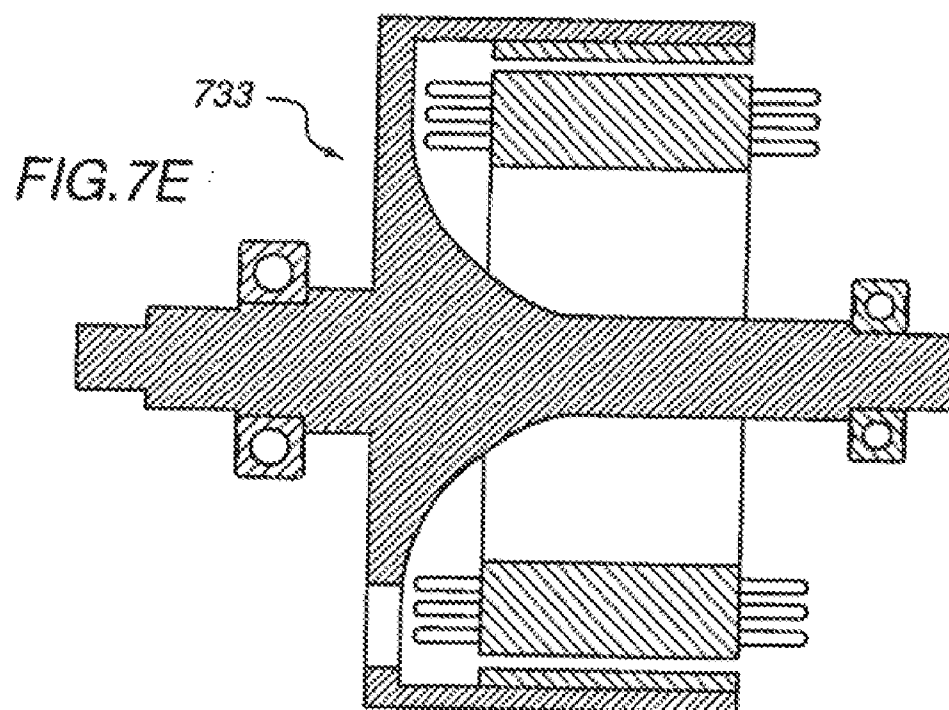
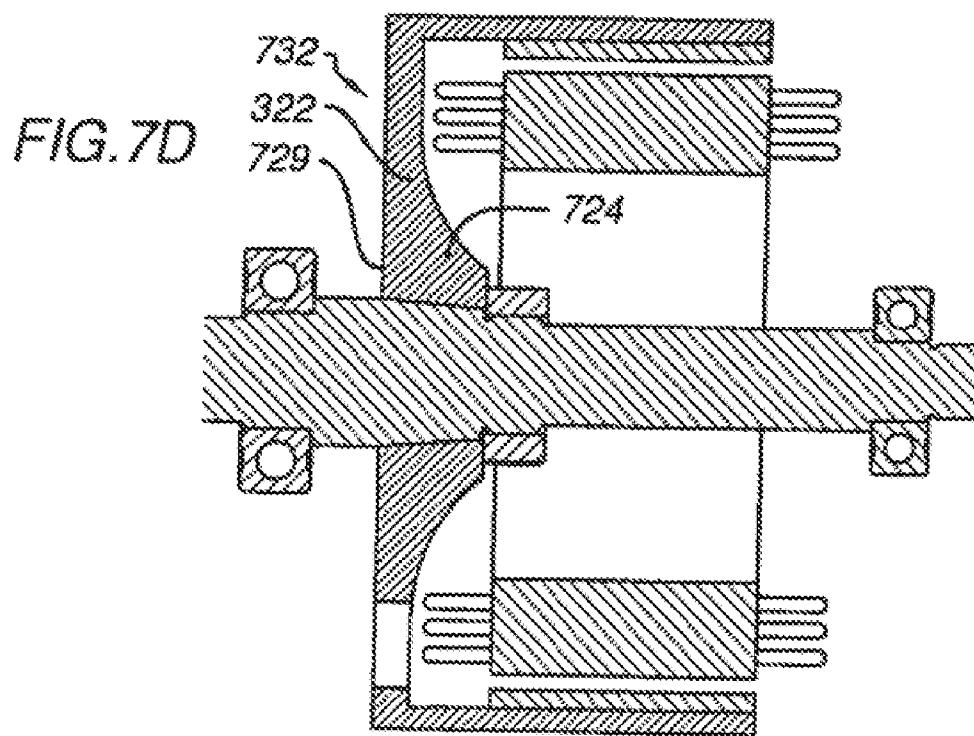
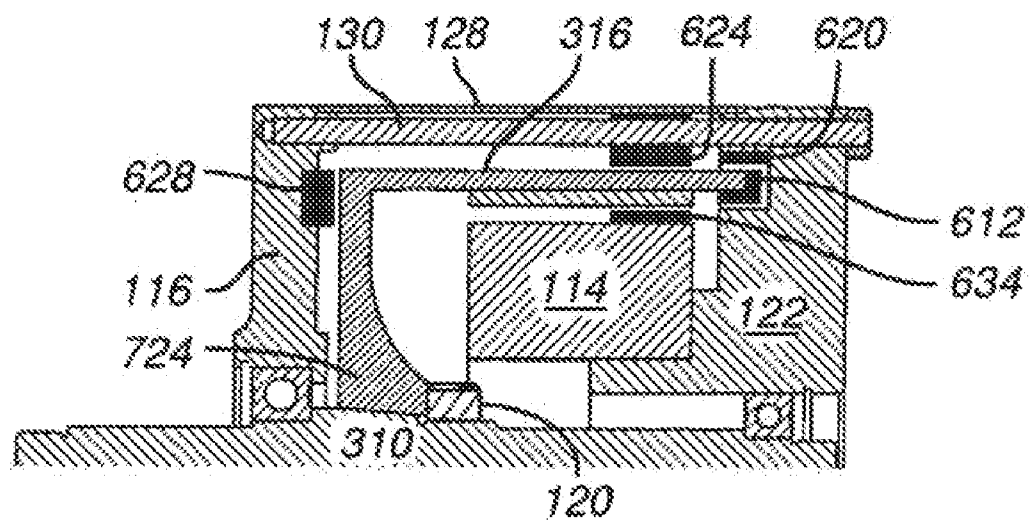


FIG 8



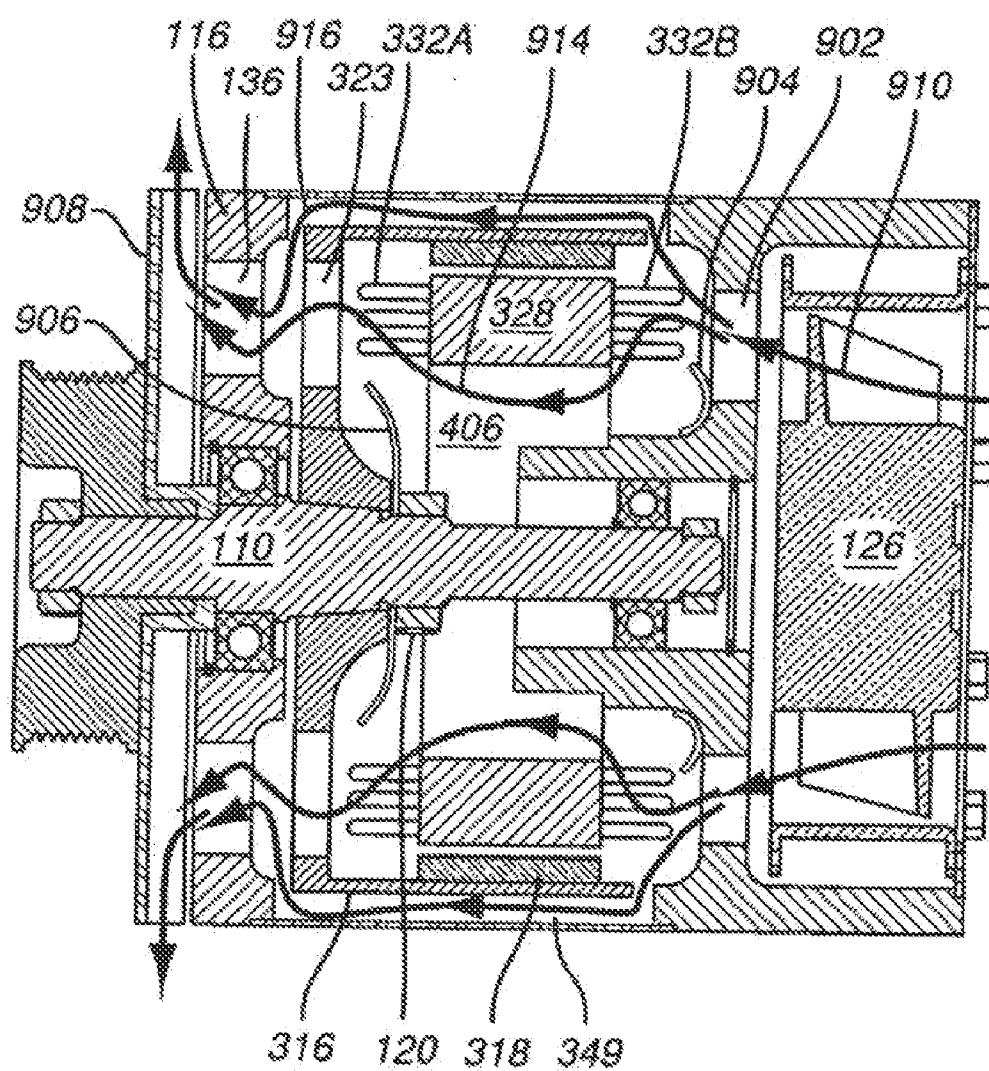
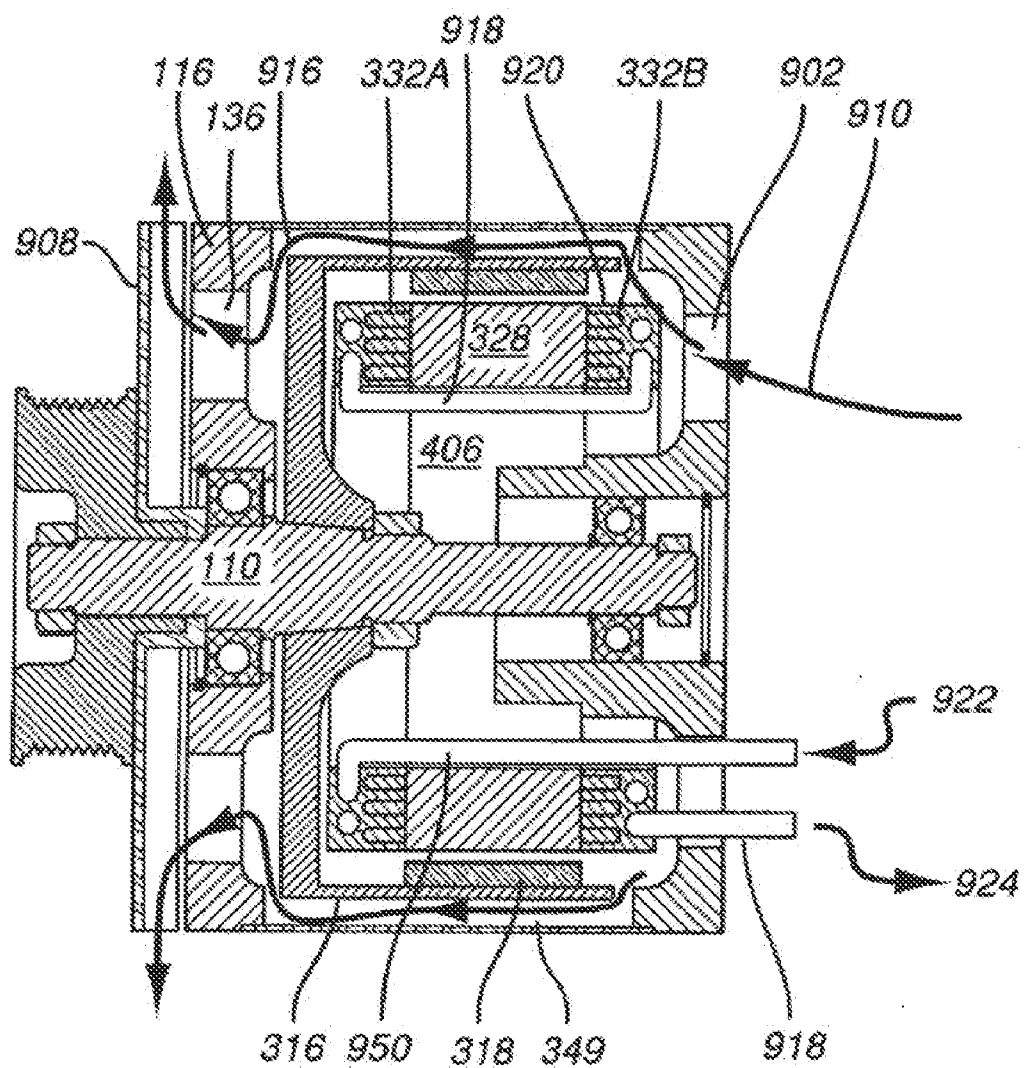


FIG. 9B



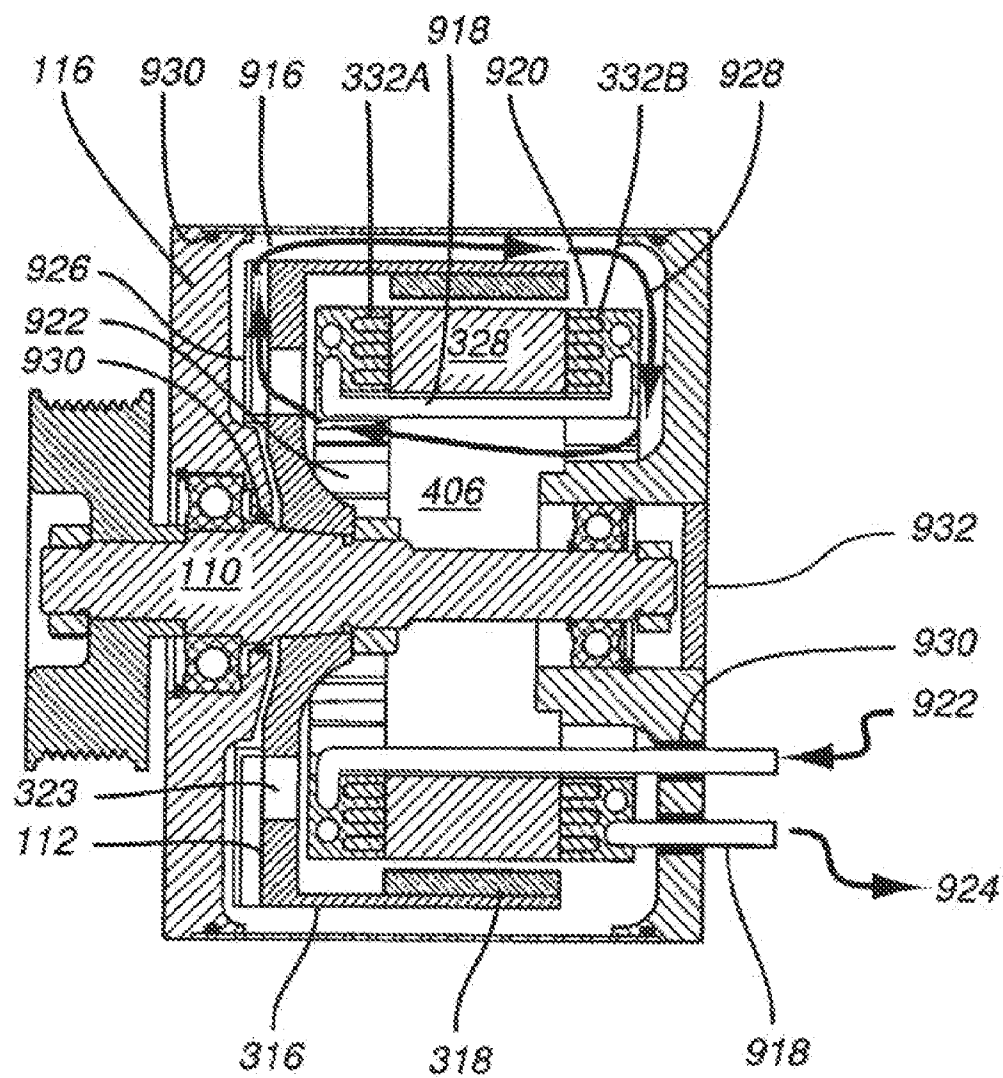


Fig. 9D

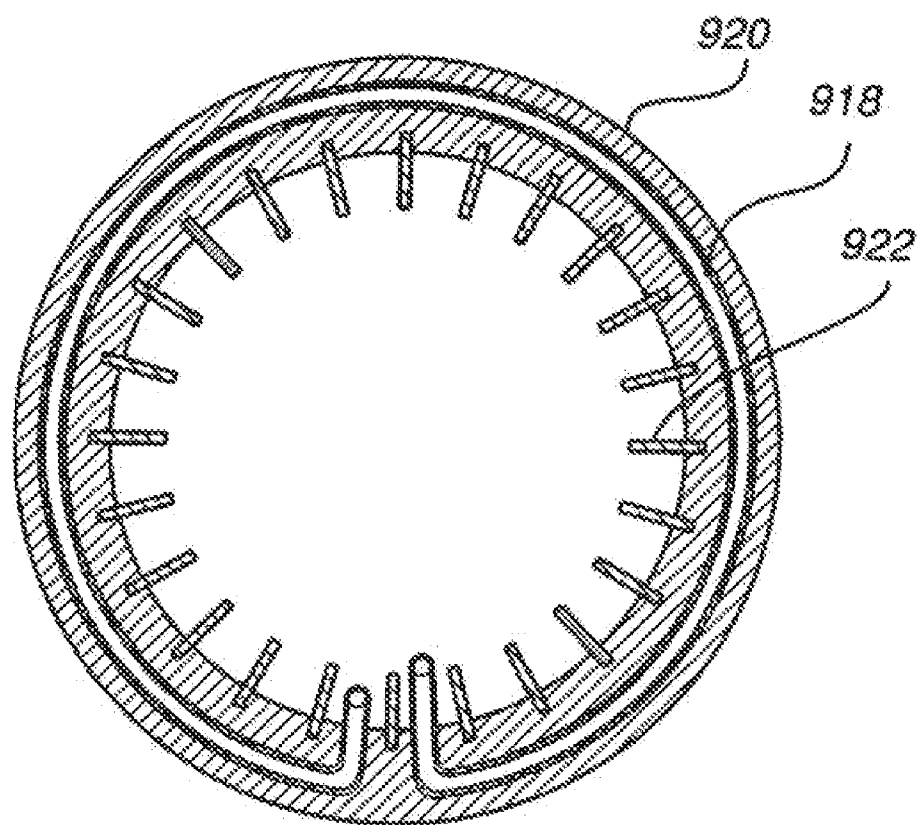
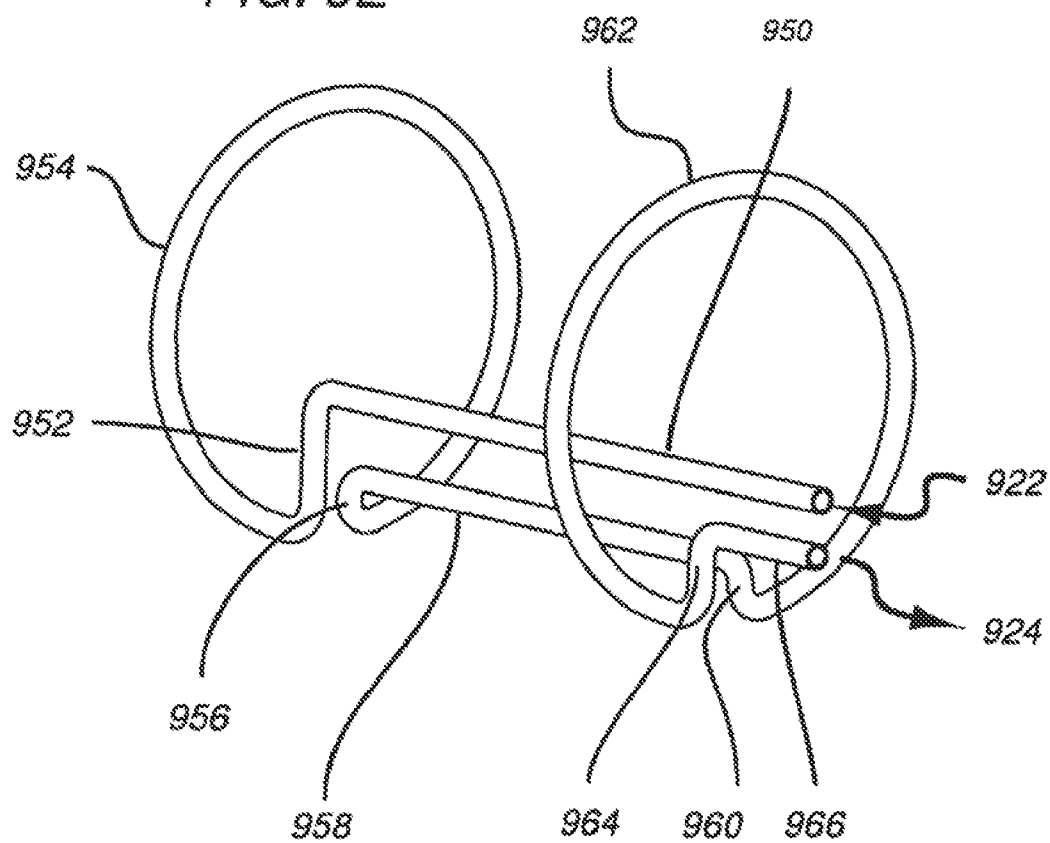


FIG. 9E



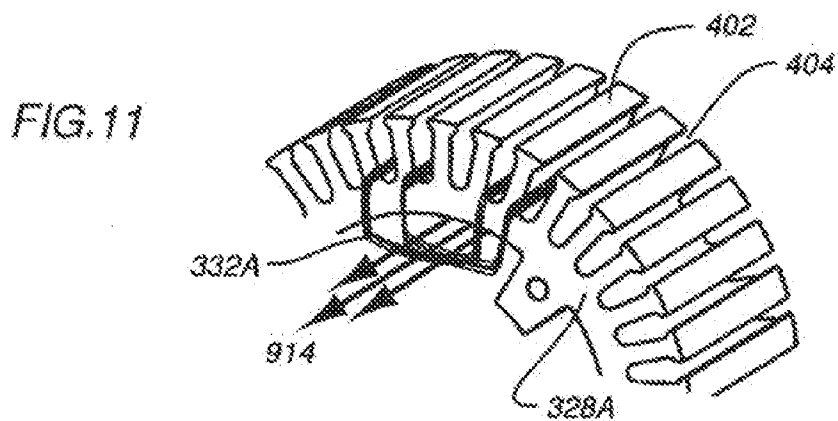
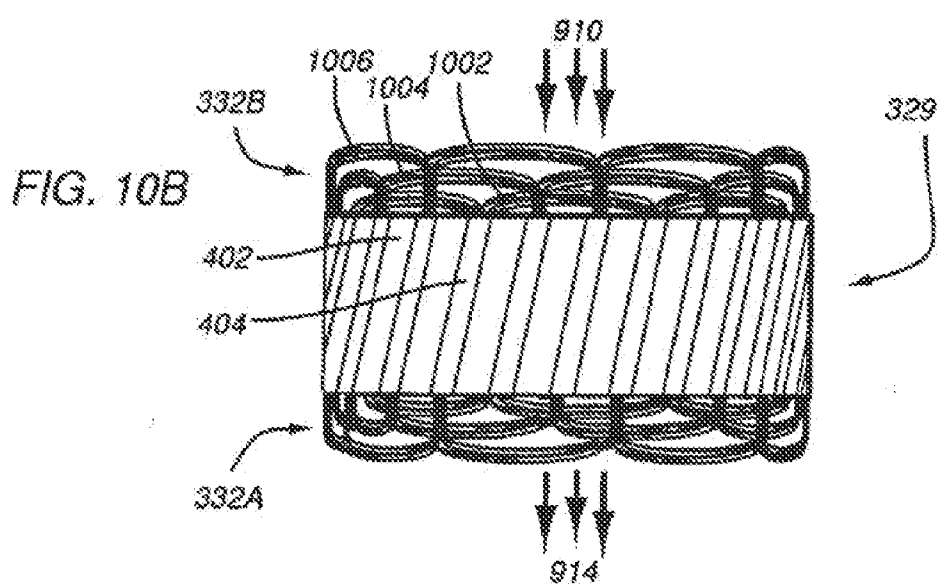
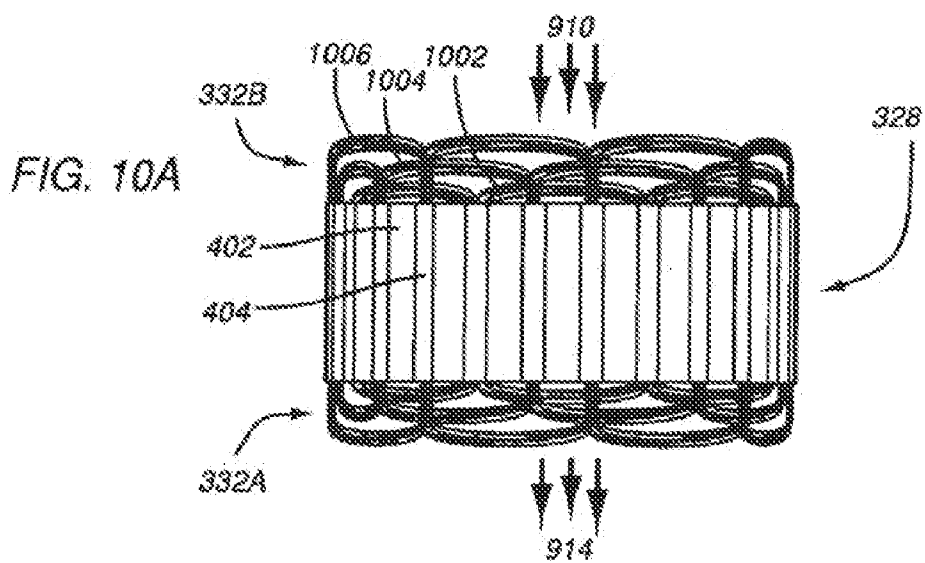


FIG. 12

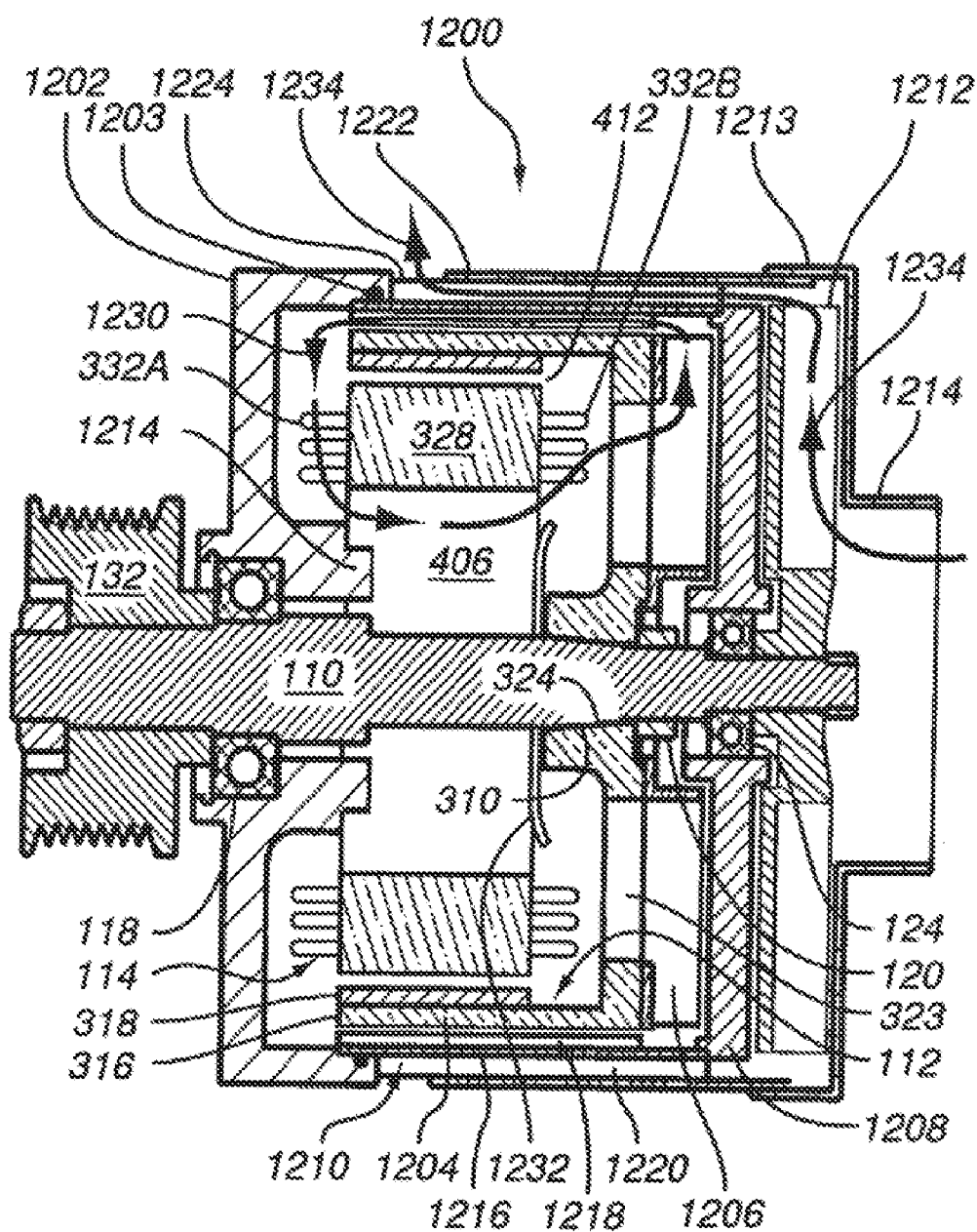


FIG. 13A

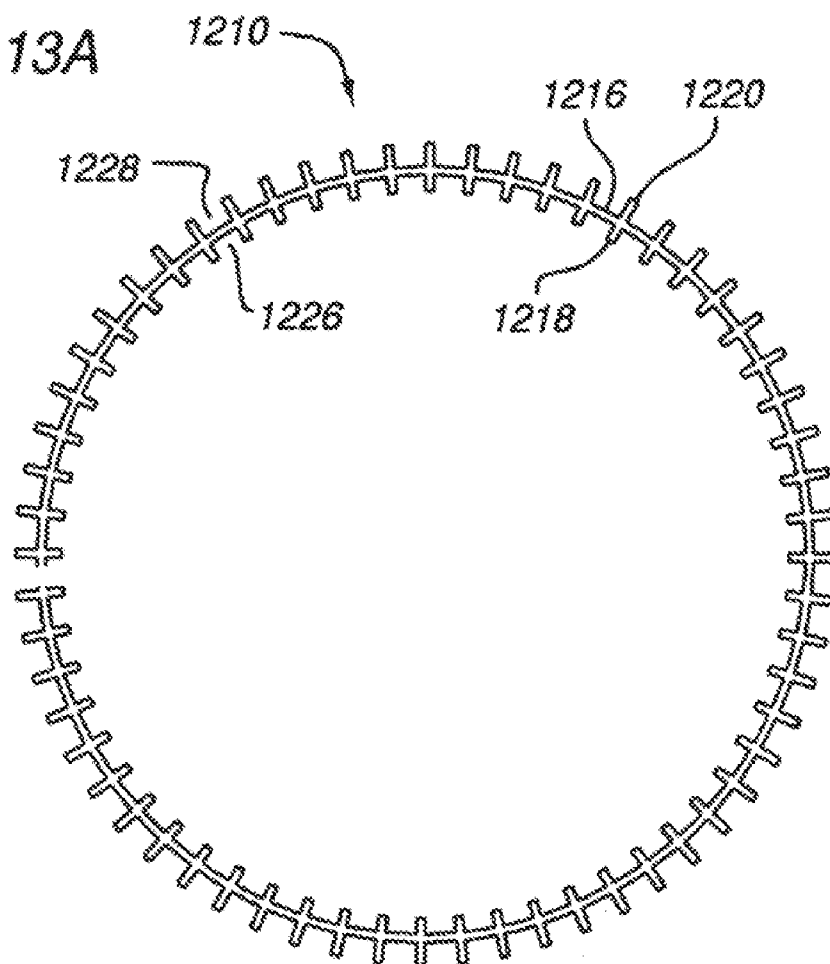
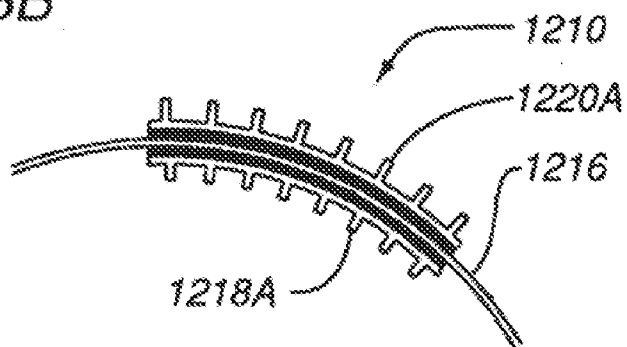


FIG. 13B



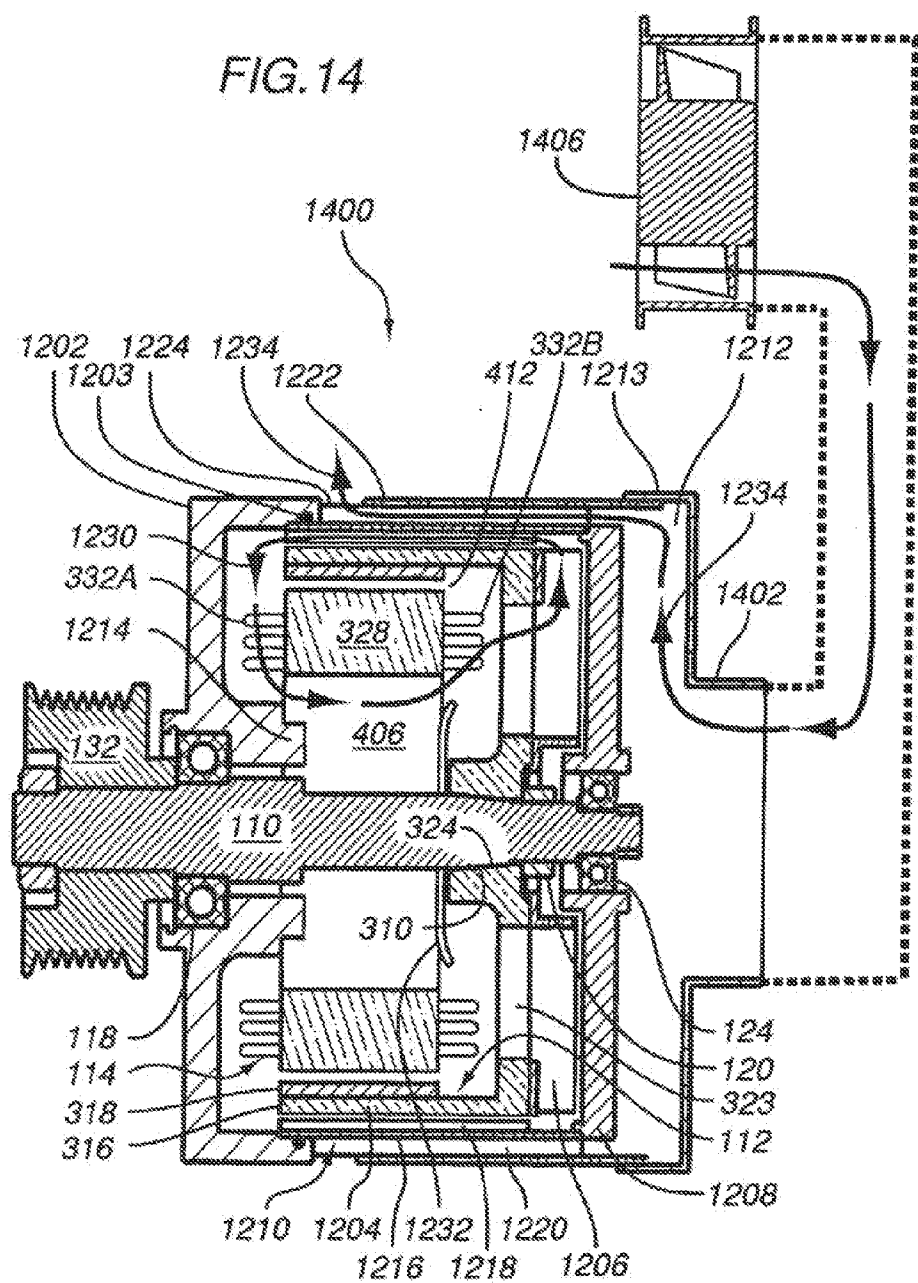


FIG. 15

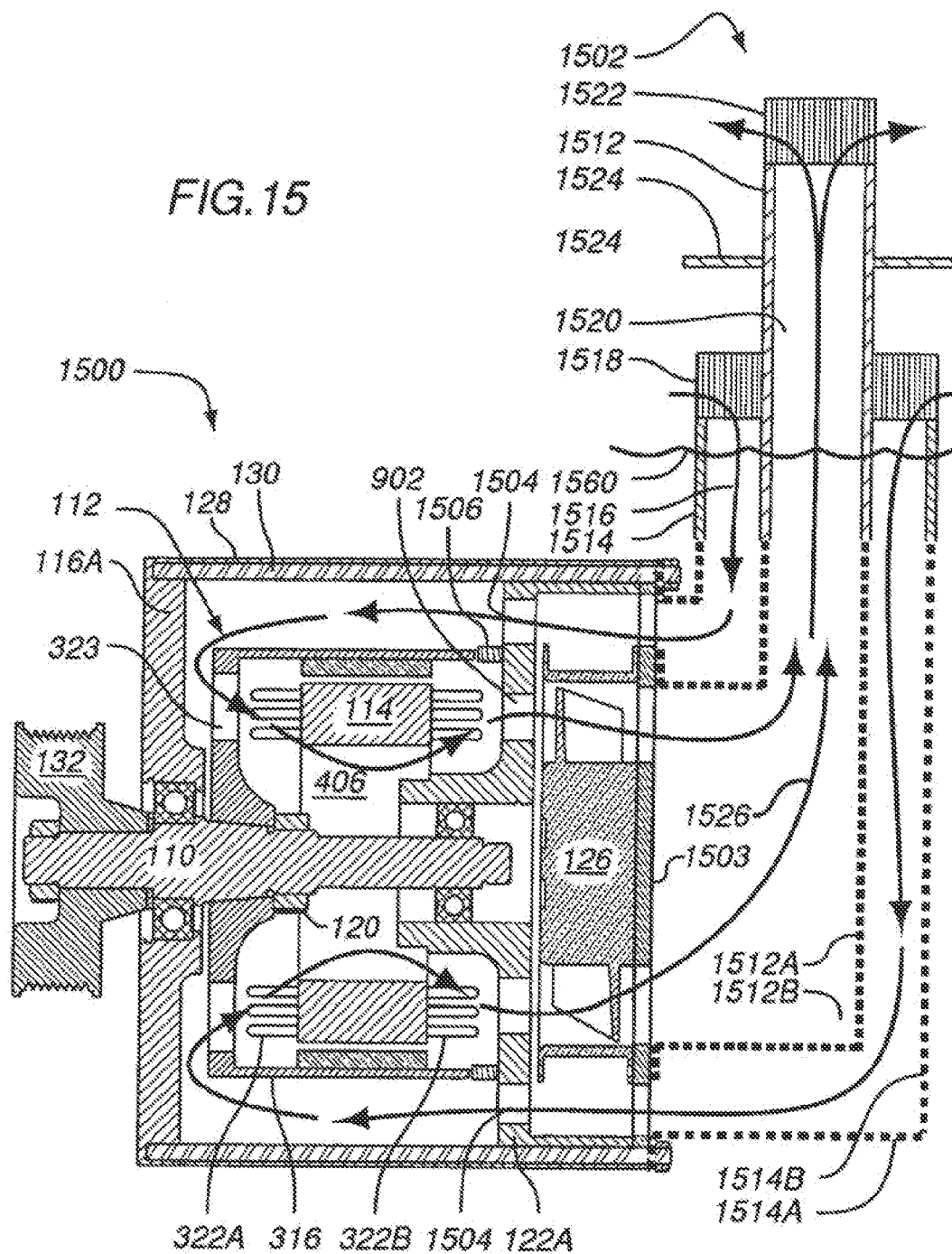
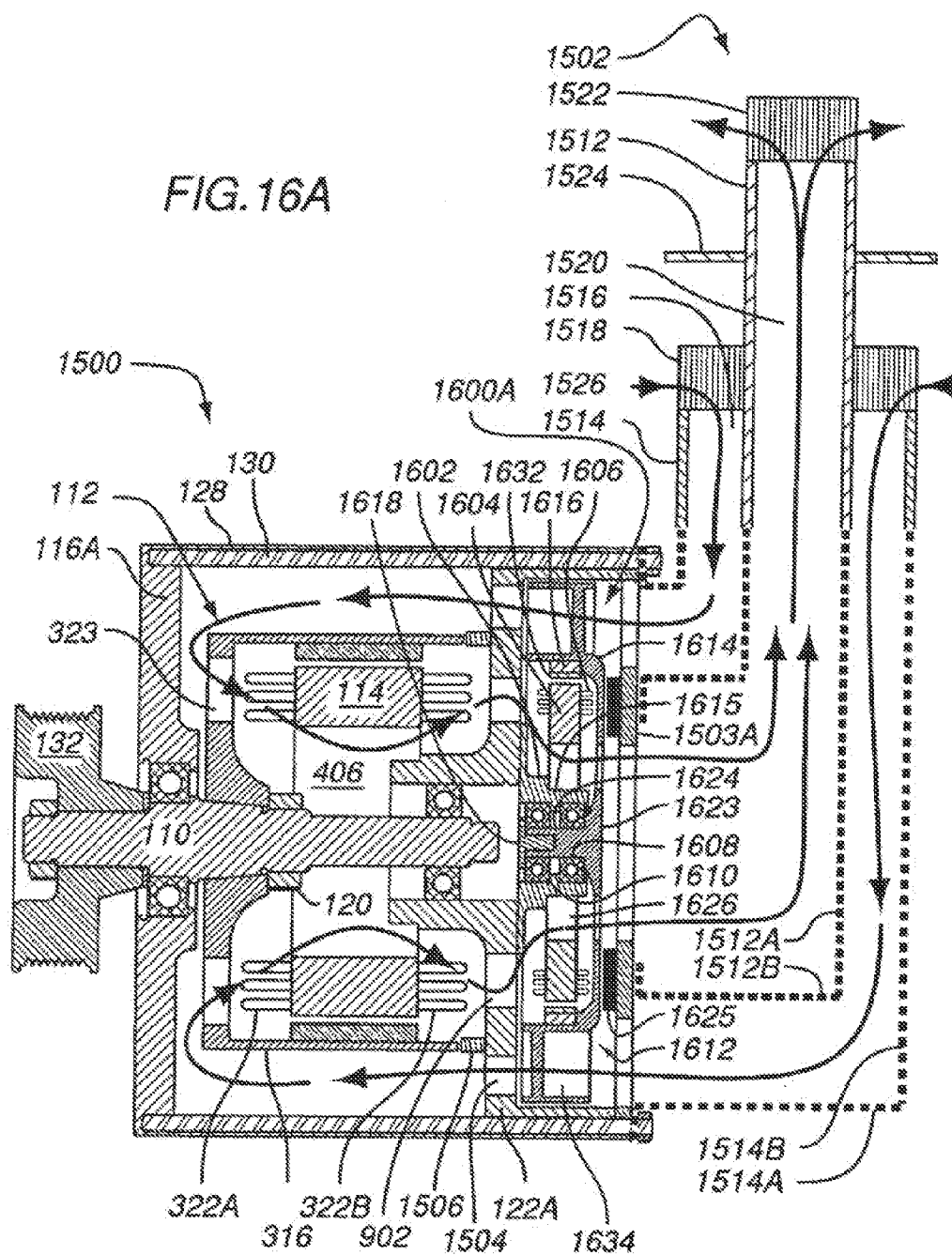


FIG. 16A



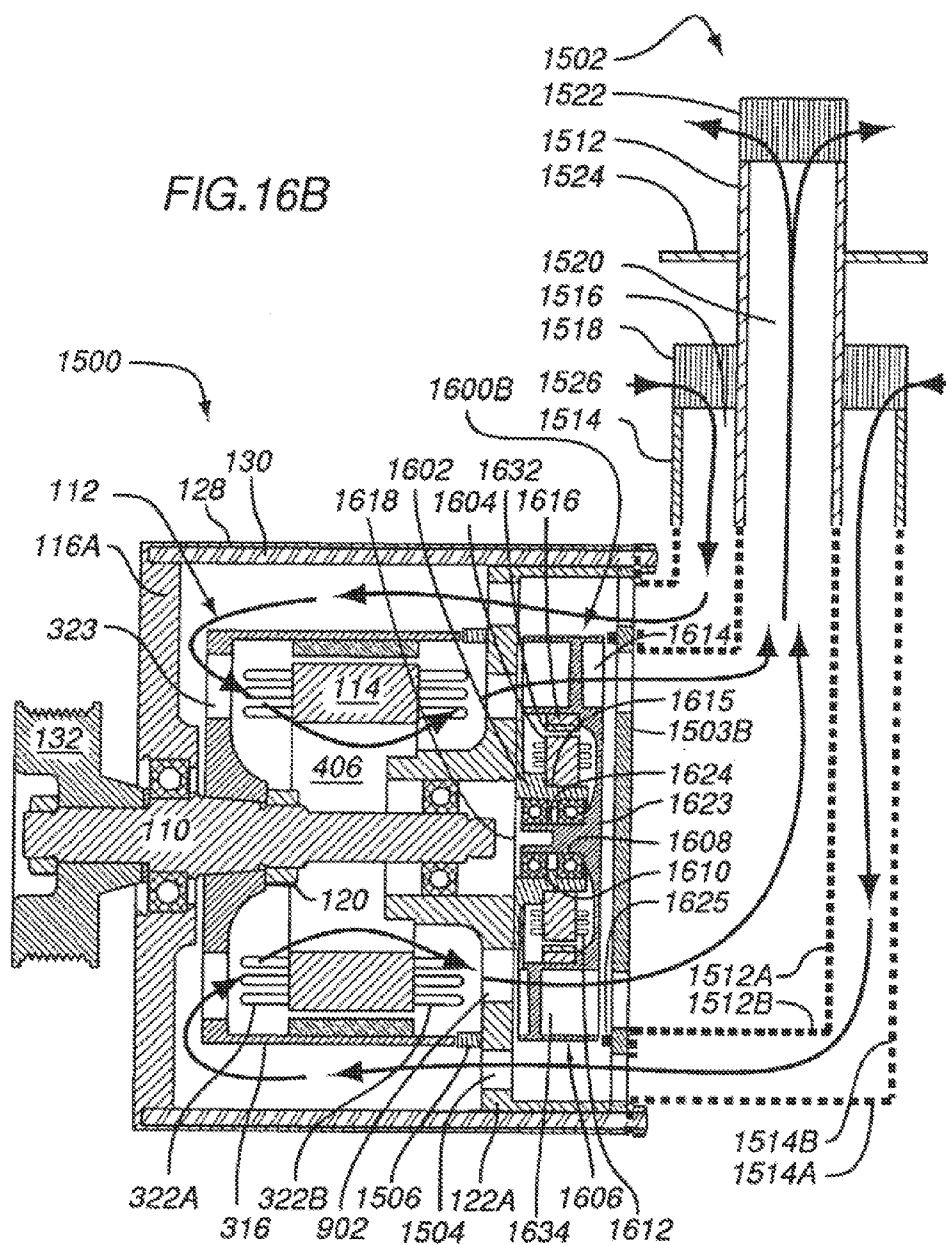


FIG. 17

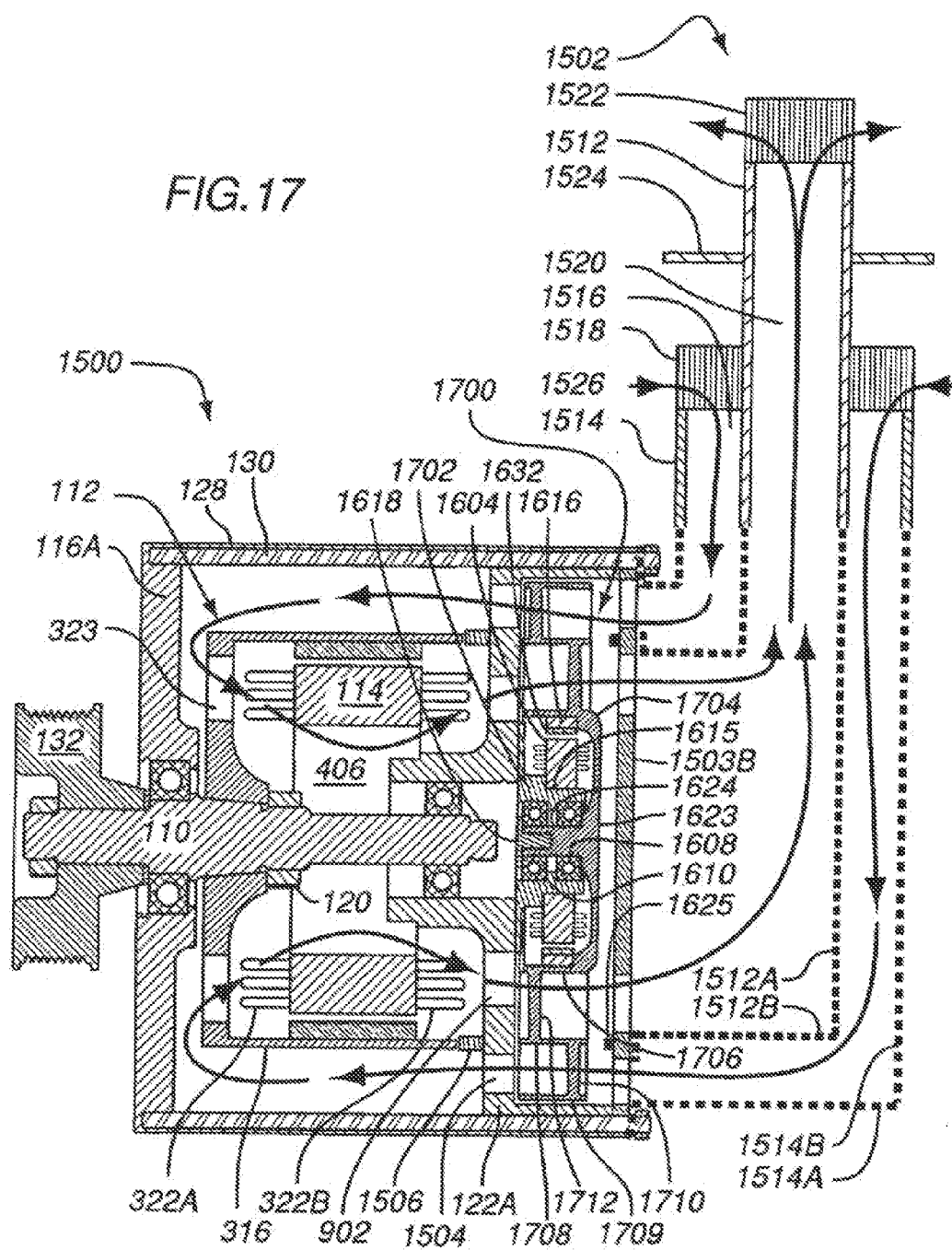


FIG. 18A

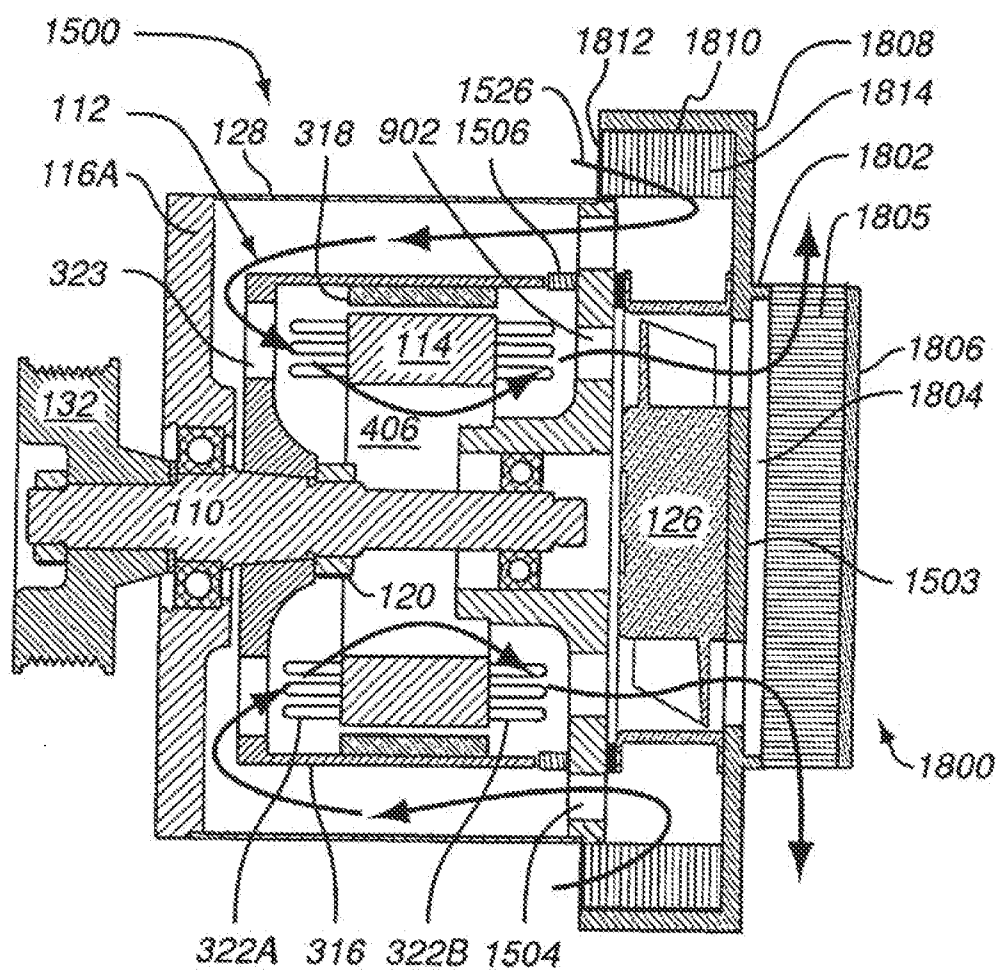


FIG. 18B

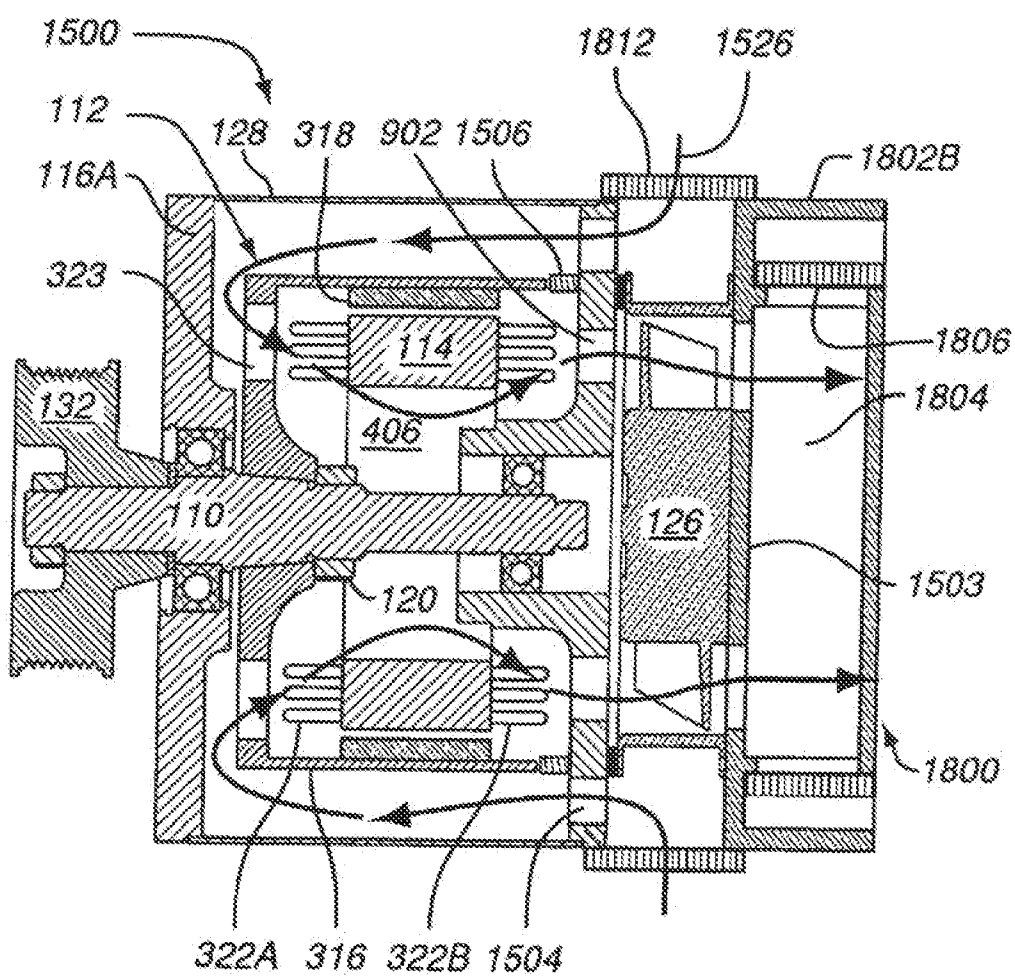


FIG. 18C

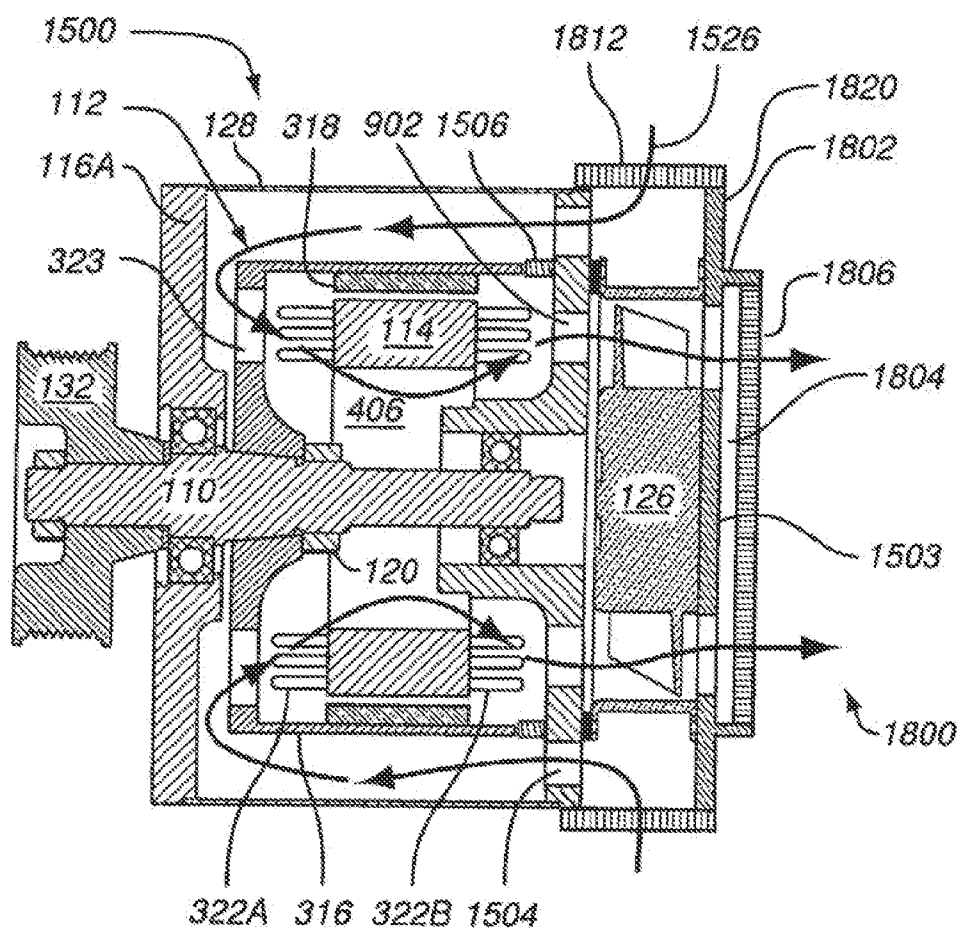


FIG. 19

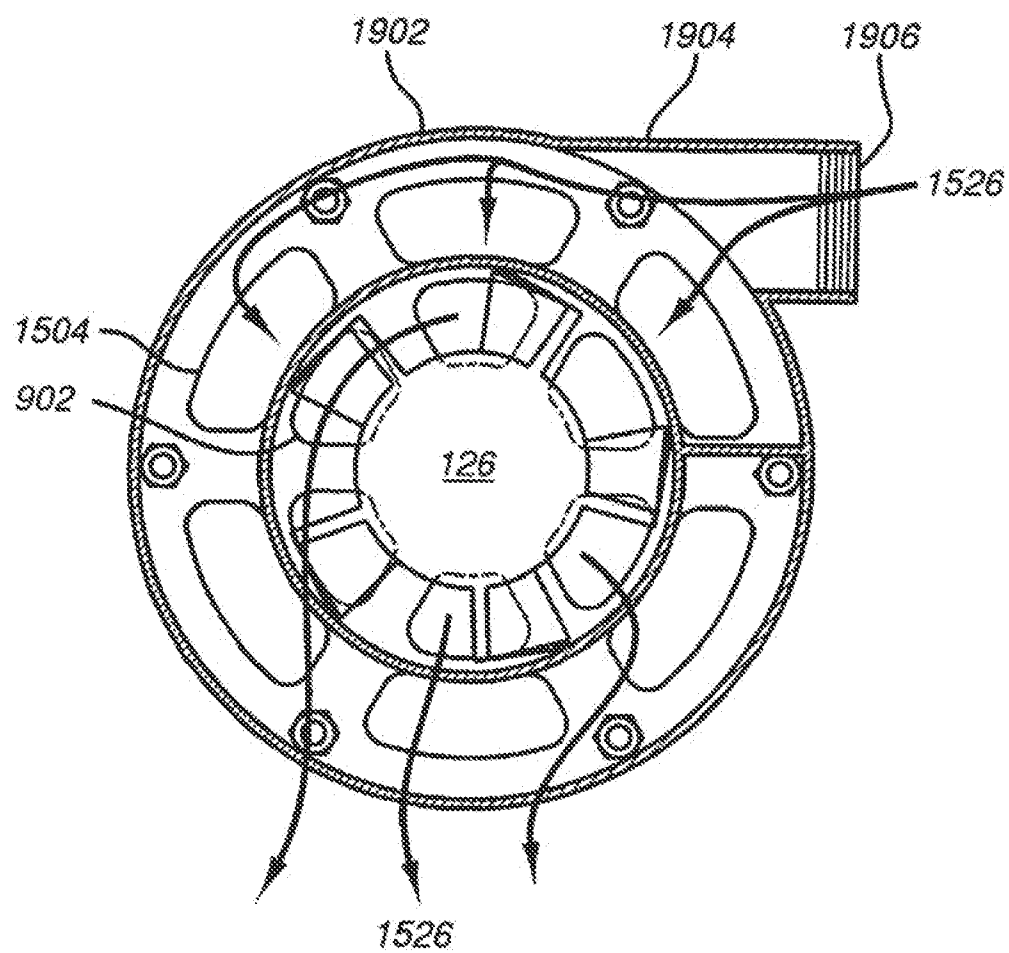
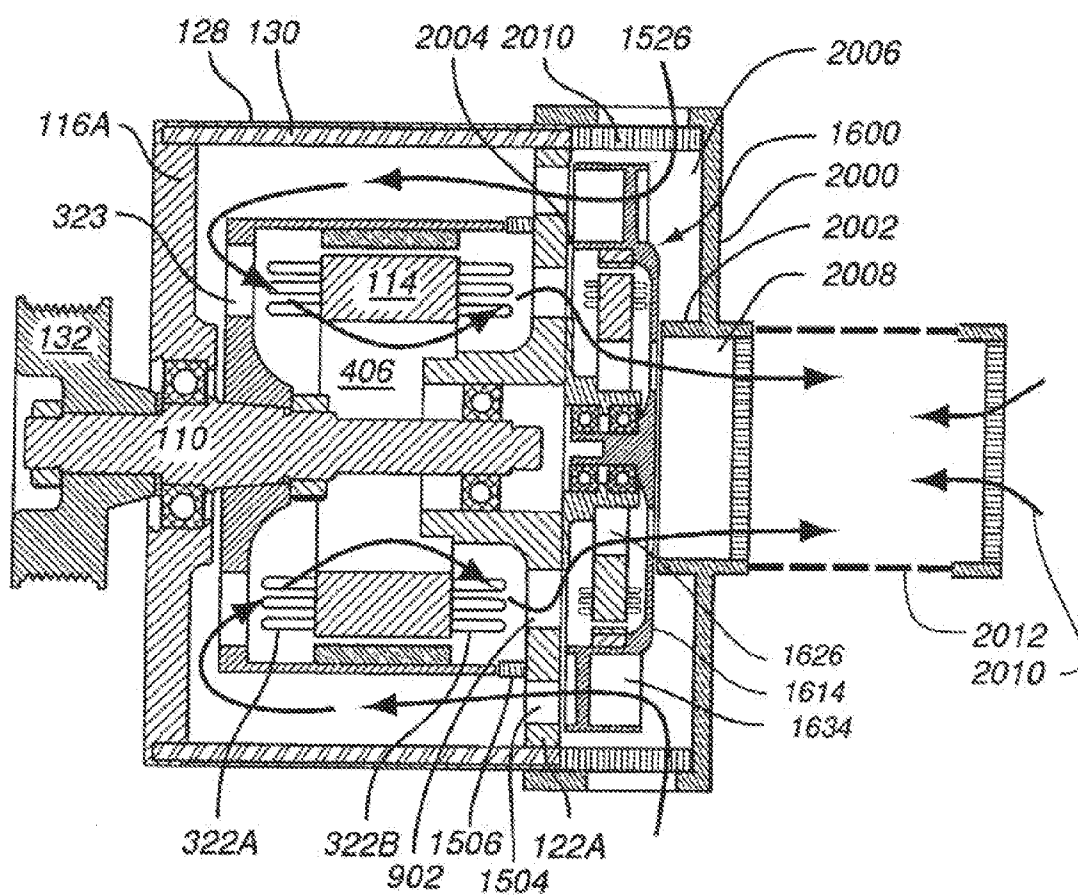


FIG.20A



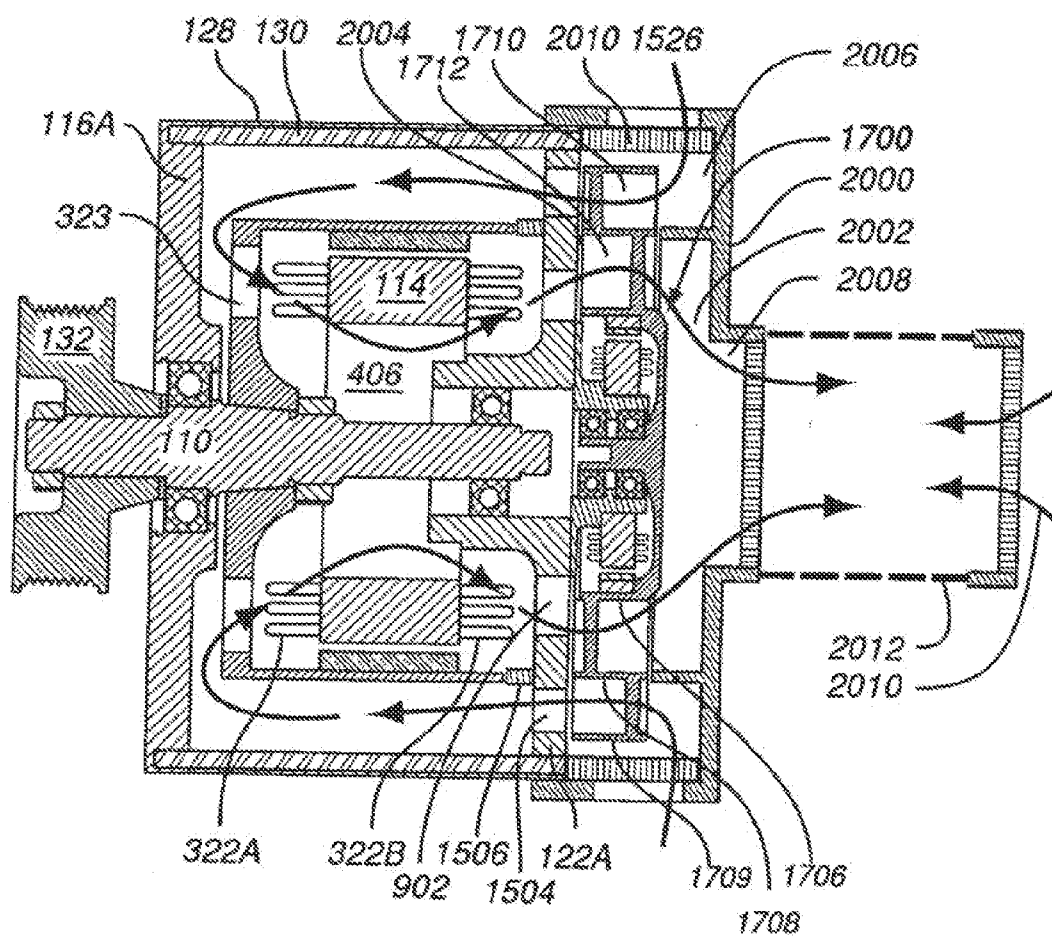


FIG.20C

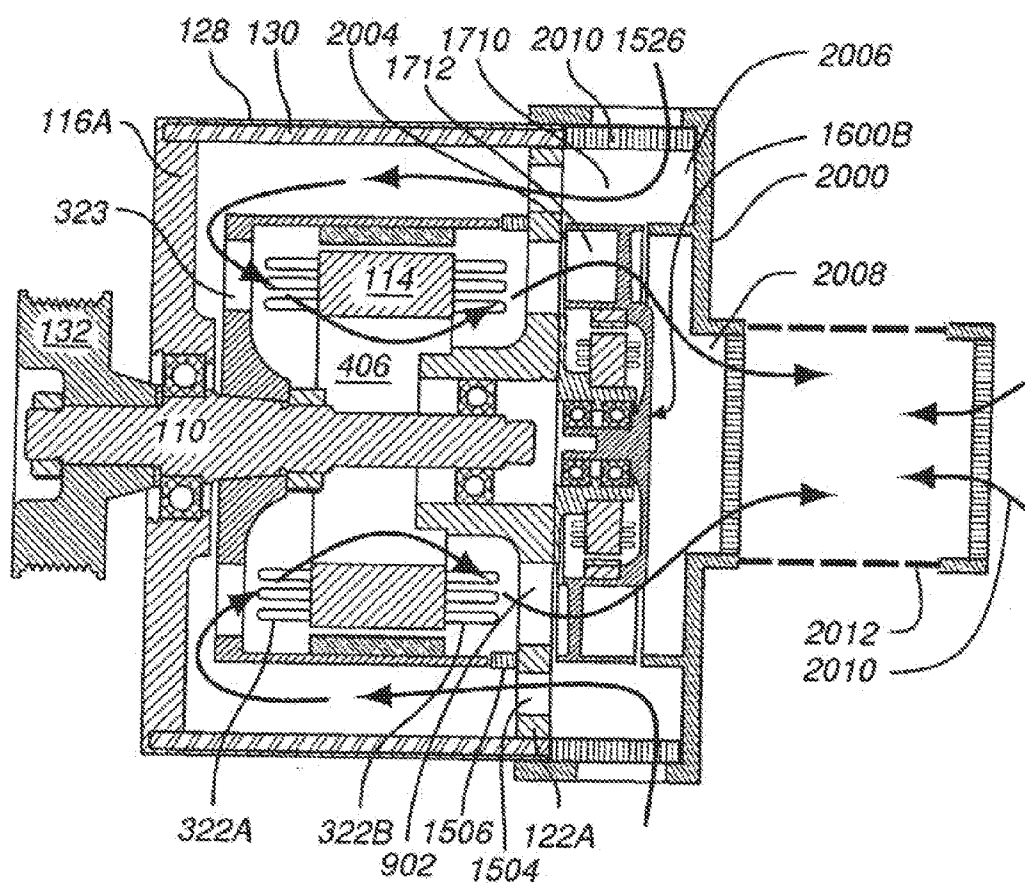


FIG. 21A

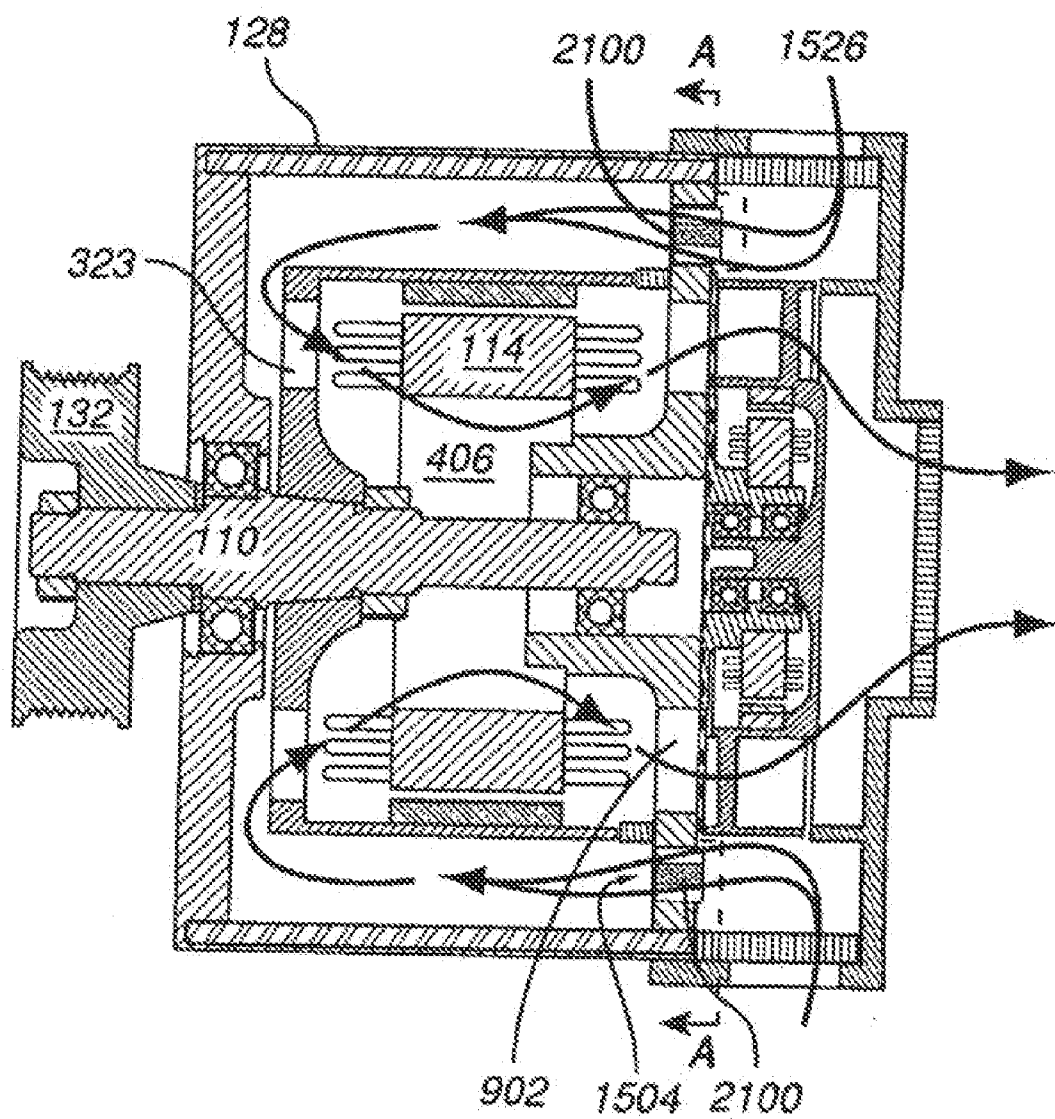
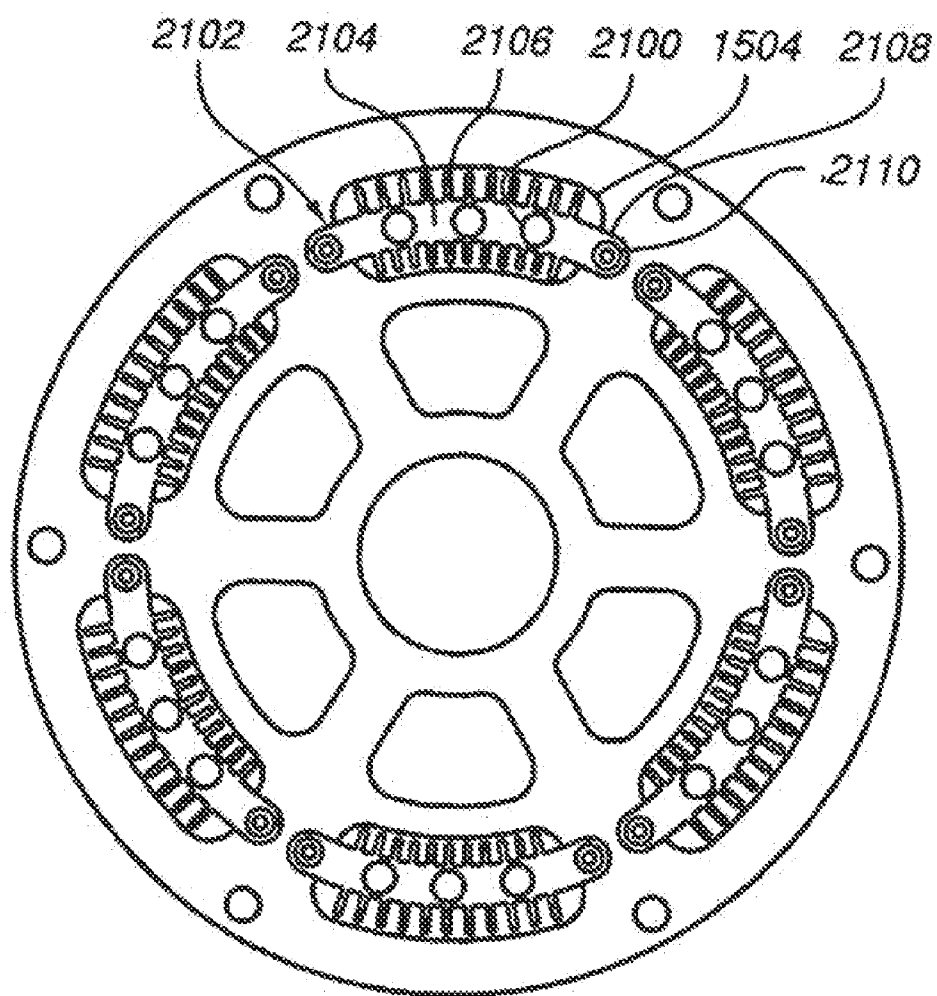


FIG. 21B



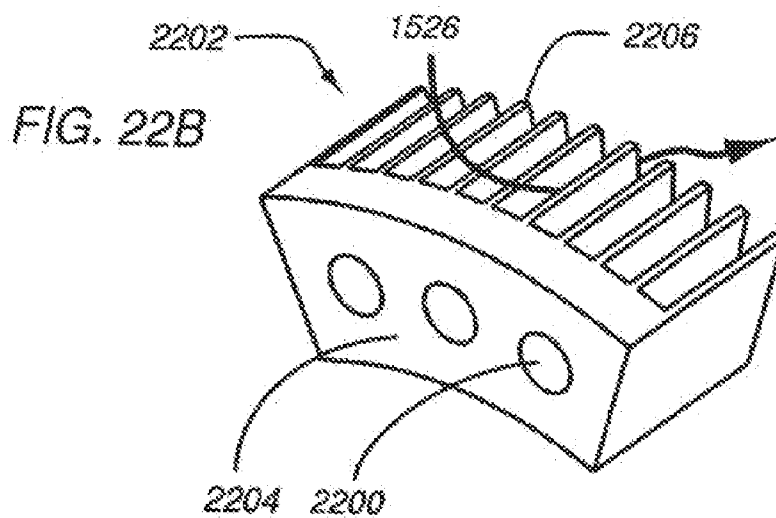
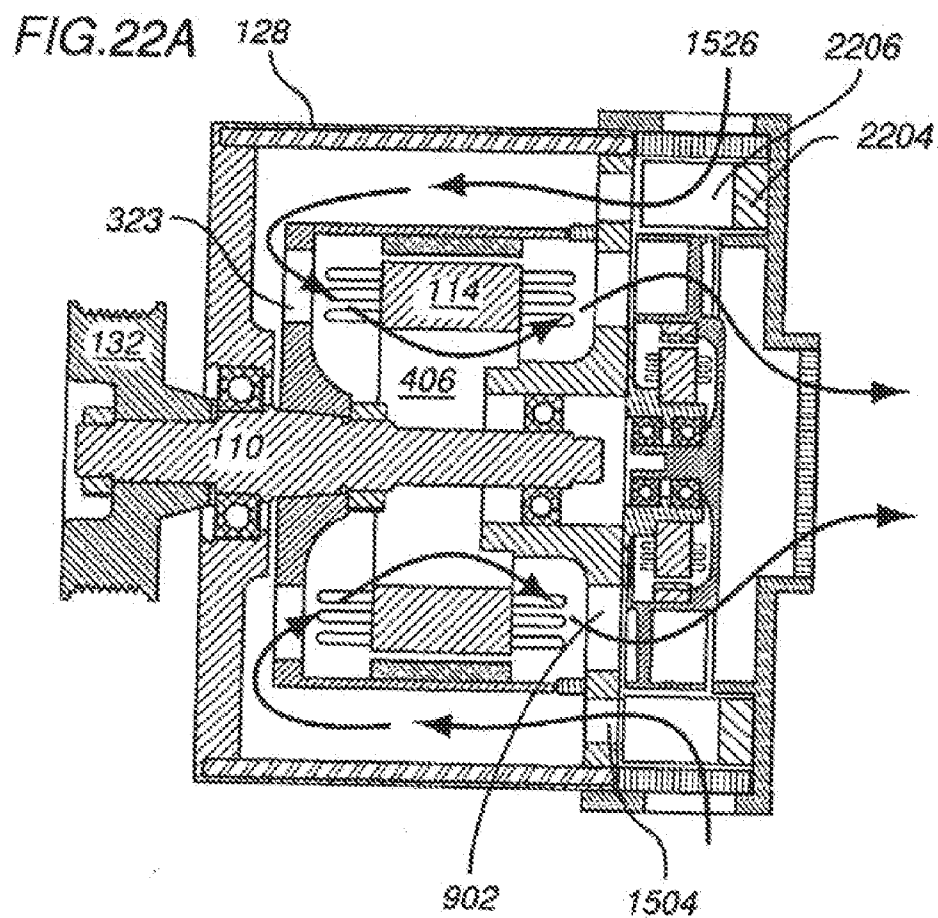


FIG. 23A

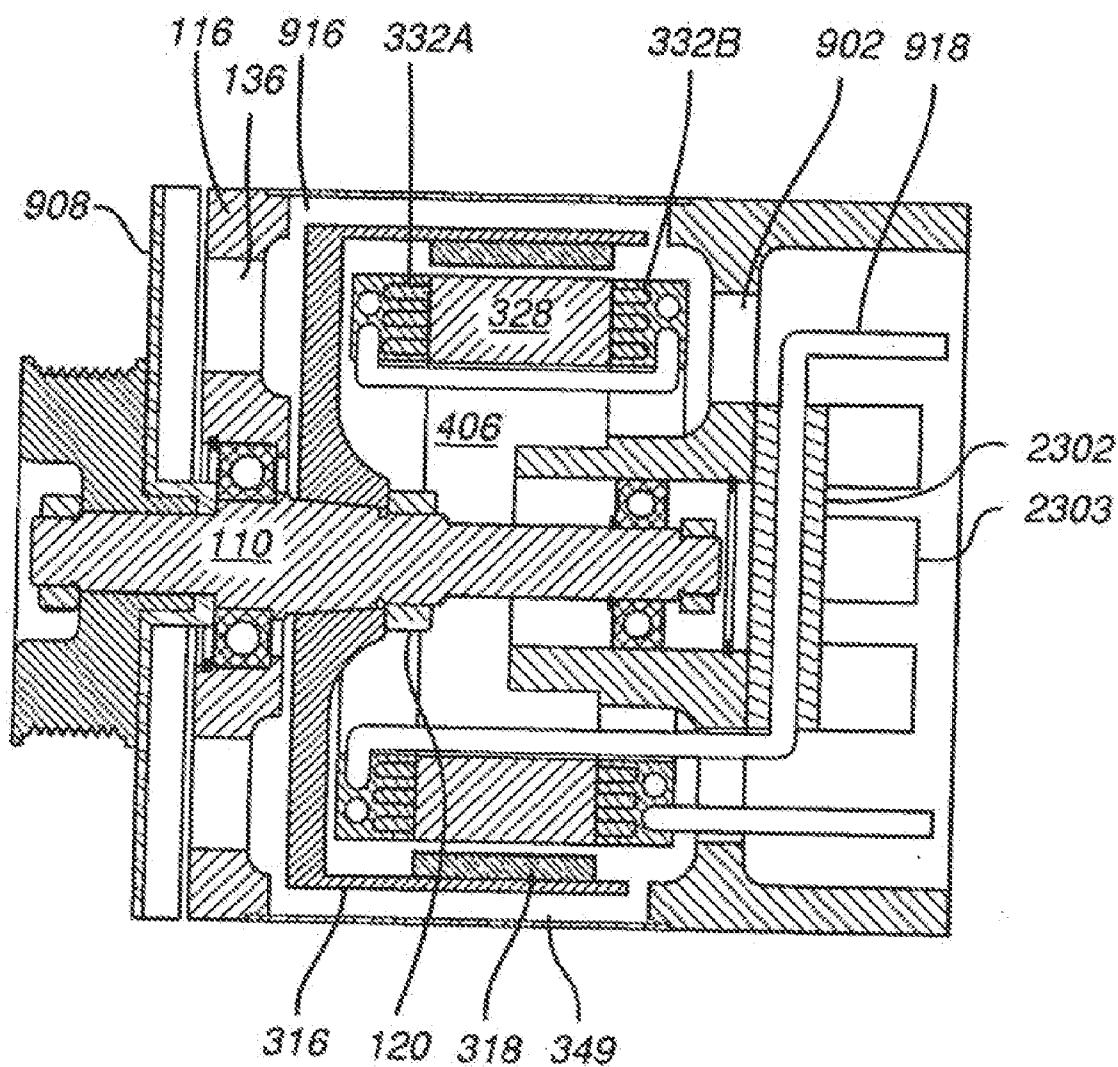
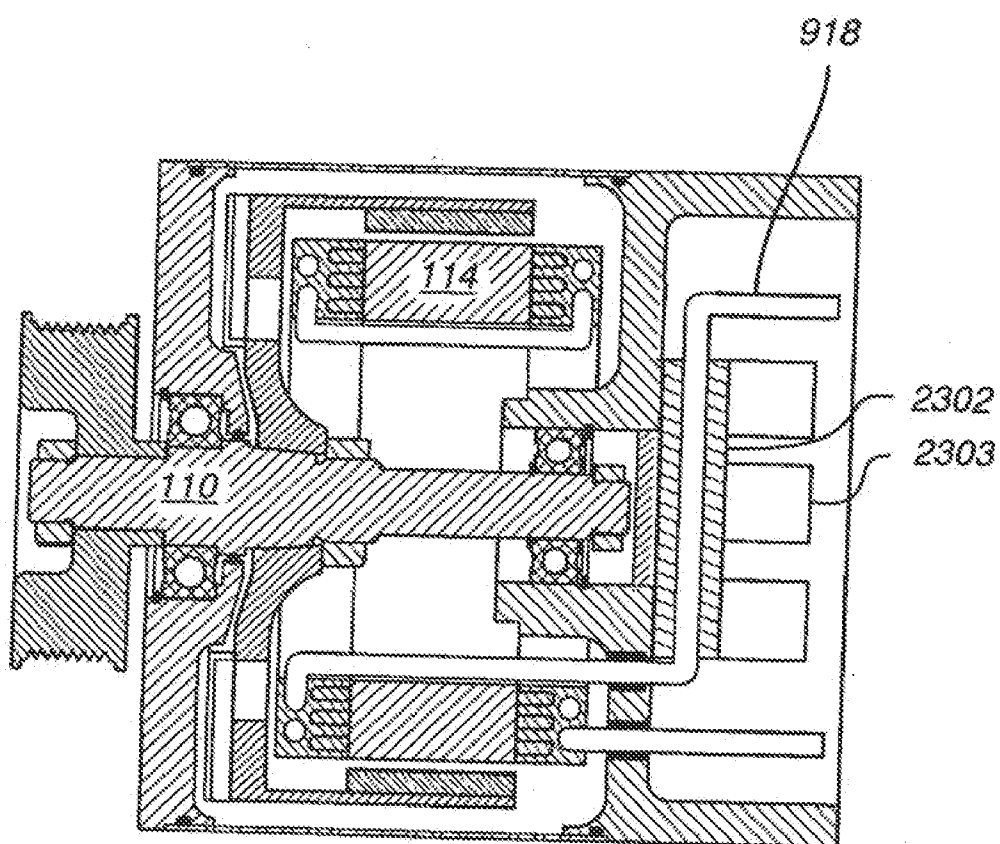


FIG. 23B



COMPACT HIGH POWER ALTERNATOR

RELATED APPLICATIONS

[0001] This application is a divisional application of and claims priority to U.S. patent application Ser. No. 12/848, 972, filed on Aug. 2, 2010, which is a continuation of and claims priority to U.S. patent application Ser. No. 11/295, 888, filed on Dec. 6, 2005, which is a divisional application of and claims priority to U.S. patent application Ser. No. 10/889, 980, filed on Jul. 12, 2004, which claims priority to U.S. Provisional Application Ser. No. 60/486,831, filed Jul. 10, 2003, by inventors Charles Y. Lafontaine and Harold C. Scott.

BACKGROUND OF THE INVENTION

[0002] The present invention relates to machines for converting between mechanical and electrical energy, and in particular to a compact high power alternator using permanent magnets suitable for automotive use.

[0003] An alternator typically comprises a rotor mounted on a rotating shaft and disposed concentrically relative to a stationary stator. Alternatively, a stationary rotor may be positioned concentrically within a rotating stator. An external energy source, such as a motor or turbine, commonly drives the rotating element, directly or through an intermediate system such as a pulley belt. Both the stator and the rotor have a series of poles. Either the rotor or the stator generates a magnetic field, which interacts with windings on the poles of the other structure. As the magnetic field intercepts the windings, an electrical current is generated, which is provided to a suitable load. The induced current is typically applied to a bridge rectifier, sometimes regulated, and provided as an output. In some instances, the regulated output signal is applied to an inverter to provide an AC output.

[0004] Conversely, the device can act as a motor if an appropriate electrical signal is applied to the windings.

[0005] Conventionally, alternators employed in automotive applications typically comprise: a housing, mounted on the exterior of an engine; a stator having 3-phase windings housed in the housing, a belt-driven claw-pole type (e.g., Lundell) rotor rotatably supported in the housing within the stator. However, the power output of such conventional claw-pole type alternators is directly proportional to the size of the alternator; to increase power output the size of the conventional alternator must be significantly increased. Accordingly, space constraints in vehicles tend to make such alternators difficult to use in high output, e.g., 5 kW, applications, such as for powering air conditioning, refrigeration, or communications apparatus. In addition, claw-type generators are also disadvantageous in that voltage regulation is by modulating the rotating field. Such modulation affects all of the windings. Accordingly, voltage regulation and control of individual windings is impractical.

[0006] In addition, the claw-pole type rotors, carrying windings, are relatively heavy (often comprising as much as half of the total weight of the alternator) and create substantial inertia. Such inertia, in effect, presents a load on the engine each time the engine is accelerated. This tends to decrease the efficiency of the engine, causing additional fuel consumption. Reductions in the mass and diameter of rotating components of an alternator will tend to reduce the overall inertia an engine has to overcome, thereby improving fuel economy. A permanent magnet alternator is ideally suited for reducing overall inertia. The mass and diameter of rotating compo-

nents are reduced as compared to that of conventional Lundell alternators, while supplying an equivalent amount of power.

[0007] A reduction of inertia in a motor vehicle alternator also translates to a reduction in horsepower required by the engine to accelerate the alternator. The savings in horsepower could then conceivably be applied to a vehicle drive train resulting in more power to propel the vehicle. This would be of great interest for example, to race car engineers who must deal with regulations limiting horsepower generated by race engines. Even a slight improvement in available horse power to the drive wheels can yield a tremendous competitive advantage. In addition, such inertia can be problematical in applications such as electrical or hybrid vehicles. Hybrid vehicles utilize a gasoline engine to propel the vehicle at speeds above a predetermined threshold, e.g. 30 kph (typically corresponding to a range of RPM where the gasoline engine is most efficient). Similarly, in a so-called "mild hybrid," a starter-generator is employed to provide an initial burst of propulsion when the driver depresses the accelerator pedal, facilitating shutting off the vehicle engine when the vehicle is stopped in traffic to save fuel and cut down on emissions. Such mild hybrid systems typically contemplate use of a high-voltage (e.g. 42 volts) electrical system. The alternator in such systems must be capable of recharging the battery to sufficient levels to drive the starter-generator to provide the initial burst of propulsion between successive stops, particularly in stop and go traffic. Thus, a relatively high power, low inertia alternator is needed.

[0008] In general, there is in need for additional electrical power for powering control and drive systems, air conditioning and appliances in vehicles. This is particularly true of vehicles for recreational, industrial transport applications such as refrigeration, construction applications, and military applications.

[0009] For example, there is a trend in the automotive industry to employ intelligent electrical, rather than mechanical or hydraulic control and drive systems to decrease the power load on the vehicle engine and increased fuel economy. Such systems may be employed, for example, in connection with steering servos (which typically are active only a steering correction is required), shock absorbers (using feedback to adjust the stiffness of the shock absorbers to road and speed conditions), air conditioning (operating the compressor at the minimum speed required to maintain constant temperature). The use of such electrical control and drive systems tends to increase the demand on the electrical power system of the vehicle.

[0010] Similarly, it is desirable that mobile refrigeration systems be electrically driven. For example, efficiency can be increased by driving the refrigeration system at variable speeds (independently of the vehicle engine rpm). In addition, with electrically driven systems the hoses connecting the various components, e.g. the compressor (on the engine), condenser (disposed to be exposed to air), and evaporation unit (located in the cold compartment), can be replaced by an electrically driven hermetically sealed system analogous to a home refrigerator or air-conditioner. Accordingly, it is desirable that a vehicle electrical power system in such application be capable of providing the requisite power levels for an electrically driven unit.

[0011] There is also a particular need for a "remove and replace" high power alternator to retrofit existing vehicles. Typically only a limited amount of space is provided within the engine compartment of the vehicle to accommodate the

alternator. Unless a replacement alternator fits within that available space, installation is, if possible, significantly complicated, typically requiring removal of major components such as radiators, bumpers, etc. and installation of extra brackets, belts and hardware. Accordingly, it is desirable that a replacement alternator fit within the original space provided, and interface with the original hardware.

[0012] In general, permanent magnet alternators are well-known. Such alternators use permanent magnets to generate the requisite magnetic field. Permanent magnet generators tend to be much lighter and smaller than traditional wound field generators. Examples of permanent magnet alternators are described in U.S. Pat. Nos. 5,625,276 issued to Scott et al on Apr. 29, 1997; 5,705,917 issued to Scott et al on Jan. 6, 1998; 5,886,504 issued to Scott et al on Mar. 23, 1999; 5,929,611 issued to Scott et al on Jul. 27, 1999; 6,034,511 issued to Scott et al on Mar. 7, 2000; and 6,441,522 issued to Scott on Aug. 27, 2002.

[0013] Particularly light and compact permanent magnet alternators can be implemented by employing an "external" permanent magnet rotor and an "internal" stator. The rotor comprises a hollow cylindrical casing with high-energy permanent magnets disposed on the interior surface of the cylinder. The stator is disposed concentrically within the rotor casing. Rotation of the rotor about the stator causes magnetic flux from the rotor magnets to interact with and induce current in the stator windings. An example of such an alternator is described in, for example, the aforementioned U.S. Pat. Nos. 5,705,917 issued to Scott et al on Jan. 6, 1998 and 5,929,611 issued to Scott et al on Jul. 27, 1999.

[0014] The stator in such permanent magnet alternators is suitably comprised of individual thin steel laminations of an appropriate shape and chemical composition which are then welded or epoxied together in a cylindrical body with teeth and slots to accept windings. The respective laminations of the stack are positioned in both axial and rotational alignment so that the resultant state or teeth and slots are aligned (disposed) axially. The power output wave produced by axially aligned teeth and slots is by its nature a square wave.

[0015] However, it would be advantageous in applications employing control systems dependant on synchronization with the output, to have a power output wave with sloping sides to enhance control timing.

[0016] The power supplied by a permanent magnet generator varies significantly according to the speed of the rotor. In many applications, changes in the rotor speed are common due to, for example, engine speed variations in an automobile, or changes in load characteristics. Accordingly, an electronic control system is typically employed. An example of a permanent magnet alternator and control systems therefor is described in the aforementioned U.S. Pat. No. 5,625,276 issued to Scott et al on Apr. 29, 1997. Examples of other control systems are described in U.S. Pat. No. 6,018,200 issued to Anderson, et al. on Jan. 25, 2000.

[0017] However, in such permanent magnet alternators, the efficiency is inversely proportional to the "air gap" separating the magnets from the stator. Such air gaps are often in the range of 20 to 40 thousandths of an inch. With such close spacing/tolerances, the permanent magnet alternators are particularly susceptible to destructive interference (clashing) between magnets and stator as a result of displacement of the rotor caused by external forces acting on the alternator. In vehicular applications relatively severe external forces are commonplace, due to, for example, engine vibration (particu-

larly diesel engines at startup), cornering, traversing bumpy roads or terrain, and other types of impact. Accordingly, an alternator in which rotor displacement is minimized, and which includes a mechanism to absorb unacceptable rotor displacement and prevent the rotor magnets from clashing with the stator is needed.

[0018] The use of a taper at the end of a motor shaft to center an attachment, e.g. attaching lawn mower blades to a motor shaft, is known. Conventionally, such a taper is provided only at the end of a shaft. An axial tapped hole is provided in the shaft end surface. The attachment includes a hub with a corresponding tapered aperture. However, the tapered aperture typically extends only partway (as opposed to through) the attachment hub; it is, in effect, a countersink to a smaller diameter through bore. The attachment is secured to the shaft by a bolt passing through the attachment hub bore and threaded into the hole in the shaft end surface. The tapered connection tends to center the attachment on the shaft, however, the attachment on the end of the shaft, is, in effect, cantilevered and susceptible to vibrational oscillations.

[0019] In addition, the heat generated by compact high power alternators can also be problematical. This is particularly true in applications where significant levels of power are generated at relatively low engine rpm; in general, the amount of air moved by a fan is proportional to the square of the fan rpm. As alternators become more compact and more efficient, significant levels of heat are generated. Permanent magnets are particularly susceptible to damage due to overheating; under high load, high temperature conditions, such magnets can become demagnetized. Similarly, the electronic components employed in the controller are susceptible to heat damage. Accordingly, a strategy must be developed to dissipate heat buildup.

[0020] Use of airflow to cool heat generating elements (e.g., rectifiers) in a gen-set are known. An example of such cooling is described in the aforementioned U.S. Pat. No. 5,929,611 issued to Scott et al on Jul. 27, 1999. Conventionally, airflow is provided by a fan driven by the same shaft on which the rotor is mounted. However, in various automotive applications, significant heat is generated at low rpm.

[0021] In general, an appreciable reduction in diameters would be employed to achieve a useful reduction in inertia. This tends to create an acute need for cooling in reduced inertia alternators. The reduction in both mass and overall diameters of these alternators tends to make the use of conventional cooling methods impractical.

[0022] Cooling techniques that permit a permanent alternator to be fully sealed are desirable in situations where exposure to the elements would be detrimental to the operation of the alternator. This is of particular interest to the military or any application subjected to harsh, dusty environments which would be detrimental to the magnets due to their affinity to ferrous particles found in most sand.

[0023] There also is a need for an alternator that can accommodate not only the power levels, but also the space and ruggedness constraints imposed by use in vehicles. For example, operation of a vehicle tends to generate forces perpendicular to the axis of the rotor that are sometimes sufficient to cause the rotor and stator to clash. The rotor and stator are separated only by a small air gap, and the external forces tend to cause transverse movement of the rotor in excess of the air gap then there will be striking interference.

SUMMARY OF THE INVENTION

[0024] The present invention provides particularly advantageous machine for converting between mechanical and electrical energy.

[0025] Various aspects of the invention provide a compact power conversion apparatus using permanent magnets that can accommodate not only the power levels, but also the space and ruggedness constraints imposed by use in vehicles. Another aspect of the invention provides a “remove and replace” high power alternator to retrofit existing vehicles.

[0026] Other aspects of the invention provide a compact high power conversion apparatus using permanent magnets in which rotor displacement is minimized, and which includes a mechanism to absorb unacceptable rotor displacement and prevent the rotor magnets from clashing with the stator.

[0027] In accordance with another aspect of the invention a power conversion apparatus comprises a rotor, a stator, and a cooling system.

[0028] The rotor comprises a cylindrical casing, and a predetermined number of permanent magnets disposed in the interior of the casing, and is adapted for rotation about the axis of the casing.

[0029] The stator comprises a core and at least one conductive winding. The core includes a generally cylindrical outer peripheral surface with a predetermined number of slots formed therein. The winding is wound around the core through the slots.

[0030] The stator is concentrically disposed within the interior of the rotor casing, with the stator core peripheral surface disposed proximate to the rotor magnets, separated from the magnets by a predetermined gap distance, such that relative motion of the rotor and stator causes magnetic flux from the magnets to interact with and induce current in the stator winding.

[0031] The cooling system directs coolant flow into thermal contact with at least one of the winding and magnets, and includes at least one passageway through the stator core.

[0032] In accordance with other aspects of the present invention, cooling is facilitated by one or more of: loosely wrapping winding end turns to, in effect, increase the surface area of the windings; establishing a directed airflow over at least a portion the stator windings, (preferably through loosely wrapped end turns of the windings); directing a portion of the airflow over elements in thermal contact with the magnets; providing airflow from a source that is asynchronous with respect to the shaft on which the rotor is mounted, e.g. an electric fan; and directing a flow of coolant fluid into thermal contact with the winding end turns.

BRIEF DESCRIPTION OF THE DRAWING

[0033] The present invention will hereinafter be described in conjunction with the figures of the appended drawing, wherein like designations denote like elements, and:

[0034] FIG. 1 is a front view of a first embodiment of an alternator in accordance with the present invention (with windings removed for clarity).

[0035] FIG. 2 is a side view of the alternator of FIG. 1.

[0036] FIG. 3 is a schematic sectional view (taken along line BB in FIG. 2) of the alternator of FIGS. 1 and 2 (with windings shown schematically).

[0037] FIG. 4A is a schematic sectional view (taken along line CC in FIG. 2) of the alternator of FIGS. 1, 2 and 3 (with windings shown only schematically for clarity).

[0038] FIG. 4B is a schematic sectional view (taken along line CC in FIG. 2) of the alternator of FIGS. 1, 2 and 3 (with windings shown only schematically for clarity), modified such that the tie rods are exterior of the case.

[0039] FIG. 4C is a detail blowup of a portion of FIG. 4A.

[0040] FIG. 4D is an isometric view of an axially and rotationally aligned stator core.

[0041] FIG. 4E is an isometric view of a skewed stator core.

[0042] FIG. 4F is a sectional view detailing the mounting of the skewed stator core of FIG. 4E.

[0043] FIG. 4G is an isometric view of a rotor utilizing magnets with an axially aligned edge.

[0044] FIG. 4H is an isometric view of a rotor utilizing magnets with a skewed edge.

[0045] (FIGS. 4A-4F are collectively referred to as FIG. 4.)

[0046] FIGS. 5A, 5B, and 5C (collectively referred to as FIG. 5) are schematic illustrations of the movement of the rotor in response to exterior forces.

[0047] FIGS. 6A, 6B, 6C, 6D, 6E, 6F, and 6G (collectively referred to as FIG. 6) are schematic sectional diagrams of respective embodiments of mechanisms for preventing destructive interference between the rotor and stator of an alternator in accordance with the present invention.

[0048] FIG. 7A is a schematic sectional diagram of an alternator employing a rotor with a conical endcap to reduce displacement of the rotor in response to external forces.

[0049] FIG. 7B is a diagram illustrating the wobble motion of the rotor.

[0050] FIG. 7C is a schematic sectional diagram of an alternator employing a rotor with a greatly increased cross-sectional area to the endcap to reduce displacement of the rotor in response to external forces.

[0051] FIG. 7D is a schematic sectional diagram of an alternator using a rotor with a welded rotor case.

[0052] FIG. 7E is a schematic sectional diagram of an alternator employing a rotor and shaft cast as a single unit.

[0053] FIG. 8 is a schematic sectional diagram (partial) of an alternator employing the rotor of FIG. 7A and a combination of the mechanisms for preventing destructive interference of FIG. 6. Gap spaces in the various figures of the drawing are exaggerated for clarity.

[0054] FIG. 9A is a schematic sectional diagram of an alternator employing air cooling in accordance with one aspect of the present invention.

[0055] FIG. 9B is a schematic sectional diagram of an alternator employing air cooling for the magnets and fluid cooling for the coil end turns in accordance with another aspect of the present invention.

[0056] FIG. 9C is a schematic sectional diagram of an alternator employing fluid cooling exclusively in a sealed alternator in accordance with one aspect of the present invention.

[0057] FIG. 9D is a detail sectional diagram of the arrangement of heat conducting encapsulant, cooling tubes and heat transfer fins in a fluid cooled alternator.

[0058] FIG. 9E is a detail of suitable routing of the cooling tubes in a fluid cooled alternator.

[0059] FIG. 10A is a simplified schematic top view of an axially aligned stator and end turns of the stator windings.

[0060] FIG. 10B is a simplified schematic top view of a skewed stator and end turns of the stator windings.

[0061] FIG. 11 is a simplified schematic perspective view of a portion of the stator and end turns of the stator windings with the end turns of the stator windings bent into the airflow.

[0062] FIG. 12 is a schematic sectional view of a first embodiment of a sealed alternator unit employing heat exchanger and internal and external fans.

[0063] FIGS. 13A and 13B (collectively referred to as FIG. 13) are schematic diagrams of respective embodiments of a heat exchanger.

[0064] FIG. 14 is a schematic sectional view of a first embodiment of a sealed alternator unit with the external airflow supplied through an air plenum.

[0065] FIG. 15 is a schematic sectional view of a first embodiment of a locally sealed alternator unit with the external airflow supplied through a doubled walled snorkel.

[0066] FIGS. 16A and 16B (collectively referred to as FIG. 16) are schematic sectional views of the alternator of FIG. 15 utilizing respective embodiments of an optimized fan.

[0067] FIG. 17 is a schematic sectional view of the alternator of FIG. 15 utilizing an alternative embodiment of an optimized fan.

[0068] FIGS. 18A, 18B and 18C (collectively referred to as FIG. 18) are schematic diagrams of respective embodiments of airflow filtering strategies suitable for use with alternator of FIG. 15.

[0069] FIG. 19 is a rear view of a fan housing suitable for use with alternator of FIG. 15 employing an air conduit transverse to the axis of the alternator.

[0070] FIGS. 20A, 20B and 20C are schematic representations of filter systems suitable for use with the optimized fans of FIGS. 16 and 17, respectively.

[0071] FIG. 21A is a schematic sectional side view electrical components mounted in air cooled alternator endplate.

[0072] FIG. 21B is a schematic sectional rear view (from direction A-A in FIG. 21A) of the mount of FIG. 21A.

[0073] FIG. 22A is a schematic sectional side view showing electrical components mounted in the fan housing of an air cooled alternator.

[0074] FIG. 22B is an isometric perspective view of the electrical component mount of FIG. 22A.

[0075] FIG. 23A is a sectional view showing electrical components mounted in an end turn fluid cooled alternator sharing alternator fluid cooling.

[0076] FIG. 23B is a sectional view showing electrical components mounted in an all fluid cooled alternator sharing alternator fluid cooling.

DETAILED DESCRIPTION OF A PREFERRED EXEMPLARY EMBODIMENT

[0077] Referring now to FIGS. 1, 2, 3, and 4 an apparatus for converting between mechanical and electrical energy, e.g., an alternator 100 in accordance with various aspects of the present invention comprises: a shaft 110, preferably including a tapered projecting portion 310 and a threaded portion 312; a rotor 112; a stator 114; a front endplate 116; a front bearing 118; a jam nut 120; a rear endplate 122; a rear shaft retaining ring 123; a rear bearing 124; a rear jam nut 125; a rear endplate retaining ring 127; an electric fan 126; an outer casing 128 and respective tie rods 130. Rotor 112 is mounted on shaft 110 for rotation with the shaft. Stator 114 is closely received within rotor 112, separated from rotor 112 by a small air gap 412. Front endplate 116, front bearing 118, rear bearing 124, rear endplate 122, outer casing 128 and tie rods 130 cooperate as a support assembly to maintain alignment of shaft 110, rotor 112, and stator 114. Shaft 110 is maintained by bearings 118 and 124, which are mounted on front endplate 116 and rear endplate 122, respectively, and rotatably maintain and align shaft 110 concentric and perpendicular with the endplates. Rotor 112 is mounted for rotation on shaft 110, positively positioned by cooperation with

tapered shaft portion 310. Rear endplate 122 mounts and locates stator 114 so that it is disposed within rotor 112 properly aligned with shaft 110 and rotor 112. Outer casing 128 has end faces perpendicular to its axis (is preferably cylindrical) and is disposed between front endplate 116 and rear endplate 122. Tie rods 130; compress endplates 116 and 122 against outer casing 128, keeping the components squared and in alignment.

[0078] In a typical automotive alternator application, a pulley 132 is mounted on the end of shaft 110. Power from an engine (not shown) is transmitted through an appropriate belt drive (not shown) to pulley 132, and hence shaft 110. Shaft 110 in turn causes rotor 112 to rotate about stator 114. Rotor 112 generates a magnetic field, which interacts with windings on stator 114. As the magnetic field intercepts the windings, an electrical current is generated, which is provided to a suitable load. The induced current is typically applied to a bridge rectifier, sometimes regulated, and provided as an output. In some instances, the regulated output signal is applied to an inverter to provide an AC output.

[0079] Shaft 110 is, in general, cylindrical, of a predetermined diameter (e.g. $\frac{3}{4}$ in) with larger diameter portions for accommodating pulley 132, (e.g., $\frac{7}{8}$ in), and front bearing 118 (e.g. $1\frac{1}{4}$ in), rotor 112 (tapered portion 310) and jam nut 120 (threaded portion 312, e.g. 1 in). Tapered projecting portion 310 is disposed at a predetermined position on shaft 110, and has a predetermined taper, i.e., its diameter increases from a minimum diameter (substantially equal to that of threaded portion 312) by a predetermined amount per unit of length, suitably in the range of 1 in. diameter per 7 inches of length to 1 in. diameter per 16 inches of length, and preferably 1 in. per foot. Tapered portion 310 is preferably held to relatively close tolerance, e.g. plus or minus 0.004". The taper is chosen to ensure sufficient surface area contact between shaft 110 and rotor 112, while still providing sufficient change in diameter to prevent unwanted axial movement of the rotor once secured.

[0080] Rotor 112 preferably comprises an endcap 314, a cylindrical casing 316 and a predetermined number (e.g. 12 pairs) of alternatively poled permanent magnets 318 disposed in the interior side wall of casing 316. FIGS. 7D and 7E will detail alternative configurations of endcap 314 and cylindrical casing 316.

[0081] Rotor endcap 314 is suitably substantially open, including a peripheral portion 321, respective cross-arms 322 and a central hub 324 to provide for connection to shaft 110. Respective air passageways 323 are provided through endcap 314, bounded by peripheral portion 321, adjacent cross arms 322, and central hub 324. If desired, cross arms 322 can be configured as fan blades to facilitate cooling internal chamber 320. As will be more fully explained, rotor hub 324 includes a through-bore 326 having a predetermined taper (e.g. 1 in. per foot) corresponding to that of shaft portion 310. In assembly, shaft 110 is journaled through bore 326, such that shaft tapered portion 310 is received in bore 326 just forward of threaded shaft portion 312. Threaded shaft portion 312 cooperates with jam nut 120 to positively locate rotor 112 on shaft 110. In general, the thickness of crossarms 322 is suitably chosen to be as thin as possible (to minimize weight and material cost) while still capable of withstanding expected loads, suitably in the range of $\frac{3}{8}$ in. to $\frac{5}{8}$ inch at its thinnest point. Since rotor casing 316 is, in effect, cantilevered from endcap 314, the necessary thickness is proportional to the length of casing 316. Rotor hub 324, in the vicinity of bore

326, is suitably thick enough to provide adequate surface contact with tapered shaft portion **310**, suitably on the order of 1½ inch.

[0082] Cylindrical rotor casing **316** is formed of “soft magnetic” (relatively transparent to magnetic flux) material (e.g. lead free steel) of a predetermined outer diameter and thickness. In general, to maximize power output, it is desirable that the diameter D_{AG} (FIG. 4) of the circle defined by the inner surface of magnets **318** (sometimes referred to herein as the air gap diameter) be as large as possible given the applicable overall size constraints for alternator **100**. For example, in many automotive applications, alternator **100** must be no more than 5 in. long and 5 in. in diameter in order to fit within the available space. The thickness of casing **316** is suitably chosen to be as thin as possible (to minimize weight and material cost) while still capable of withstanding expected loads and without the flux density from magnets **318** saturating the casing. The thickness of casing **316** is suitably in the range of ⅛ to ½ inch, typically in the range of ⅜ to ¼ inch, and, in the embodiments of FIGS. 1-4, ⅜ inch.

[0083] Magnets **318** preferably comprise high energy product magnets having a flux density of at least on the order of five kilogauss, preferably ranging from eight to 11 kilogauss, suitably formed of a rare earth alloy such as neodymium iron boron, or samarium cobalt. Such rare earth materials tend to be extremely expensive, and, accordingly, it is desirable to minimize the amount of material used. However, at the same time, it is desirable to generate relatively high flux densities. In the preferred embodiment, magnets **802** are relatively thin, e.g. on the order of 0.1 to 0.15 an inch thick, but present a relatively large area, 0.75 inch wide by from approximately one inch to 2.5 in. long, to minimize the amount of high energy product magnet used.

[0084] Magnets **318** may be secured to casing **316** in any suitable manner. For example, magnets **318** may be glued to casing **316**. The disposition of magnets **318** on the interior of casing **316** is advantageous in that, inter alia, magnetic force tends to secure magnets **318** to casing **316**; even in the event that the adhesive fails, the magnets will tend to stay in place. If desired, in some applications where less power density is acceptable, soft magnetic consequence poles **318A** may be employed in place of one set of permanent magnet poles.

[0085] Stator **114** suitably comprises a core **328** and conductive windings **330** (FIG. 3, shown only schematically). As best seen in FIG. 4, core **328** is generally cylindrical, with an axially crenellated outer peripheral surface, i.e., includes a predetermined number of teeth **402** and slots **404**. Core **328** is preferably substantially open (except in an all fluid cooled alternator as will be discussed), with a central aperture **406** defined by the cylindrical interior surface **407** of core **328**.

[0086] One embodiment of core **328** suitably includes crossarms **408** extending radially inward from surface **407**. Crossarms **408** suitably include axial through-bores **410** to facilitate mounting core **328** to rear endplate **122**. As best seen in FIG. 3, stator core **328** may be secured to rear endplate **122** by respective bolts **352** journaled through bores **410** and secured in tapped holes **350**.

[0087] Core **328** suitably comprises a laminated stack of thin sheets of soft magnetic material, e.g. non-oriented, low loss (lead free) steel, that are cut or punched to the desired shape, aligned and joined (e.g., welded or epoxied together in a precision jig to maintain the separate laminations in predetermined alignment). In general, the respective laminations are axially and rotationally aligned so that the resultant stator

teeth and slots are straight, aligned (disposed) parallel to the core axis, as illustrated in FIG. 4D.

[0088] However, it is advantageous, in applications employing control systems dependant on synchronization with the output, to have a power output wave with a particular waveform, e.g., sloping sides, to enhance control timing. This can be accomplished by establishing progressive (gradual) interaction between the rotor magnets and core teeth. Such progressive interaction can be provided by, for example, by utilizing teeth and slots with an edge skewed with respect to magnets **318**, e.g., manifesting a generally helical shape. In a laminar core such teeth and slots can be formed using a slight and progressive radial skewing of each successive lamination so that the net effect after welding or epoxying is a lamination stack with a predetermined offset in the radial position of a given tooth from the front face of the lamination stack to the rear face. In the preferred embodiment, the offset is the equivalent of one tooth (e.g., the “nth” tooth on the front face is aligned with tooth “n+1” on the rear face). The predetermined amount of offset is suitably any offset up to the equivalent of approximately 1 tooth, and preferably ranges from the equivalent of approximately 0.01 to approximately 1 tooth. An example of such a “skewed core” embodiment of core **328**, designated **329**, is shown in FIG. 4E. (Except when specifically otherwise, references hereinafter to core **328** are intended to refer to both the axially aligned embodiment of core **328** and the skewed embodiment **329**.)

[0089] As shown in FIG. 4F, if crossarms **408** are omitted, e.g. as in skewed core **329**, core **328** may be secured to rear endplate **122** using a suitable mounting ring **412**, including a locating shoulder and throughbores **416** (corresponding to crossarm bores **410**) cooperating with bolts **352** (in lieu of crossarms **408**). In most cases, sufficient torque applied to mounting bolts **352** will be adequate to prevent rotation of core **328** relative to mounting ring **412** and rear endplate **122**. However, if desired a suitable fastening method, such as, for example, epoxy, a pin, or key, can be incorporated to help prevent rotation of the lamination stack when in use.

[0090] Progressive (gradual) interaction between the rotor magnets and core teeth can also be provided by skewing the edge of magnets **318** by a predetermined amount relative to the stator teeth. For example, a rotor utilizing magnets with a skewed edge is shown in FIG. 4H. For contrast, a rotor utilizing magnets with an axially aligned edge is shown in FIG. 4G. As in the case of the skewed core, the predetermined amount of offset is suitably any offset up to the equivalent of approximately 1 tooth, and preferably ranges from the equivalent of approximately 0.01 to approximately 1 tooth.

[0091] Windings **330**, formed of a suitably insulated electrical conductor, preferably varnished copper motor wire, are provided on core **328**, wound through a respective slot **404**, outwardly along the side face of core **328** around a predetermined number of teeth **402**, then back through another slot **404**. The portion of windings **330** extending outside of slots **404** along the side faces of core **328** are referred to herein as front-side and rear-side end turns **332A** and **332B**, respectively (collectively referred to as end turns **332**). Conventionally, end turns **332** of windings **330** are drawn tightly against the side face of core **328** to minimize the amount of wire (and hence impedance) in the windings. However as will be further discussed, in accordance with one aspect of the present invention, cooling may be facilitated by loosely winding end turns **332**, such that end turns **332** extend outwardly from core **328** providing air spaces between the various wires and core **328**.

[0092] If desired, windings 330 may be separated into a predetermined number of phases and/or into independent groups as described in the aforementioned Scott et al. U.S. Pat. No. 5,625,276.

[0093] In assembly, stator 114 is disposed coaxially with rotor 112, and is closely received within interior cavity 320 of rotor 112. As will be explained, rear endplate 122 mounts and locates stator 114 so that it is properly aligned within internal chamber 320 of rotor 112. The peripheral surface of stator core 328 is separated from the interior surface of magnets 318 by a small predetermined air gap 412 (best seen in FIG. 4B). Air gap 412 is suitably in the range of 20 to 40 thousands of an inch, and in the embodiments of FIGS. 1-4 on the order of 30 thousands of an inch, e.g., 31 thousands of an inch. Accordingly, the inner diameter of casing 316, magnets 318, and outer diameter of stator core 328 are preferably held to close tolerances to maintain alignment. It is important that rotor 112 and stator 114 be carefully aligned, and displacement of the elements from their normal positions due to external forces on the alternator held below a threshold value.

[0094] As noted above, alignment of shaft 110, rotor 112, and stator 114 achieved by a bearing structure comprising front endplate 116, front bearing 118, rear bearing 124, rear endplate 122, outer casing 128 and tie rods 130. Bearings 118 and 124, in effect, provide respective points of rotatable connection between shaft 110 and the bearing structure. Bearings 118 and 124, and hence shaft 110, are disposed concentric and perpendicular with endplates 116 and 122, respectively. Rotor 112 is preferably positively positioned with respect to shaft 110 through cooperation of tapered rotor hub through bore 326 and tapered shaft portion 310. Stator 114 is located relative to and aligned with shaft 110, and hence rotor 112, by rear endplate 122. The alignment of endplates 116 and 122 is maintained by outer casing 128 and tie rods 130.

[0095] Front endplate 116 is suitably generally cylindrical, including: a centrally disposed hub, including a coaxial aperture 334 with a counterbore 336; a peripheral portion 133 including respective (e.g. eight) tapped holes 337 disposed at predetermined radial distances from the center of aperture 334, distributed at equal angular distances, to receive tie rods 130; and respective (e.g., 4) crossarms 134 connecting peripheral portion 133 to hub 333, and defining respective air passages 136. Front endplate 116 is dimensioned and machined to high tolerance (e.g. plus or minus 0.0008 TYP for counterbore 336, 0.005 TYP for other features, such as tie rod hole 337 patterns, outer case shoulder, mounting hole patterns), suitably formed of metal e.g. cast aluminum, and should be sufficiently strong to withstand the rotational loads created by the turning of shaft 110 and rotor 112, as well as side loading that occurs as a result of the belt pulling on pulley 132. Front bearing 118 is closely received in counterbore 336 and suitably secured, e.g. by a suitable retaining ring 338. Front endplate 116 thus locates front bearing 118 to center shaft 110.

[0096] Rear endplate 122 carries and locates rear bearing 124, mounts and locates stator core 328, and suitably provides a mounting surface for fan 126. Rear endplate 122 suitably includes a stepped central hub 340 having a forward reduced diameter portion 342 and central aperture 344 there through, and a generally cylindrical rearward going outer portion 346, preferably having the same outer diameter as front endplate 116, connected to hub 340 by respective crossarms 348. As will be further described, rear endplate 122 also suitably includes respective air passageways 347, bounded by adja-

cent crossarms 348, outer portion 346, and hub 340. Respective through bores 350 are provided cylindrical outer portion 346, at the same radial distance from center and angular dispositions as tapped holes 337 in front endplate 116. A predetermined number of tapped holes (e.g. 4) corresponding to stator crossarm bores 410 (or mounting collar bores 416) are provided in the stepped surface of projection 340. The outer diameter of reduced diameter portion 342 is substantially equal to (but slightly less than) the diameter of stator aperture 406, so that rear endplate portion 342 may be closely received within stator aperture 406. Rear endplate 122 is dimensioned and machined to high tolerance (e.g. plus or minus 0.0008 TYP for central aperture 344, 0.005 TYP for other features, such as tie rod hole 350 patterns, outer case shoulder, mounting hole patterns), suitably formed of metal e.g. cast aluminum. Rear bearing 124 is closely received within aperture 344 of rear endplate hub 340 and thus centers shaft 110.

[0097] Stator core 328 is mounted on hub 340, with reduced diameter hub portion 342 received within stator aperture 406 and the stator rear sidewall abutted against the hub step. If core 328 includes crossarms 408, the crossarms suitably abut hub 340. If core 328 does not include crossarms 408, e.g., skewed core 329, the core interior surface 407 suitably abuts reduced diameter hub portion 342. Respective bolts 352 journaled through bores 410 (or 416) and secured in tapped holes 350, secure stator core 328 to rear endplate 122. Stator 114 is thus positively located and aligned relative to shaft 110.

[0098] In accordance with one aspect of the present invention, rotor 112 is positively located on and aligned with shaft 110. More specifically, as previously noted, includes a portion 310 with a predetermined taper (e.g. suitably in the range of 1 in. diameter per 7 inches of length to 1 in. diameter per 16 inches of length, and preferably 1 in. per foot.), just forward of threaded portion 134, between front bearing 118 and rear bearing 124. The minimum diameter of shaft tapered portion 310 is suitably slightly greater than the diameter of threaded portion 134. Rotor hub 324 includes a through-bore 326 having a predetermined taper corresponding to that of shaft portion 310. The maximum diameter of tapered through bore 326 corresponds to (e.g. is substantially equal to or slightly less than) the maximum diameter of shaft of tapered portion 310, and the minimum diameter of tapered through bore 326 corresponds to (e.g. is substantially equal to or slightly smaller than) the minimum diameter of shaft of tapered portion 310. The axial dimension of hub 324 is such that when fully seated, it extends slightly beyond the end of shaft section 310 axial dimension of hub 324 is such that when fully seated, it extends slightly beyond the end of shaft section 310. In assembly, shaft 110 is journaled through bore 326, such that shaft tapered portion 310 is received in bore 326. Threaded shaft portion 312 cooperates with jam nut 120 to force rotor hub tapered surface 326 axially into wiping contact with the tapered surface of shaft portion 132 until the surfaces mate. Rotor 112 is thus accurately positioned, centered and aligned on shaft 110 with a strong mechanical bond.

[0099] Since endplates 116 and 122 are held in alignment with each other by outer casing 128 and tie rods 130, shaft 110 (and tapered portion 310) is held in alignment with endplates 116 and 122 by bearings 118 and 124, and stator 114 is positively positioned and aligned with shaft 110 by endplate 122, the positive positioning and a centering of rotor 112 on shaft 110 also provides relative positioning and alignment between rotor 112 and stator 114.

[0100] In vehicular applications alternator 110 may be subjected to relatively severe accelerations that tend to cause distortion and/or displacement of rotor 112 due to the moment of inertia inherent in the rotational case. Such accelerations are, due to, for example, engine vibration (particularly diesel engines at startup), cornering, traversing bumpy roads or terrain, and other types of impact. The efficiency of permanent magnet alternator 100 is inversely proportional to the width of “air gap” 412 separating the magnets from the stator. As previously noted, air gap 412 is suitably in the range of 20 to 40 thousands of an inch, and in the embodiments of FIGS. 1-4 on the order of 30 thousands of an inch, e.g., 31 thousands of an inch. Displacement of rotor 112 need only exceed the width of air gap 412 to cause clashing and possibly destructive interference. Further, for a variety of reasons, e.g. to minimize inertia in operation of alternator 100, it is desirable that rotor 112 be as light as possible. Accordingly, rotor 112 tends to be susceptible to distortion due to such forces.

[0101] Referring to FIG. 5A, in the absence of external forces, rotor 112 is concentric and perpendicular with shaft 110; rotor casing 316 is in a nominal normal position (designated by lines 502 and 504) coaxial with shaft 110 and the forward (closest to forward endplate 116) edge of rotor endcap 314 is in a nominal normal position (designated by line 506) perpendicular to the axis of shaft 110. Components of external forces typically encountered parallel to the axis of shaft 110 tend to have little effect on the disposition of rotor 112; rotor endcap 314 and cooperation of rotor hub 324, tapered shaft portion 310, and jam nut 120 are sufficiently strong to resist axial movement or distortion of rotor 112, and, in any event, there is greater tolerance to axial distortions. However, external forces tend to be encountered with components perpendicular to the axis of shaft 110 of sufficient strength to distort rotor 112. In addition to deflection of rotor 112 due to external forces, as a practical matter, due to limitations (tolerances) in the manufacturing process, rotor 112 tends to be very slightly out of round (cylinder casing 316 will not be absolutely parallel to shaft 110), causing a conical wobble during rotation further reducing the air gap eccentrically.

[0102] More specifically, when subjected to accelerations perpendicular to the axis of shaft 110, rotor casing 316 tends to maintain its cylindrical shape. However, a distortion is manifested in rotor endcap 314. In effect, rotor 112 is cantilevered at the conjunction of rotor endcap 314 and shaft 110 (indicated a schematically as anchor (cantilever) point 508). In response to perpendicular acceleration, rotor 112, in effect, pivots about anchor point 508 in the direction of the force. Maximum deflection from the nominal normal position is experienced at the portions of rotor 112 farthest from anchor point 508, i.e. the distal (rear) end of casing 316, and the outer periphery of endcap 314 (where endcap 314 joins casing 316). If the deflection in the vicinity of magnets 318 exceeds air gap 412, e.g. 31 thousands of an inch, magnets 318 will clash with stator 114, causing possibly destructive interference. Similar issues arise if out of round wobble causes a deviation from the norm that exceeds air gap 412.

[0103] For example, as shown in FIG. 5B, in response to an upward acceleration, rotor 112 will in effect pivot downwardly (as shown, in a clockwise direction). The upward side of rotor casing 316 will effectively pivot inwardly towards shaft 110, with the distal end deflected inwardly from the nominal normal position 502 by an amount generally indi-

cated as 510. The upward periphery of endcap 314 similarly moves to the rear of its nominal normal position 506 by an amount generally indicated as 512. Conversely, the distal end of downward side of rotor casing 316 will be deflected outwardly from the nominal normal position 502 by an amount generally indicated as 514 and the downward periphery of endcap 314 similarly moves forward of its nominal normal position 506 by an amount generally indicated as 516. Since cylindrical rotor casing 316 maintains its shape, the amount of deflection of the corresponding upper and lower portions are substantially proportional i.e. deflections 510 and 512 are substantially proportional (and in many geometries equal) to deflections 514 and 516, respectively.

[0104] Forces from opposite directions will cause mirror image deflections. For example, as shown in FIG. 5C, in response to a downward acceleration, rotor 112 will in effect pivot upwardly (as shown, in a counterclockwise direction). The downward side of rotor casing 316 will effectively pivot inwardly towards shaft 110, with the distal end deflected inwardly from the nominal normal position 504 by an amount generally indicated as 518. The downward periphery of endcap 314 similarly moves to the rear of its nominal normal position 506 by an amount generally indicated as 520. Conversely, the distal end of upward side of rotor casing 316 will be deflected outwardly from the nominal normal position 502 by an amount generally indicated as 522 and the upward periphery of endcap 314 similarly moves forward of its nominal normal position 506 by an amount generally indicated as 524. Again, since cylindrical rotor casing 316 maintains its shape, the amount of deflection of the corresponding upper and lower portions are substantially proportional (and in many geometries equal) i.e. deflections 518 and 520 are substantially proportional essays to deflections 522 and 524, respectively.

[0105] In accordance with a further aspect of the present invention, clashing is prevented by disposing one or more bumpers to arrest rotor deflection from the nominal normal position before the deflection of magnets 318 exceeds air gap 412. The bumpers can be disposed on either or both of the interior or exterior of rotor 112, interacting with one or both of casing 316 or end cap 314; since rotor casing 316 maintains its shape preventing either inward or outward deflection of casing 316 or end 314 from exceeding predetermined limits corresponding to the width of the air gap will prevent clashing. Bumpers are formed of a relatively smooth and resilient material with a predetermined durometer such that it deforms no more than a predetermined amount before arresting deflection of rotor 112 in response to maximum loads (e.g. 20 g's gravities). Examples of such a material are Teflon, glass impregnated Teflon and oil impregnated sintered bronze. The bumpers can be disposed on, for example, a feature of rear endplate 122, front endplate 116 or other support structure (e.g. tie rods 130), and use a portion of rotor 112 as a bearing surface. Alternatively, the bumper can be disposed on rotor 112 and utilize a feature of the support structure as a bearing surface, or in some instances be interposed in air gap 412 between magnets 318 and stator 114. The bumpers are disposed separated from the cooperating bearing surface by a predetermined amount, sometimes referred to herein as a “support gap”, e.g. 0.01 in. The support gap is chosen such that the support gap plus the maximum amount of deformation of the bumper is less than magnetic air gap 412. In addition the bearing surfaces interacting with the bumper may

be treated, e.g. to minimize friction and/or hardened. For example, chrome or some other type metallic zinc type finish may be employed.

[0106] As previously noted, clashing of magnets 318 and stator 114 can be avoided by preventing inward deflection of rotor casing 316. Referring to FIGS. 6A and 8, a generally cylindrical shoulder 602 may be formed on rear endcap 122, extending forward to underlie the end of rotor casing 316, i.e. received within rotor internal chamber 320. The outer diameter of shoulder 602 is less than the inner diameter of rotor casing 316 by a predetermined amount. A cylindrical bumper 604 is disposed about shoulder 602. The outer surface of bumper 604 is thus coaxial with rotor casing 316, and separated from the inner surface of rotor casing 316 by a support gap 606. Bumper 604 is formed of a material with a predetermined durometer such that it deforms no more than a predetermined amount before arresting deflection of rotor casing 316. Support gap 606 is chosen to be sufficiently less than magnetic air gap 412, that the inner surface of rotor casing 316 overlying bumper 604 comes into contact with bumper 604 and maximum deformation of bumper 604 occurs before magnets 318 come into contact with stator core 314, i.e. the support gap plus the maximum amount of deformation of bumper 604 is less than magnetic air gap 412. If desired, a surface treatment, e.g. a chrome, metallic zinc or hard anodize layer 608 can be provided on the bearing surface of rotor casing 316.

[0107] Alternatively, as shown in FIG. 6B, a cylindrical bumper 610, having outer diameter substantially equal to the inner diameter of rotor casing 316, can be affixed (e.g. glued) to the inner surface of rotor casing 316. The inner surface of bumper 604A would be separated from the outer surface of rear end shoulder 602 (which acts as the bearing surface) by support gap 606. If desired, a surface treatment 608A can be provided on the bearing surface of shoulder 602.

[0108] In some applications it may be desirable to employ a bumper (or surface treatment) in the form of a collar or sleeve received about the mouth of rotor casing 316. An example of such a structure is shown in FIG. 6C. A collar bumper 612 having a cylindrical body 614 of predetermined length and thickness and a lip 616 is affixed (e.g. glued by, for example, epoxy) to the mouth of rotor casing 316. Collar bumper 612 cooperates with rear endplate 122 to prevent clashing of magnets 318 and stator 114. Collar body 614 is separated from the sidewall of shoulder 602 (which acts as a bearing surface with respect to collar body 614) by a support gap 606. If desired, the end surface of collar lip 616 may cooperate with the sidewall of rear endplate 122 separated from rear endplate 122 by an appropriate support gap 606A to provide additional protection against deflection of rotor casing 316.

[0109] In general, it is desirable to dispose as little as possible on rotor 112 to minimize rotor weight, and thus inertia. In some instances, however, ease of assembly may make the embodiments of FIG. 6B or 6C desirable.

[0110] As previously above, clashing of magnets 318 and stator 114 can be avoided by preventing outward deflection of rotor casing 316. Referring to FIGS. 6D and 8, a generally cylindrical shoulder 618, coaxial with rotor casing 316 but having an inner diameter greater than the outer diameter of rotor casing 316 by predetermined amount, is provided on rear endcap 122, extending forward to overlie the end of rotor casing 316. A cylindrical bumper 620, is affixed (e.g. glued) to the interior sidewall of shoulder 618, positioned coaxial

with rotor casing 316. The inner diameter of bumper 620 is greater than the outer diameter of rotor casing 316 by an amount equal to a support gap 622. The outer surface of rotor casing 316 acts as a bearing surface. If desired, a surface treatment 608B can be provided on the bearing surface of rotor casing 316.

[0111] Bumpers can be disposed on other support structure, and use a portion of rotor 112 as a bearing surface. For example, referring to FIGS. 6E and 8, respective cylindrical bumper sleeves 624 are disposed coaxially one or more (preferably each) of tie rods 130. The outer diameters of bumper sleeves 624 are chosen such that the surface of the sleeve nearest rotor casing 316 is separated from casing 316 by an appropriate support gap 626. Bumper sleeves 624 may be affixed to tie rods 130, but are preferably rotatable, i.e. act as rollers with tie rods 130 as axes. Rotation of bumper sleeves 624 will tend to reduce wear, and extend the life of the bumpers. Disposition of bumper sleeves 624 at least two sets of opposing tie rods 130 (at 180° from each other) around rotor casing 316 tends to counteract forces on rotor 112 from any direction transverse to shaft 110.

[0112] Bumpers may also be disposed on front endplate 116, with the front surface of rotor endcap 314. Referring to FIGS. 6F and 8, an annular bumper 628, is affixed (e.g. glued) to the interior sidewall of front endplate 116, positioned coaxial with rotor casing 316. The inner and outer diameters of bumper 628 are preferably chosen to correspond to (e.g. bracket) the outer periphery of endcap 314. A annular depression 630 for receiving and locating bumper 628 is suitably provided in the interior sidewall of front endplate 116. If desired, other locating features (e.g. projections or a shoulder) may also be provided on the interior sidewall of front endplate 116 to position bumper 628. Such projections, however, are suitably lower in profile than the maximum deflection of bumper 628. The thickness of bumper 628 is chosen such that the face opposing rotor endcap 314 is separated from endcap 314 by an appropriate support gap 632. The forward surface (closest to front endplate 116) of rotor endcap 314 acts as a bearing surface. By limiting the extent that the forward (closest to forward endplate 116) edge of rotor endcap 314 from its nominal normal position, clashing of magnets 318 and stator 114 can be averted. If desired, a surface treatment 608B can be provided on the bearing surface of rotor endcap 314.

[0113] In some instances (e.g. in the case of bumper sleeves 622) it may be desirable to initially place bumper 604 in contact with the bearing surface i.e. establish an initial support gap of zero. In such cases the material of the bumpers would-be chosen such that relative motion and interaction between the bearing surface and the bumpers would abrade the bumpers to ultimately establish an appropriate support gap.

[0114] In some instances, it may be desirable to interpose a thin band of bumper material in air gap 412 between magnets 318 and stator 114. For example, referring to FIGS. 6G and 8, a thin band 634 of relatively robust substantially magnetically transparent material (e.g. Teflon tape) is disposed within air gap 412 on the outer surface (crenellated cylindrical sidewall) of stator 114 along the rear edge (edge of nearest rear endplate 122). Band 634 is made of a material having a durometer sufficient, given the thickness of band 634, to avoid total compression under maximum load and prevent magnets 318 from impact with stator 114. In addition, it is desirable that band 634 exhibits a relatively low coefficient of friction. If

desired, a chromium surface treatment can be applied to magnets **318** to further reduce friction.

[0115] In addition to preventing potential clashes by using bumpers to limit the extent that rotor **112** can be deflected from its nominal normal position. It is also desirable to minimize the effect of external forces and out of round conditions due to manufacturing tolerances.

[0116] In accordance with another aspect of the present invention, deflection of rotor casing **316** (magnets **318**) from the nominal normal position in response to force components perpendicular to shaft **110**, and wobble due to out of round components can be reduced by reducing the axial distance between magnets **318** and the anchor point. This is achieved while still providing sufficient space in internal cavity **320** for stator windings **330**, by contouring endcap **314** to couple the forward most end of rotor casing **316** (nearest front endplate **116**) to an anchor point closer to magnets **318** within the interior of casing **316**. At least a portion of rotor endcap **314** (e.g. crossarms **322**) would effectively be at an angle other than 90° relative to rotor casing **316** (and hence shaft **110**). The angled portion could be straight (e.g. such that a portion of endcap **314** was generally conical) or curved (e.g. such that a portion of endcap **314** was generally bell-shaped).

[0117] As previously noted, rotor **112** is, in effect, cantilevered at the conjunction of rotor endcap **314** and shaft **110** (anchor point **508** in FIG. 5). Maximum deflection from the nominal normal position due to external forces occurs at the portions of rotor **112** farthest from the anchor point, i.e. the distal (rear) end of casing **316**, and the outer periphery of endcap **314** (where endcap **314** joins casing **316**). Similarly, the greatest deviation from the normal path due to out of round wobble occurs at the portions of rotor **112** farthest from the anchor point, i.e. the distal (rear) end of casing **316**. Out of round conditions due to tolerances result in a conical displacement from the nominal position of casing **316** i.e. as rotor **112** rotates around a given point on stator **114**, rotor casing **316** will approach, and retreat from that point on stator **114**. The greater the axial distance of the point on stator from the pivot point the greater the relative motion of the casing **316**. For example, as shown in FIGS. 7A and 7B, at an axial distance X1 from the pivot point (e.g. the axial distance from pivot point **508** of a “flat” hub to the rear end of rotor casing **316**), out of round conditions due to tolerances will tend to cause a wobble toward and away from the stator in the amount W1. However, at a lesser distance X2 (e.g. the axial distance from pivot point **708** of a conical hub to the rear end of rotor casing **316**), a lesser amount W2 is experienced. Accordingly, by moving the anchor point closer to the rear end of rotor casing **316** (and magnets **318**), wobble in the vicinity of magnets **318** and stator **114** is reduced.

[0118] Referring to FIG. 7A, reduced wobble rotor **712** includes an endcap **714** having a hub **724** that establishes an anchor (cantilever) point **708** disposed within the interior of rotor casing **316**. Anchor point **708** is rearwardly displaced along the axis of shaft **110** from the forward edge of casing **316** (nearest front endplate **116**), by a predetermined distance D1. In typical automotive applications, the diameter of casing **316** is suitably in the range of 2½ to 5 in., and preferably 4½ inches; and the length of casing **316** is suitably in the range of 3 to 6 in., and preferably 5 in. Distance D1 is suitably in the range of ½ to 1 inch and preferably ¾ inch. In certain military and commercial vehicles (e.g. Hummers), the diameter of casing **316** is suitably in the range of 5 to 8 in., and preferably 6½ inches; and the length of casing **316** is suitably in the

range of five ½ to 10 in., and preferably 7 in. Distance D1 is suitably in the range of ¾ to 2 inch and preferably 1½ inch.

[0119] Rotor endcap **714** is contoured to connect the forward end of casing **316** to hub **724**, while at the same time providing sufficient space in interior cavity **320** to accommodate stator windings **330**. For example, in the embodiment of FIG. 7A, endcap **714** comprises a conical portion **726** (which may include a plurality of apertures (e.g. 3) to, in effect, provide prospective angled cross arms), and a generally annular peripheral portion **728** connecting cross arms **722** to the forward end of casing **316**. Peripheral portion **728** extends perpendicularly from casing **316** towards shaft **110** a predetermined distance, suitably in the range of ½ inch to 2 inches, and preferably ¾ inches. Internal chamber **320** thus extends farther forward in the vicinity of the crenellated outer edge of stator core **328**, and windings **330**.

[0120] FIG. 7C shows a hub similar to that shown in FIG. 7A except that external surface **729** meets shaft **110** perpendicularly greatly increasing the cross sectional area. This increases the strength of endcap **714** helping it to better resist deflection as outlined in FIG. 5. In FIG. 7C casing **316** is welded **731** to endcap **714**.

[0121] FIG. 7D shows both endcap **714** and casing **316** formed as a single integral unit **732**. Unit **732** is suitably cast then machined, further increasing its strength. Unit **732** can also be machined entirely from a single billet of e.g., steel.

[0122] FIG. 7E shows all three, endcap **714**, casing **316** and shaft **110** casts then machined as a single unit **733**. This configuration allows for maximized strength and alignment since both the shaft portion and inner casing will be machined together minimizing wobble. This configuration also has the benefit of reducing parts and assembly time. Unit **733** can also be machined entirely from a single billet of steel eliminating the need for a casting.

[0123] As shown schematically in FIG. 8, a variety of bumpers can be used in combination, together with a contoured rotor endcap.

[0124] As previously noted, the heat generated by compact high power alternators can also be problematical. The stator windings are formed of a suitably insulated electrical conductor, e.g. varnished copper motor wire, and are wound through respective slots and about a predetermined number of teeth in the periphery of the stator core. As the rotor rotates relative to the stator, the magnetic field generated by the rotor magnets interacts with the windings, causing an electrical current to be generated. The windings, however, have a characteristic, and current flow through the windings generates heat that must be dissipated. Conventionally, the windings are tightly wound about the stator core, to minimize the length of the windings, and hence impedance, and airflow to effect cooling has been provided by fans driven by the motive force to the rotor, e.g. off of the shaft on which the rotor is attached. Accordingly, little airflow is provided at low rpm.

[0125] However, in various automotive applications, such as, for example, hybrid vehicles, demand for relatively high levels of power, and thus an elevated need for cooling, can occur at low rpm, e.g. at idle speeds. This is also particularly true in those instances when a starter-generator or other electric motor is employed to provide an initial burst of propulsion when the driver depresses the accelerator pedal, facilitating shutting off the vehicle engine when the vehicle is stopped in traffic to save fuel and cut down on emissions. Further, in compact high power alternators, significant heat levels are generated in a relatively small area. The efficacy of

air cooling of alternator components is a function of the quantity of air flowing through the alternator. In compact high power alternators the cross-sectional area available for air flow for a given power output is less than that available in a conventional alternator. Accordingly, air cooling tends to be less efficient. However, permanent magnets are particularly susceptible to damage due to overheating; under high load, high temperature conditions, such magnets can become demagnetized. Similarly, the electronic components employed in the controller are susceptible to heat damage. Thus, conventional cooling techniques tend to be inadequate for such compact high power alternators, particularly in automotive applications.

[0126] In accordance with other aspects of the present invention, cooling is facilitated by one or more of: loosely wrapping winding end turns 332 to, in effect, increase the surface area of windings 330; establishing a directed airflow over at least a portion the stator windings, (preferably through loosely wrapped end turns of the windings); directing a portion of the airflow over elements in thermal contact with magnets 318 (e.g. over rotor casing 316) to cool magnets 318; providing airflow from a source that is asynchronous with respect to the shaft on which the rotor is mounted, e.g. an electric fan; and directing a flow of coolant fluid into thermal contact with end turns 332 (preferably through thermally conductive conduits including one or more portions disposed in loops generally concentric with the stator core in thermal contact with front end turns 332A and/or rear end turns 332B).

[0127] As previously noted in conjunction with FIGS. 3 and 4, windings 330 are wound through a respective slot 404, outwardly along the side face of core 328 around a predetermined number of teeth 402 forming an end turn 332, then back through another slot 404. More particularly, with reference to FIGS. 9A, 10A and 10B, each of windings 330 comprises at least one associated bundle of individual strands of insulated conductive wire (e.g. varnished copper motor wire). In contradistinction to the conventional practice, end turns 332 are loosely wrapped around the side faces of the stator core, with air spaces between the various bundles and the core side face, (rather than drawing the winding end turns tightly against the side face of the stator core to minimize cost and impedance). The inefficiencies inherent in loosely extending the winding end turn beyond the stator has been determined to be insignificant in comparison to the increased cooling capacity provided by exposed surface areas of the open winding structure. Preferably, as best seen in FIG. 10A, respective end turns 332 extend varying distances from stator side face 328, presenting a lattice-like structure to the airflow. End turns 332 suitably extend distances from stator side face 328, ranging from 0 to 1½ inch, and preferably from ¼ to 1 in. For example, adjacent end turns would extend outwardly by incrementally different distances e.g. increments of one half-inch to progressively fan out from the stator. In the embodiment of FIG. 10, a first end turn 1002 is offset from stator side face 328 by approximately a first predetermined distance, e.g. ½ inch. The next adjacent end turn 1004 is offset from stator side face 328 by approximately an incrementally increased distance, e.g. ¾ inch. Likewise, the next adjacent end turn 1006 is offset from stator side face 328 by approximately a further incrementally increased distance, e.g. 1 inch. The pattern is then suitably repeated. This arrangement is equally valid for a skewed core 329 as shown in FIG. 10B.

[0128] If desired, the lattice pattern can be established by offsetting respective end turns 332 associated with each phase a different offset distance from stator side face 328; for a three-phase system, the end turns of phases A, B, and C, suitably have offset distances of approximately ½ in., ¾ in., and 1 in., respectively.

[0129] Referring to FIG. 9A, a cooling airflow is directed over stator windings 330 (preferably through loosely wrapped front-side and rear-side end turns 332A and 332B) by employing a cooling system comprising air passageways 902 in rear end plate 122 (bounded by adjacent rear end plate crossarms 348, outer portion 346, and hub 340), stator central aperture 406, rotor air passages 323 and front end plate air passages 136. Air exiting rear end plate air passage way 902 is directed to impinge on windings 330 (rear-side end turns 332B), by virtue of suitable relative disposition or contouring, or, as in the embodiment of FIG. 9A, cooperation with a rear deflector 904. Similarly, air exiting stator central aperture 406 is directed to impinge on windings 330 (front-side end turns 332A), by virtue of suitable relative disposition or contouring, or, as in the embodiment of FIG. 9A, cooperation with a front deflector 906. An asynchronous forced air supply, e.g., electric fan 126, mounted on the back of rear end plate 122 is preferably utilized. In the preferred embodiment, a conventional fan 908 is also mounted for rotation with shaft 110 between pulley 132 and front end plate 116. The cross sections, contours (turns and edges) and relative dispositions of the various air passageways are preferably chosen to minimize decreases in air velocity, and maximize airflow over end turns 332.

[0130] More specifically, cooling air, generally indicated by arrows 910 (preferably forced air from asynchronous fan 126) is introduced into alternator 100 through end plate air passageways 902. Airflow 910 impinges upon rear deflector 904, and is redirected in a radially outward direction; air that would otherwise flow through stator central aperture 406 flows outward and about stator core 328. In the preferred embodiment, the outwardly redirected air impinges upon and flows through the spaces between rear-side loosely wrapped rear-side end turns 332B of windings 330. Airflow 910 then splits into respective streams 914 and 916. After exiting the end turns 332B, air stream 914 flows through stator central aperture 406, impinges upon front deflector 906, is directed through the front-side loosely wrapped end turns 332A, rotor passageways 323 and then exits alternator 100 through air passageways 136 in front end plate 116. Air stream 914 comprises the bulk of airflow 910, since stator central aperture 406 represents the largest diameter path, and hence the path of least resistance. Air stream 916, after exiting rear-side end turns 332B, flows around the outside of rotor casing 316, then exits alternator 100 through air passageways 136 in front end plate 116. Air stream 916 provides cooling of magnets 318.

[0131] Rear deflector 904 comprises an element presenting a predetermined contour to the impinging air stream 910 to redirect the air stream onto windings 330 (preferably rear-side end turns 332B) to dissipate heat generated in windings 330. The diameter and predetermined contour of the reflector 904 is chosen effectively redirect the air as much as possible through the windings without creating too a large a decrease in air velocity. Rear deflector 904 is suitably a generally conical or dish shaped element with a central aperture, concentrically disposed on rear end plate hub 340, disposed with the apex facing into the airflow. Rear deflector 904 extends radially outward into the path of air stream 910 as it exits rear

end plate air passageway **902**, preferably at or just under the outer periphery of stator central aperture **406**. Rear deflector **904** may be formed of any suitable relatively rigid material, such as, e.g., sheet metal, or plastic, or may be formed integrally with rear end plate **122**. The choice between use of a separate deflector component, or a deflector feature integrally formed in end plate **122** is primarily an issue of cost.

[0132] Front deflector **906** likewise suitably comprises an element presenting a predetermined contour to the impinging air stream **914** to redirect the air stream onto windings **330** (preferably front-side end turns **332A**) to dissipate heat generated in windings **330**. The diameter and predetermined contour of deflector **906** is chosen effectively redirect the air as much as possible through the windings without creating too large a decrease in air velocity. Deflector **906** suitably comprises a generally conical or dish shaped element with a central aperture, disposed with the apex facing into the air-flow. Front deflector **906** is concentric with rotor hub **324** (shaft **110**), suitably rotates with rotor **112**, and extends radially outward into the path of air stream **914** exiting stator central aperture **406**. Front deflector **906** may be formed of any suitable relatively rigid material, such as, e.g., sheet metal, or plastic, or may be formed integrally with rotor **112** or jam nut **120**. The choice between use of a separate deflector component, or a deflector feature integrally formed in rotor **112** or jam nut **120** is primarily an issue of cost. In the embodiment of FIG. **9A**, front deflector **906** suitably has an outer diameter such that the outer periphery extends approximately $\frac{3}{4}$ of the way into stator central aperture **406**.

[0133] If desired, in addition to (or in some instances in lieu of) deflectors **906** and **904**, heat transfer efficiency can be increased by bending end turns **332** into the air stream. More particularly, referring to FIG. **11**, end turns **332** are bent inwardly beyond the periphery of stator central aperture **406**, and into the path of air flowing through the aperture.

[0134] As previously noted, in the embodiment of FIG. **9A**, a conventional synchronous fan **908** is mounted for rotation with shaft **110** between pulley **132** and front end plate **116**. Fan **908** in effect, creates a vacuum that pulls air through alternator **100**. However, alternator **100** is capable of generating high levels of power at idle, or just above idle, speeds. Fan **908**, rotating synchronously with shaft **110**, is typically unable to provide sufficient airflow for cooling under such conditions. Electric fan **126**, which operates a synchronously from shaft **110**, suitably provides an auxiliary cooling, providing a positive pressure to push air through alternator **100**.

[0135] Fan **126** is, as previously noted, mounted on the back of rear endplate **122**. In general, it is desirable to maximize airflow through alternator **100**. Accordingly, fan **126** is preferably chosen to provide the largest cubic feet per minute (CFM) zero pressure given the size constraints of alternator **100**. Commercially available fans can be employed. However, preferably fan **126** is a permanent magnet fan, with a blade diameter approaching that of alternator outer casing **128**.

[0136] The use of fluids for cooling in addition to, or in lieu of, forced air can be advantageous under operating conditions of low airflow, or extreme heat and, in sandy, wet, or otherwise harsh conditions.

[0137] For example, in some cases it is advantageous to supplement air cooling with fluid cooling of coil end turns **332**. In general, a coolant fluid is directed into thermal contact with end turns **332** while maintaining electrical isolation. For example, coolant fluid can be routed through thermally con-

ductive conduits including one or more portions disposed in thermal contact with front end turns **332A** and/or rear end turns **332B**. The conduit portions suitably track the shape of end turns **332**, e.g., comprise generally circular or helical loops generally concentric with the stator core disposed proximate to the end turns. The conduits can be formed of any thermally conductive material that is capable of withstanding the elevated temperatures found in the alternator and nonreactive with the chosen coolant. Suitable materials include, for example, copper, and aluminum tubing. The conduit is preferably thermally connected to the adjacent end turns by an electrically insulating heat conductor, such as, for example, engineered epoxy. The coolant fluid can be any fluid, preferably liquid, having suitable thermal and flow characteristics. One example is conventional engine coolant. In vehicular applications, the engine coolant would preferably be directed into the alternator immediately after exiting the radiator.

[0138] Referring to FIGS. **9B** and **9E**, in a preferred embodiment, a coolant fluid is directed into thermal contact with end turns **332** through a conduit (e.g., copper tubing) **918**. Conduit **918** suitably includes an inlet **922**, axially directed portions **950**, **958** and **966**, radially directed portions **952**, **956**, **960**, and **964**, and looped portions **954** and **962**. Looped portions **954** and **962** each suitably comprises one or more circular or helical turns centered about the axis of stator core **328**, with diameter(s) corresponding to the annulus formed by end turns **332** (e.g., bounded by the bottom of slots **404** and the outer perimeter of core **328**). Conduit portions **952**, **954** and **956** are suitably all disposed in a plane perpendicular to the axis of stator core **328**, (parallel to the front face) just in front of front end turns **332A**. Conduit portions **960**, **962** and **964** are likewise suitably all disposed in a plane perpendicular to the axis of stator core **328**, (parallel to the back face) just behind rear end turns **332B**. Axial portions **950** and **958** suitably extend through stator central aperture **406**. Axial portions **950** and **966** suitably extend through rear endplate inner passageway **902**. Coolant is introduced at inlet **922**, and then flows through portions **950**, **952**, **954**, **956**, **958**, **960**, **962**, **964**, and **966**, in sequence, then exits through an outlet **924**.

[0139] Conduit **918** is thermally connected to end turns **332** by an electrically insulating, thermally conductive material **920** (e.g. engineered epoxy). Material **920** suitably encapsulates end turns **332**, looped portions **954** and **962**, and a part of radial portions **952**, **956**, **960** and **964**. Material **920** conducts heat from end turns **332** to the coolant, while at the same time providing electrical isolation.

[0140] In the embodiment of FIG. **9B**, magnets **318** are cooled using air stream **916**. Air stream **916** flows around the outside of rotor casing **316**, then exits alternator **100** through air passageways **136** in front end plate **116**. The air flow is supplied by fan **908**. An asynchronous fan **126** as shown in FIG. **9A** can be used to enhance the cooling of magnets **318**.

[0141] If desired, the coolant flow through conduit **918** can also be used to cool magnets **318** to permit an essentially closed system. An airflow, cooled by the coolant flow through conduit **918**, is directed across magnets **318**.

[0142] Referring to FIGS. **9C** and **9D**, respective thermally conductive heat exchange fins **922** are provided, thermally connected to the conduit **918**. Fins **922** are suitably incorporated into thermally conductive encapsulant **920**. Fins **922** suitably extend radially into central aperture **406**.

[0143] Respective blades are disposed on the forward face of rotor **112** to form a centrifugal fan **926**. Fan **926** generates

an airflow **916**; air is drawn through stator core central aperture **406**, over heat exchange fins **922**, through apertures **323** in the end plate of rotor **112**, and forced to flow around the outside of rotor casing **316**. The airflow, after flowing around the outside of rotor casing **316**, is directed by passageway **928** back into central aperture **406**. The airflow around the outside of rotor casing **316** carries the heat created by magnets **318** across the heat exchanger fins **922** embedded in encapsulant **920**. Fluid coolant flowing in cooling tubes **918** thus carries away heat generated by both the windings of stator **328** and magnets **318**.

[0144] Since the need for air circulation from an outside source is no long required, the alternator is suitably sealed using o-rings **930** and plugs **932**. This has the advantage of sealing out most if not all contamination detrimental to the operation of a permanent magnet alternator. If desired, a one-way valve or membrane (not shown) located at the lowest point of the alternator can be provided to assist in draining possible accumulation of water. In the event a greater air flow is required, an asynchronous fan **126** can be installed.

[0145] Under some circumstances, e.g., in sandy, wet, or otherwise harsh conditions, an air cooled alternator can be sealed with respect to potential external contaminants. In accordance with another aspect of the present invention, a sealed air cooled alternator is provided by establishing separate internal and external cooling airflows over an external alternator case acting as a heat exchanger. The internal and external airflows are suitably provided by internal and external fans. The internal airflow is directed over the stator coils, rotor and interior of the heat exchanger to transfer heat from the coils and magnets to the heat exchanger. The exterior airflow is directed over the exterior of the exchanger to dissipate the heat. If desired, the source for the external airflow can be remotely located from the alternator, e.g., provided through plenums or snorkels.

[0146] Referring to FIG. 12, a first embodiment of a sealed alternator **1200** comprises: shaft **110**; a sealed front end plate **1202**; front bearings **118**; stator **114**; a forward facing rotor **1204**; jam nut **120**; an internal fan **1206**; rear bearing **124**; a sealed rear endplate **1208**; a heat exchanger **1210**; an external fan **1212** and a fan housing **1213** with an air intake **1214**. (In this embodiment, tie rods **130** (not shown) may be disposed externally, as illustrated in FIG. 4) Front end plate **1202** suitably includes a stepped central hub **1214** (generally analogous to rear endplate hub **340** in the embodiment of FIG. 3) for mounting and locating front bearing **118**, and stator core **328**. Tapered portion **310** of shaft **110** is disposed at a predetermined axial distance from front end plate **1202** (generally corresponding to the axial length of rotor **1204**). Rotor **1204** is essentially the same as rotor **112**, but with the tapered portion of hub **324** reversed to accommodate a forward facing disposition of rotor **112**. As in the embodiment of FIG. 3, rotor **1204** is mounted for rotation on shaft **110**, positively located on and aligned with shaft **110** by cooperation of hub **324** with shaft tapered portion **310**, and stator **114** is closely received within rotor **1204**, separated from rotor **1204** by a small air gap **412**. Heat exchanger **1210** is generally cylindrical and disposed coaxially with shaft **110**, exteriorly of rotor casing **316**. Front end plate **1202**, bearings **118** and **124**, heat exchanger **1210** and rear endplate **1208** provide a sealed compartment enclosing stator **114**, rotor **1204** and internal fan **1206**.

[0147] Referring to FIGS. 12 and 13A, heat exchanger **1210** suitably comprises a cylindrical separator (casing) **1216**

and bearing radially extending internal and external fins, **1218** and **1220** respectively, all in thermal contact. Heat exchanger **1210** is suitably a unitary extrusion of thermally conductive material, such as aluminum or steel. Alternatively, as shown in FIG. 13B, for ease of construction, heat exchanger **1210** can be formed of a separate cylindrical casing formed of a first material, e.g., steel, with a plurality (e.g. 12, only one shown) of separate (suitably extruded) fin sections **1218A** (each extending over a predetermined arc) formed of a second material, e.g. aluminum, covering the interior face of cylinder **1216** and a plurality (e.g. 12, only one shown) of separate (suitably extruded) fin sections **1220A** covering the exterior face of cylinder **1216**. For example, twelve 30° sections of fins or four 90° sections of fins can be employed. The respective fin sections **1216A** and **1220A** are fixed on, and in thermal contact with, casing **1216**, suitably by an adhesive (that remains sufficiently flexible to accommodate the different rates of thermal expansion of the first and second materials).

[0148] Heat exchanger **1210** is disposed coaxially with and radially outward from rotor casing **316**. Respective axial channels **1226** are defined between adjacent internal fins **1218**, casing **1216** and the outer surface of rotor casing **316**. As will be explained, airflow through channels **1226** transfer heat from rotor **112** and windings **330** to internal fins **1218** (and casing **1216**). The heat is then conducted from fins **1218** to external fins **1220**. Airflow over exterior fins **1220** (and casing **1216**) is employed to dissipate the heat.

[0149] As best seen in FIG. 12, heat exchanger **1210** preferably includes a cylindrical exterior cover **1222** to facilitate airflow over external fins **1220**. Cover **1222** is disposed coaxially with separator (casing) **1216**, radially outward of heat exchanger external fins **1220**. Cover **1222** suitably nests within with exterior fan housing **1213** and is suitably fastened at its rear end, and provides an outlet **1224** for heat exchanger **1210** at its forward end. Respective axial channels **1228** communicating with the interior of fan housing **1213** are thus defined between adjacent external fins **1220**, casing **1216**, and heat exchanger cover **1222**.

[0150] Internal fan **1212**, suitably attached to or integral with rotor **112**, generates an internal airflow directed over stator coils **330** (preferably through end turns **332**), rotor **112** and through interior channels **1226** of heat exchanger **1210**. More particularly, internal fan **1212** is configured to propel air outwardly, creating a negative pressure in the interior of rotor **112**, and an air stream, generally indicated by arrows **1230**, is forced through channels **1226**, cooling rotor casing **316** (and thus magnets **318**), and transferring heat to internal heat transfer fins **1218** and casing **1216**. Air stream **1230** exits channels **1226**, flows through front-side end turns **332A**, into stator central aperture **406**. The airflow exiting the rear side of stator aperture **406** is directed to flow through rear-side end turns **332B**. This is suitably implemented using a deflector **1232**. After flowing through end turns **332B**, the air stream flows through rotor apertures **323**, and is recirculated by fan **1206**. Heat in stator coils **330** and magnets **318** is thus dissipated and transferred to heat exchanger interior fins **1218**. Fins **1218** are in thermal contact with casing **1216** and external fins **1220** such that heat is conducted from fins **1218** to external fins **1220**. Airflow over exterior fins **1220** (and casing **1216**) is employed to dissipate the heat.

[0151] Airflow, generally indicated as **1234**, over exterior fins **1220** is suitably generated by external fan **1212**. External air provided through intake **1214**, is propelled outwardly

within the interior of housing 1213 by rotation of fan 1212, and forced through channels 1228, ultimately exiting through outlet 1224. If desired, filters (not shown) can be provided over outlet 1224, and fan housing air intake 1214.

[0152] In some instances, it may be desirable to employ pressurized external air from a source located remotely from sealed alternator unit. Such an embodiment 1400 is shown in FIG. 14. Sealed alternator 1400 is substantially similar to alternator 1200 except that instead of being driven by a dedicated external fan 1212, alternator 1400 employs a rear housing 1402, the interior of which communicates with heat exchanger exterior channels 1228, cooperating with a plenum 1404 and a suitable remote pressurized air source, such as a remote fan 1406. External air flow 1234 is supplied by remote fan 1406, directed through a plenum 1404, through the interior of housing 1402 and channels 1228, and ultimately exiting through outlet 1224.

[0153] An alternative embodiment of the present invention particularly adapted for use in sandy, wet, or otherwise harsh conditions, employs a locally sealed alternator cooperating with a double walled snorkel to provide a cooling air from remote, less harsh source. Referring to FIG. 15, a locally sealed alternator 1500 cooperates with a snorkel 1502. Alternator 1500 is suitably similar in most respects to alternator 100 described in conjunction with FIGS. 1-4. However, the front endplate 116A (analogous to front endplate 116) and front bearing 118A (analogous to front bearing 118) are sealed, the rear endplate 122A (analogous to rear endplate 122) includes a separate outer set of air passageways 1504, in addition to air passageways 902, and (like the embodiment of FIG. 4) tie rods 130 are disposed exteriorly of outer casing 128. In addition, alternator 1500 includes an air dam 1506, to separate respective airflows, as will be described. Air dam 1506 is suitably formed of felt, or integrally formed with rear endplate 122A.

[0154] Snorkel 1502 suitably includes generally vertical, generally cylindrical inner and outer chimney portions (1512A, 1514A, respectively) and transverse inner and outer connecting portions (1512B, 1514B, respectively), formed by interior and exterior walls 1512 and 1514, respectively. The number of vertical and transverse portions is kept to the lowest number possible (i.e., the least number of bends) for any given installation to maximize air velocity. Inner wall 1512 (and proximate mouth of inner connecting portion 1512B) is disposed between endplate inner and outer passageways 902 and 1504; the outer diameter of inner wall 1512 is suitably less than or equal to the inner diameter of passageway 1504, and the inner diameter of inner wall 1512 is greater than or equal to the outer diameter of passageways 902. An intake airway 1516 communicating with endplate outer passageways 1504 is defined between exterior wall 1512 and interior wall 1514. An output airway 1520 communicating with endplate inner passageways 902 is defined within interior wall 1512. Intake airway 1516 and output airway 1520 are suitably capped by first and second air filters 1518 and 1522, respectively. Input filter 1518, in effect, scrubs air introduced into the alternator. Output filter 1520 prevents dust from entering the alternator through the exhaust when the alternator is not running. Interior chimney portion 1512A suitably extends beyond the external chimney portion 1514A defined by exterior wall 1514. The mouths of intake airway 1516 and output airway 1520 (filters 1518 and 1522) are both disposed above a predetermined height, corresponding to the maximum depth of water to be traversed by the vehicle in

which alternator 1500 is mounted. A suitable deflector 1524 is suitably disposed on the between air passageways 902 to minimize introduction of exhaust air from output airway 1520 into intake airway 1516.

[0155] Snorkel 1502 is fixed to rear endplate 122A of alternator 1500 through the use of an adapter plate 1503. In the embodiment of FIG. 15, snorkel 1502 and endplate 122A are secured by tie rods 130. Alternatively, the mouth of exterior connecting portion 1514B can be force fit over the periphery of rear endplate 122A, and if desired, secured by metal banding. In any case, suitable sealant, gaskets or o-rings (not shown) are preferably employed to establish an essentially waterproof seal. Electric fan 126 is suitably disposed on an adapter plate 1503 (suitably disk-shaped with respective air passageways there through) within the interior of interior connecting portion 1512B, with blades arranged to create a negative pressure within the interior of rotor 112.

[0156] Fan 126 circulates air along a coolant path to create a cooling airflow 1526 through the rotor and stator; air is taken in through filter 1518 and intake airway 1516, flows through transverse outer connecting portion 1514B, outer air passageways 1504 in rear endplate 122A, the space between outer casing 128 and the exterior of rotor casing 316, passageways 323 in rotor endcap 314, over end turns 332A, through aperture 406 of stator core 328, over end turns 332B, through inner air passageways 902 in rear endplate 122A, through fan 126, and through snorkel inner connecting portion 1512B, output airway 1520 and filter 1522. Alternator 1500 is thus locally sealed, and can be submerged in water up to the depth defined by snorkel 1502.

[0157] Fan 126 can be a conventional electric fan. However, it is desirable that coolant circulation by fan 126 be maximized. A permanent magnet fan design develops very high horse power for little in terms of energy input, and facilitates large diameter blades for increased air velocity and pressure while still manifesting relatively small axial dimensions.

[0158] Accordingly, a fan specifically optimized for the available space is desirable. Referring now to FIG. 16A, a first embodiment 1600A of such a fan comprises: a stator frame 1602; a stator core 1604 and windings 1606; front and back fan bearings 1608 and 1610; and a fan 1612. Stator frame 1602 is suitably includes a generally cylindrical body 1615 and suitably includes fan bearings 1608 and 1610 centrally disposed therein. Stator frame 1602 is suitably secured to rear endplate 122A, concentrically with shaft 110. Fan stator core 1604 is suitably generally cylindrical, and disposed about stator frame body 1615.

[0159] Fan 1612 suitably comprises a cast fan body of engineered plastic, aluminum or other suitable material 1614, a fan rotor 1616, and a retaining fastener 1618. Fan body 1614 suitably includes a central hub 1623 with a perpendicular central interior shaft 1624 (rotatably maintained by bearings 1608 and 1610), connected to body 1614 by respective crossarms forming respective passageways 1626. Passageways 1626 communicate with snorkel inner connecting portion 1512B. If desired, an air dam 1625, suitably formed of felt or low friction material, can be provided to between snorkel inner wall 1512 and fan rotor end cap 1612, to minimize movement of air between input and output passageways.

[0160] Fan rotor 1616 suitably fastened (i.e., epoxied or other suitable fastening method) to fan body 1614, includes respective magnets 1632 disposed on the interior thereof. Magnets 1632 are disposed in close proximity to fan stator

core 1604, separated only by a small air gap, to electromechanically interact with fan stator windings 1606; electrical signals applied to windings 1606 cause relative motion of magnets 1632, and hence fan 1612. Electrical power can be provided internally from the power generated by alternator 1500, or can be supplied from the external source (e.g. a vehicle battery). Fan blades 1634 are disposed to move air from snorkel exterior connecting portion 1514B through rear endplate outer passageways 1504. By disposing blades at the furthest diameter possible, maximum air movement and pressure are provided. Fan blades push air stream the 1526 through outer air passageways 1504 in rear endplate 122A. Air stream 1526 then circulates through the interior of alternator 1500 as described in connection with FIG. 15, then exits through inner air passageways 902 in rear endplate 122A, through passageway 1626 of fan 1600 and exhausts through snorkel inner connecting portion 1512B which has been suitably fixed to adapter plate 1503A, output airway 1520 and filter 1522 as described in connection with FIG. 15.

[0161] If desired, the fan blade can be configured to have respective differently angled sections aligned with endplate inner and outer passageways 902 and 1504 to push air into passageways 1504 and pull air out of passageways 902. Referring to FIG. 17, a fan 1700 employing such a blade is suitably generally similar to fan 1600. However, fan 1700 utilizes more compact stator frame 1702 (suitably without air passages), and a fan rotor 1704 including concentric inner and outer cylinders 1706 (analogous to cylindrical body 1630) and 1708, respectively. A first set of fan blades 1710 (generally analogous to blades 1634) are provided on the exterior of outer cylinder 1708 (connecting it to an outer cylinder 1709). A second set of fan blades 1712 connect cylinders 1706 and 1708.

[0162] Outer cylinder 1708 is suitably concentric with and has approximately the same diameter inner snorkel wall 1512. Fan blades 1710 (like blades 1634 in the embodiment of FIG. 16) are disposed to move air from snorkel exterior connecting portion 1514B through rear endplate outer passageways 1504. Cylinders 1706 and 1708 are disposed such that endplate inner passageway 902 is bracketed by the cylinders (e.g., the outer diameter of cylinder 1706 is less than or equal to the inner diameter of passageway 902, and the outer diameter of passageway 902 is less than or equal to the inner diameter of outer cylinder 1708). Fan blades 1712 manifest a reversed angle as compared to fan blades 1710, such that a negative pressure is created at passageway 902 (i.e. air is pulled out of alternator 1500 through passageway 902). The side faces of fan rotor 1614A proximate to endplate 122A are suitably maintained to close tolerances, and separated from endplate 122A only by a relatively small air gap, generally indicated as 1714, suitably in the range of 0.01 inch to 0.05 inch, and preferably 0.03 inch. Gap 1714 is small enough that any migration of air between paths is insignificant. As the fan rotates it develops pressure in opposite directions the outer ring in and the inner ring out of the alternator creating the required flow to cool the alternator.

[0163] In sandy, dusty, wet, or otherwise harsh conditions (e.g. desert or agricultural applications) it may be desirable to filter air introduced into the alternator. Dust and air born contaminants are potentially abrasive and sand very commonly carries iron compounds which can accumulate on the permanent magnets (in the alternator and/or fan). An input filter is employed to, in effect, scrub air introduced into the alternator. An output filter is employed to prevent dust from

entering the alternator through the exhaust when it is not running. Any suitable filtering strategy may be employed, preferably with provisions for minimizing introduction of exhaust air into the alternator intake. For example, in the embodiment of FIG. 18A, fan 1600B, (with blades arranged to create a negative pressure within alternator 1500) is disposed within a housing 1800 comprising a central cylindrical duct and a concentric dish shape deflector 1808. Fan 126 is suitably mounted concentrically within duct 1802 on a frame 126A (suitably with an outer periphery conforming to the interior of duct 1802 with passages there through). Frame 126A may be integral with housing 1800. Duct 1802, suitably disposed proximate to the side-wall of endplate 122A at one end, and closed at the other, is suitably concentric with and disposed between endplate inner and outer passageways 902 and 1504; the outer diameter of duct 1802 is suitably less than or equal to the inner diameter of passageway 1504, and the inner diameter of duct 1802 is greater than or equal to the outer diameter of passageways 902. Duct 1802 defines respective input and output airways 1810 and 1804. Output airway 1804, within the interior of duct 1802, communicates with inner passageways 902 in the alternator endplate 122A and exhausts radially through a mouth 1805. A ring-type air filter 1806, concentric with duct 1802, is disposed at the mouth of output airway 1804. Deflector 1808 is disposed about the exterior of duct 1802, and provides a forward facing mouth 1812. A ring-type air filter 1814, concentric with duct 1802, is disposed within input airway 1810. Deflector 1808 cooperates with duct 1802 to defining input airway 1810. Deflector 1808 with forward facing mouth 1812 tends to minimize introduction of exhaust air into alternator 1500.

[0164] Introduction of exhaust air into alternator 1500 through the air intake can also be minimized by relative disposition of the air intake and exhaust. For example, in FIGS. 18B, and 18C, the input airway opens radially exteriorly of duct 1802, and the output airway opens axially at the rear. In the embodiment of FIG. 18B, input and output filter 1814 and 1806 are both ring-type filters. Duct 1802 includes a stepped (increased diameter) portion 1802B, the sidewall of which cooperates with endplate 122A to define the input airway. In the embodiment of FIG. 18C, input filter 1814 is a ring-type filter and output filter 1806 is a flat plate type filter. In this case, the input airway is defined by an annular plate 1820 disposed on the exterior of duct 1802, in cooperation with endplate 122A. If desired, duct 1802 and plate 1820 can be integral part of fan frame 126A.

[0165] It is sometimes desirable to intake air from a location remote from the alternator, e.g. where the ambient air temperature in the vicinity of the alternator is higher than desirable. In the embodiment of FIG. 15, this is accomplished utilizing a snorkel attaching to the rear, and initially extending axially from the alternator. In some applications, the axial extent of free space is limited, and it is desirable to provide an air intake duct extending transversely relative to the axis of the alternator. Referring to FIG. 19, such a transversely ducted alternator is suitably generally similar to the embodiment of FIG. 18C, except that a conduit 1902 with a tangentially extending extension 1904, suitably capped with an air filter 1906, is employed rather than plate 1820 and ring-type filter 1812.

[0166] Filters can also be utilized with the optimized fans of FIGS. 16 and 17. For example, referring to FIG. 20A, fan 1600 may be concentrically disposed within a generally cylindrical fan housing 2000. Housing 2000 suitably includes

a concentric inner cylindrical wall **2002** that extends inwardly and terminates proximate fan rotor end cap **1614**, separated from end cap **1614** only by a small gap **2004**. The diameter of wall **2002** is suitably intermediate those of rotor body **1630**, and air passageway **1626**, preferably with an outer diameter equal to that of body **1630**. Wall **2002** defines respective input and output airways **2006** and **2008**. Gap **2004** is small enough that any migration of air between airways **2006** and **2008** is insignificant. Input airway **2006**, on the exterior of wall **2002**, communicates with fan blade **1634**, and ultimately with endplate outer passageway **1504** and includes an intake adapted to receive a ring-type air filter **2010**, concentric with wall **2002**. Output airway **2008**, within the interior of wall **2002**, communicates with passageways **1626**, **1620** and **1622** of fan **1600** and ultimately inner passageways **902** in the alternator endplate **122A**. Output airway **2006** exhausts through a filter **2009**, suitably a flat plate type filter. The ability to reverse fan air flow **2010** allows for an extension of airway **2008** using rubber flex tubing **2012** or other suitable material to a more environmentally friendly location, feeding alternator **1500** with cooler air than would be available close to the alternator under very harsh conditions. Similarly, referring to FIG. **20B**, fan **1700** may also be concentrically disposed within fan housing **2000**. In such case inner cylindrical wall **2002** aligns with fans rotor outer cylinder **1708**; the outer diameter of wall **2002** is suitably equal to that of cylinder **1709**.

[0167] As previously noted, the electrical current induced in the alternator stator windings is typically applied to a bridge rectifier, sometimes regulated, and provided as an output. In some instances, the regulated output signal is applied to an inverter to provide an AC output. In addition, electronic control systems to accommodate changes in the rotor speed or changes in load characteristics may be employed. The components employed in such electronic systems tend to be susceptible to heat damage. Accordingly, it is desirable to dispose the electronic components (particularly those components that produce heat during operation) into a die cast heat sink in the path of the coolest air, e.g., in the vicinity of the air intake. For example, referring to FIGS. **21A** and **21B**, the heat producing electronic components **2100** are mounted on (pressed into) a heat sink **2102**, which is, in turn, mounted within air passageway **1504** in alternator endplate **121A**. Heat sink **2102** is formed (e.g. machined or extruded) of a light thermally conductive material, e.g. aluminum, and includes a main rib **2104**, with transverse (e.g. perpendicular) cooling fins **2106** and respective fastening tabs **2108** at either end. Components **2100** are suitably mounted on main rib **2104**. Heat sink **2102** is contoured to fit within endplate passageway **1504**, such that the cooling air flow (generally indicated as **1526**) runs over and between fins **2106**. Heat sink **2102** is suitably fastened to endplate **121A** by respective screws **2110** passing through tabs **2108** and threading into endplate **121A**.

[0168] Alternatively, a heat sink bearing the electronic components can be disposed within the input airway of a fan housing (e.g., **1800**, **2000**), snorkel (e.g., **1502**), plenum (e.g., **1402**) or the like cooperating with the alternator. For example, components **2200** can be mounted on a heat sink **2202**, which is in turn mounted in input airway **2006** of fan housing **2000**.

Heat sink **2202** is suitably comb-like, formed (e.g. machined or extruded) of a light thermally conductive material, e.g. aluminum, with a base **2204**, and transverse (e.g. perpendicular) cooling fins **2206**. Components **2200** are suitably mounted on base **2204**. The cooling air flow, generally indicated as **1526**, flows through filter **2010**, through the respective cooling fins **2206**, and into the alternator through rear endplate passageway **1504**.

[0169] In a sealed unit, such as the embodiments described in connection with FIGS. **12-14**, the heat generating power components are preferably disposed exteriorly of the sealed alternator, e.g., on a heat sink disposed on heat exchanger cover **222** within exterior channels **1228**.

[0170] Referring to FIGS. **23A** and **23B** the heat producing electrical components can be mounted to a heat plate that uses the alternator coolant fluids outlined in FIGS. **9B** and **9C**. prior to entering the alternator cooled fluid flow through heat plate **2302**. The heat producing components **2303** are suitably fastened to heat plate **2302**. Note that in FIG. **23B** the seal of the alternator is maintained by locating the **2302** and **2303** exterior of the alternator.

[0171] Although the present invention has been described in conjunction with various exemplary embodiments, the invention is not limited to the specific forms shown, and it is contemplated that other embodiments of the present invention may be created without departing from the spirit of the invention. Variations in components, materials, values, structure and other aspects of the design and arrangement may be made in accordance with the present invention as expressed in the following claims.

What is claimed is:

1. Power conversion apparatus comprising a shaft, a stator including at least one winding; and a rotor including a plurality of permanent magnets, the shaft, stator and rotor being coaxially disposed, with the rotor mounted on the shaft, such that, in the absence of external forces, the rotor is disposed in a predetermined position relative to the stator with the magnets proximate to the stator, separated from the stator by a predetermined gap distance, such that relative motion of the rotor and stator causes magnetic flux from the magnets to magnetically interact with the stator winding, further including at least one bumper disposed to prevent the position of rotor from deviating, in response to external forces, more than a predetermined amount from the predetermined position relative to the stator, such that clashing between the magnets and the stator is avoided

2. The apparatus of claim 1 wherein:

the stator comprises a core including front and back side-faces and a generally cylindrical outer peripheral surface with a predetermined number of slots formed therein, the stator winding is wound around the core, such that with respect to at least one end face, the winding passes through a first slot, forms an end turn extending outwardly beyond the core side face, providing a space between the end turn and end face, then passing back through another slot, whereby dissipation of heat generated in the winding is facilitated.

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