US007919894B2

(12) **United States Patent**
Dooley

(10) **Patent No.: US 7,919,894 B2**
(45) **Date of Patent: *Apr. 5, 2011**

(54) **ARCHITECTURE FOR ELECTRIC MACHINE**

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(73) Assignee: **Pratt & Whitney Canada Corp.**, Longueuil (CA)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **12/717,986**

(22) Filed: **Mar. 5, 2010**

(65) **Prior Publication Data**

US 2010/0148622 A1 Jun. 17, 2010

Related U.S. Application Data

(63) Continuation of application No. 12/509,636, filed on Jul. 27, 2009, now Pat. No. 7,709,980.

(51) **Int. Cl.**
H02K 3/00 (2006.01)

(52) **U.S. Cl.** **310/201**

(58) **Field of Classification Search** .... 310/58, 310/59, 60 R, 60 A, 201, 206, 207
See application file for complete search history.

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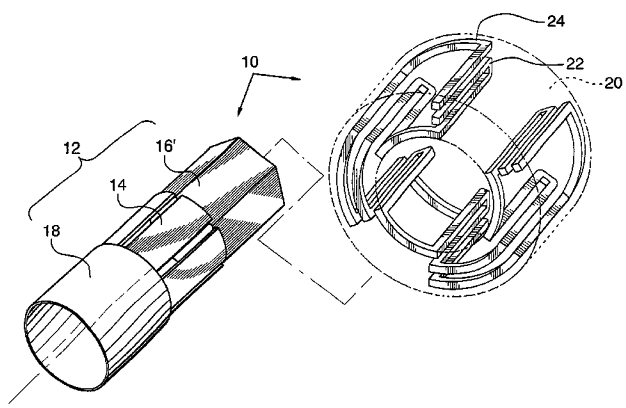
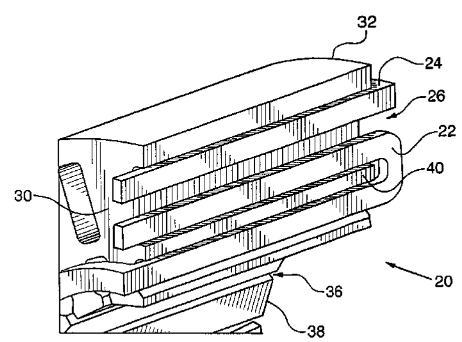
(74) *Attorney, Agent, or Firm* — Ogilvy Renault LLP

(57) **ABSTRACT**

The invention includes an electric machine having a rotor, stator and at least one winding in the stator adapted to conduct a current, and a secondary winding, electrically isolated from the first winding and inductively coupled to the first winding, which may be used to control at least one of the output voltage and current of the first winding.

2 Claims, 29 Drawing Sheets





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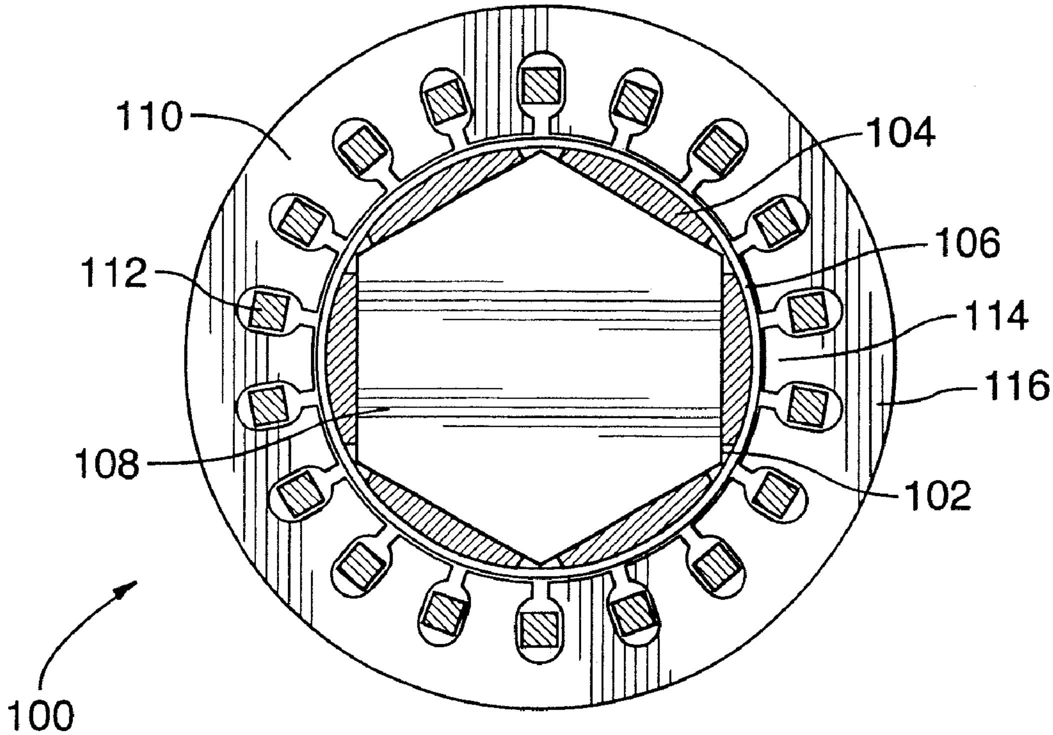

FIG.1A
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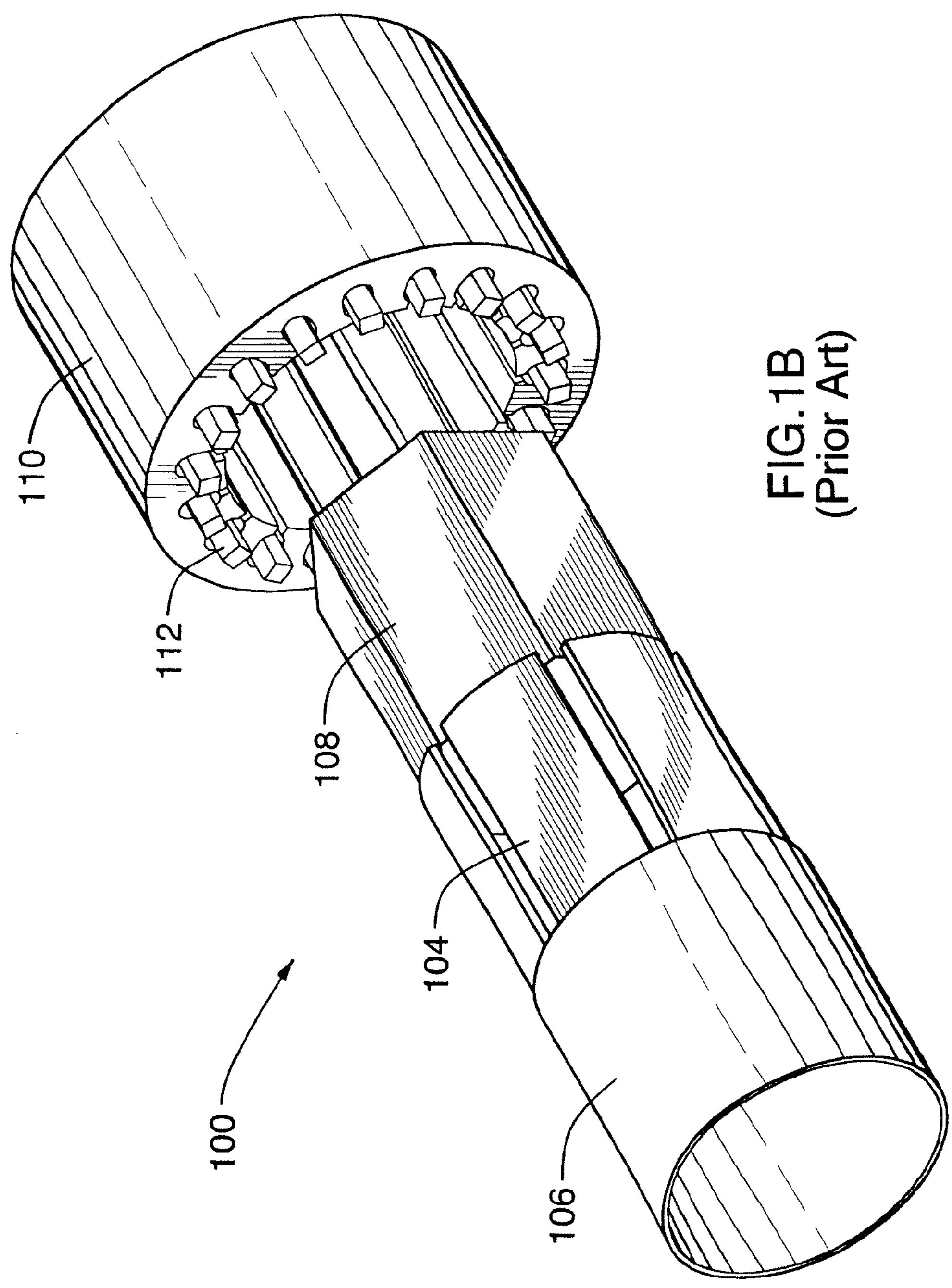

FIG.1B
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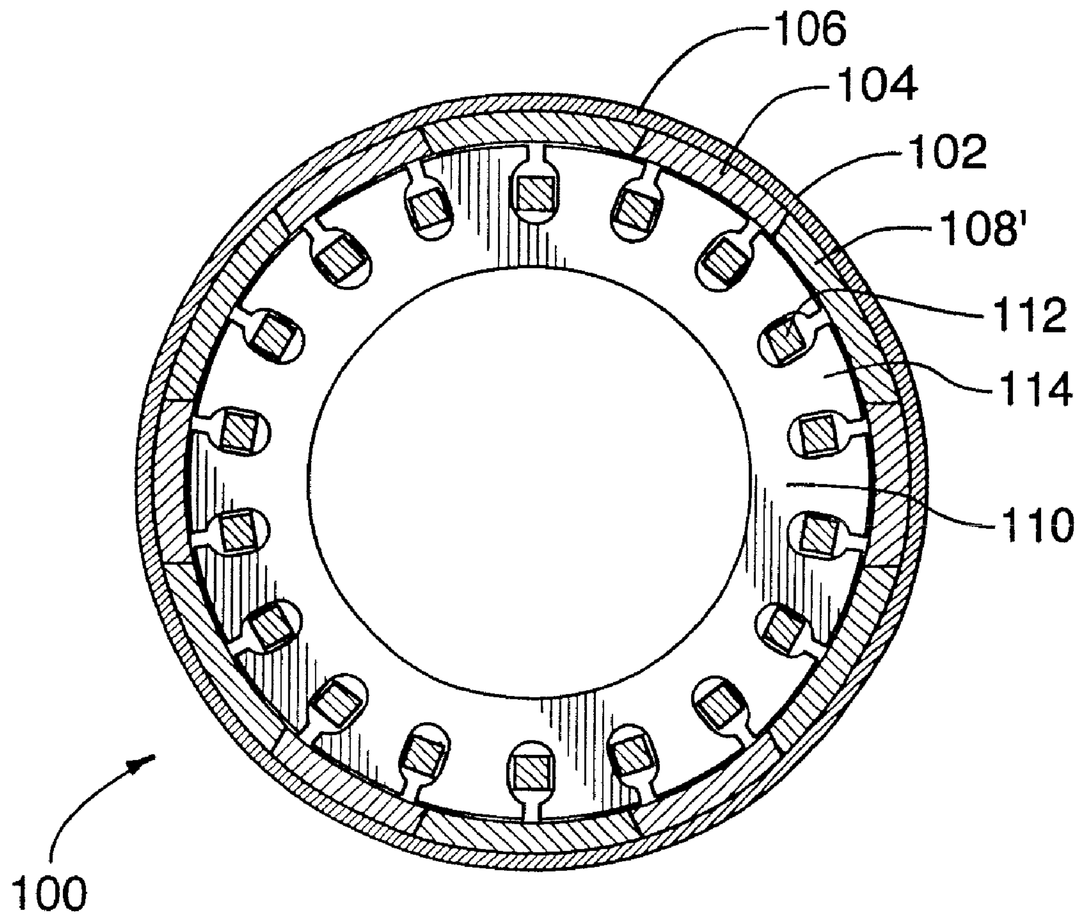

FIG.2A
(Prior Art)

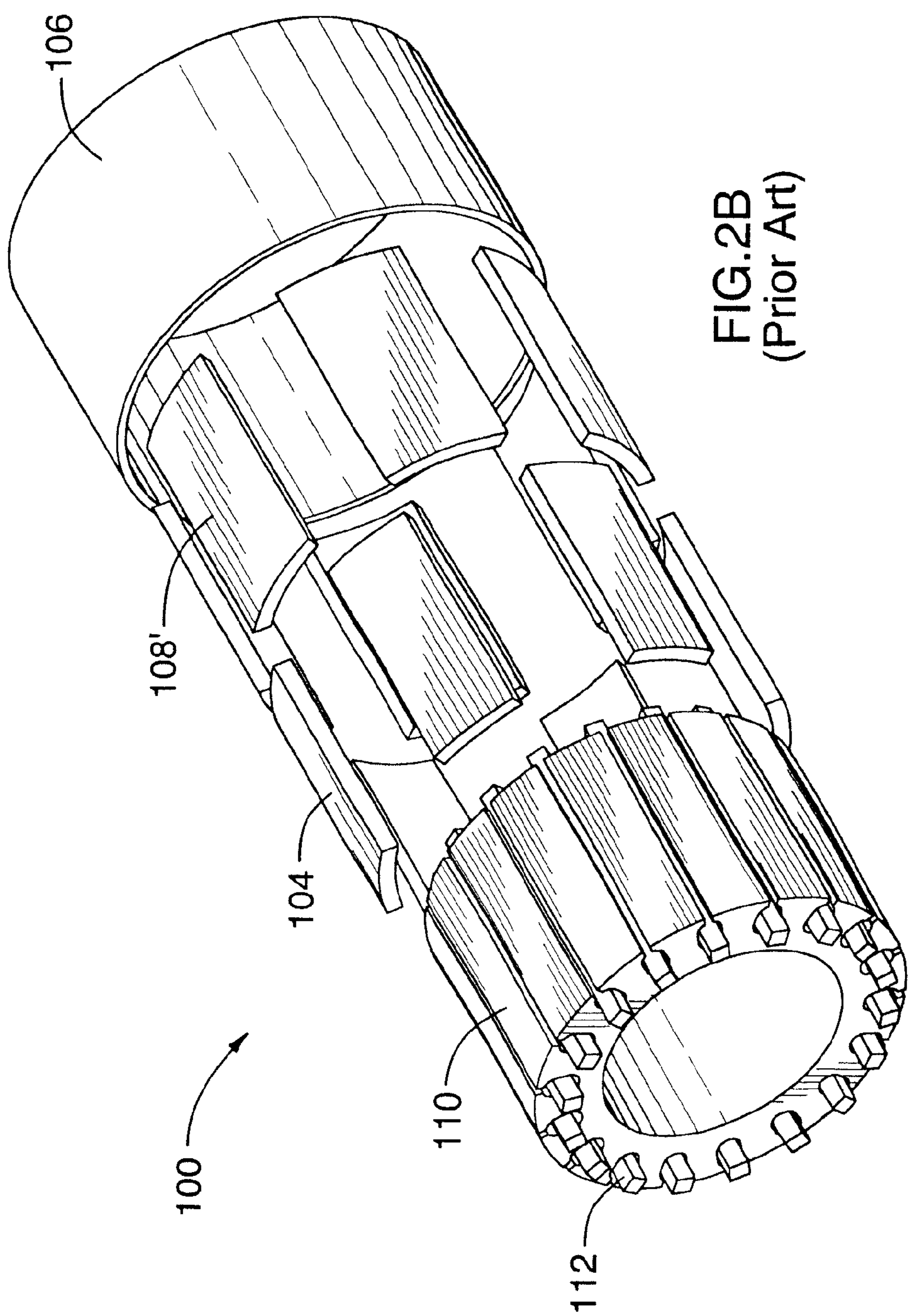

FIG.2B
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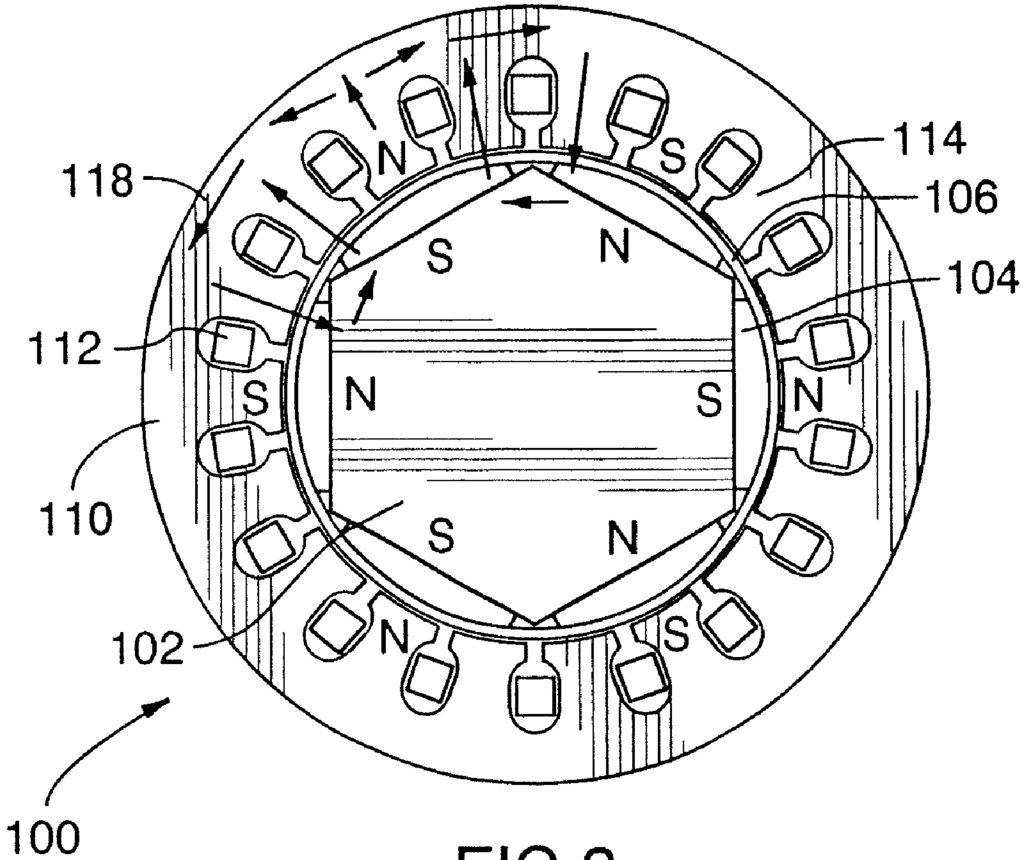

FIG.3
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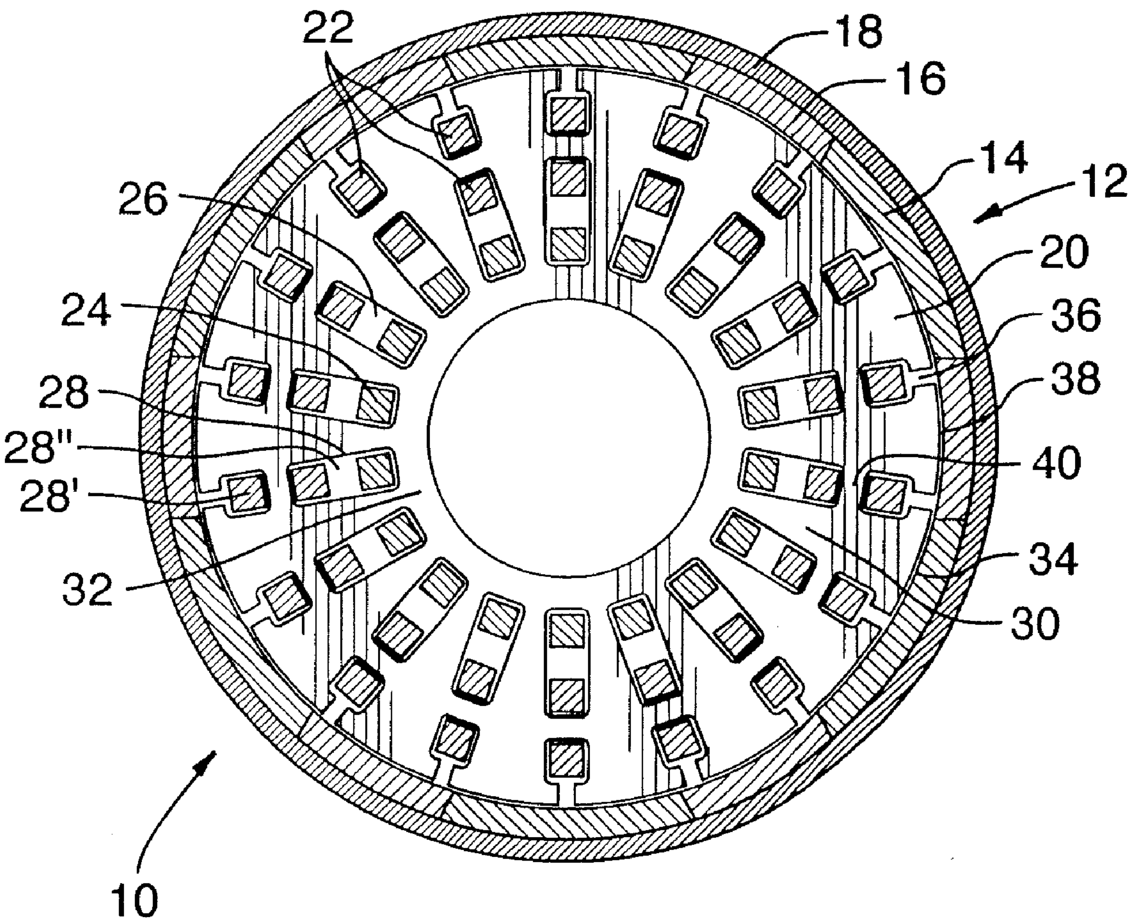


FIG.4A

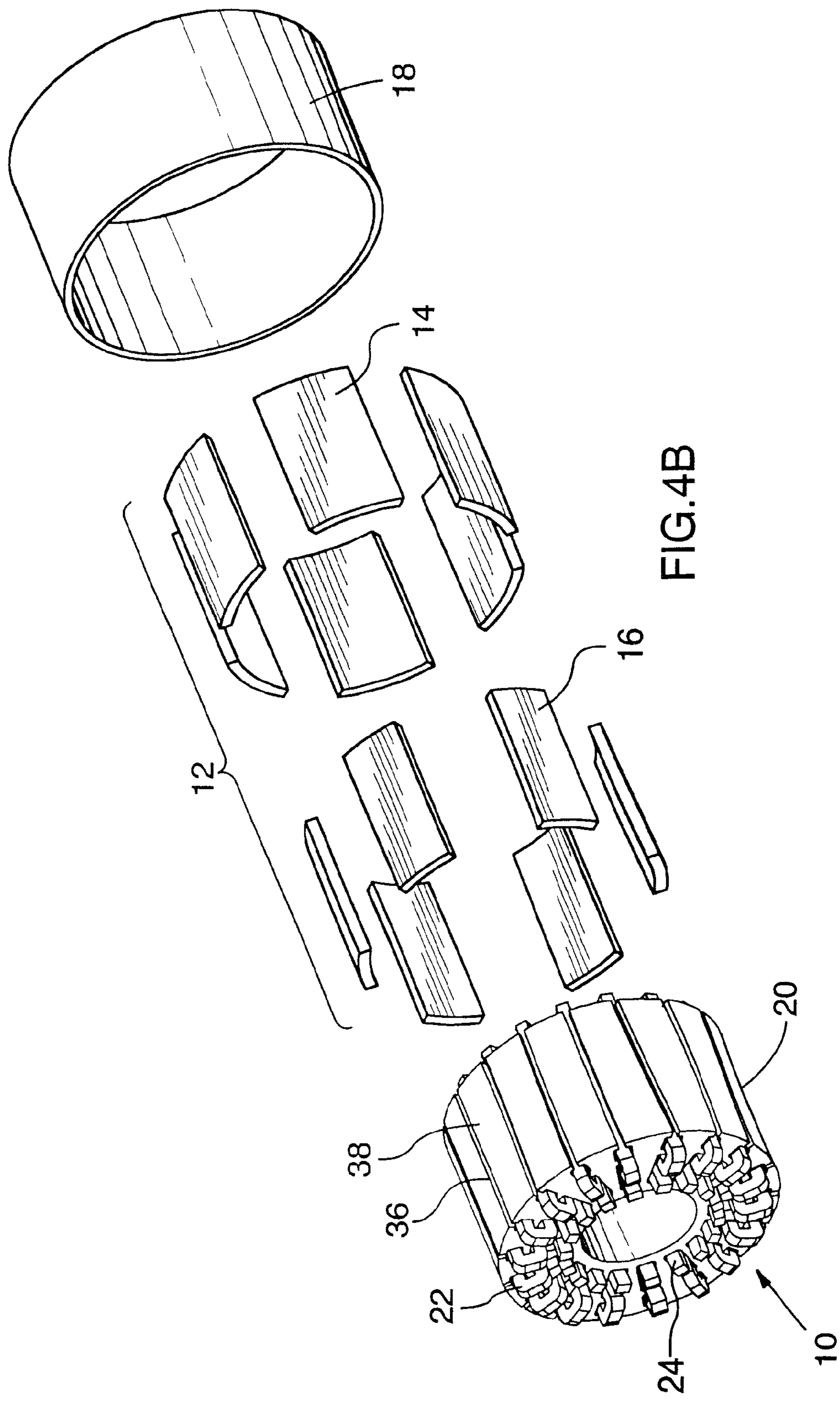


FIG.4B

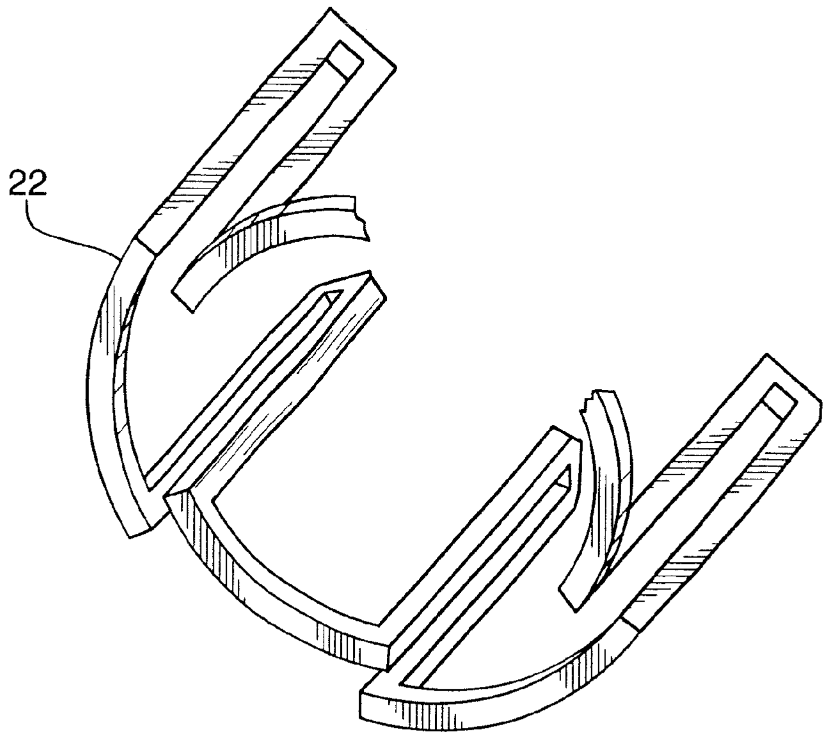


FIG.4C

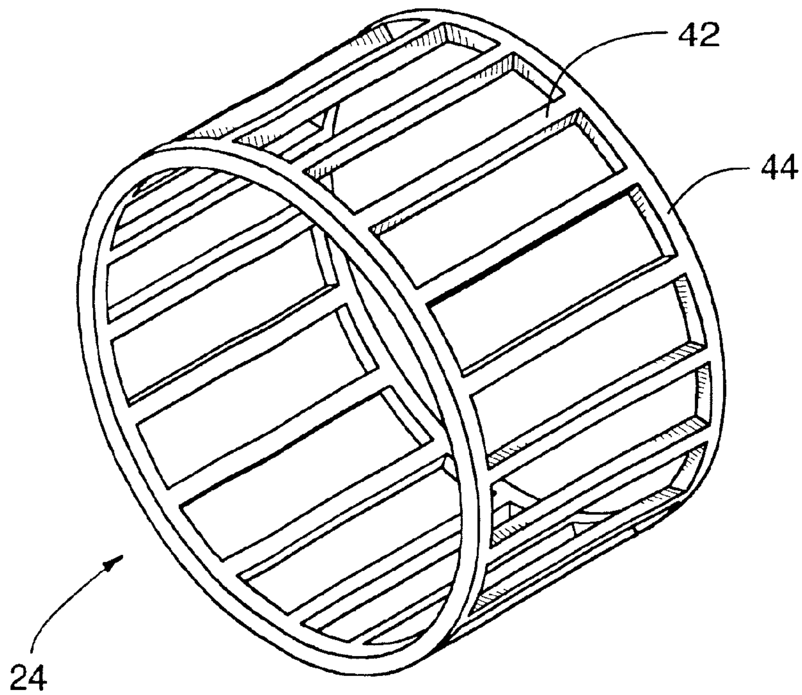
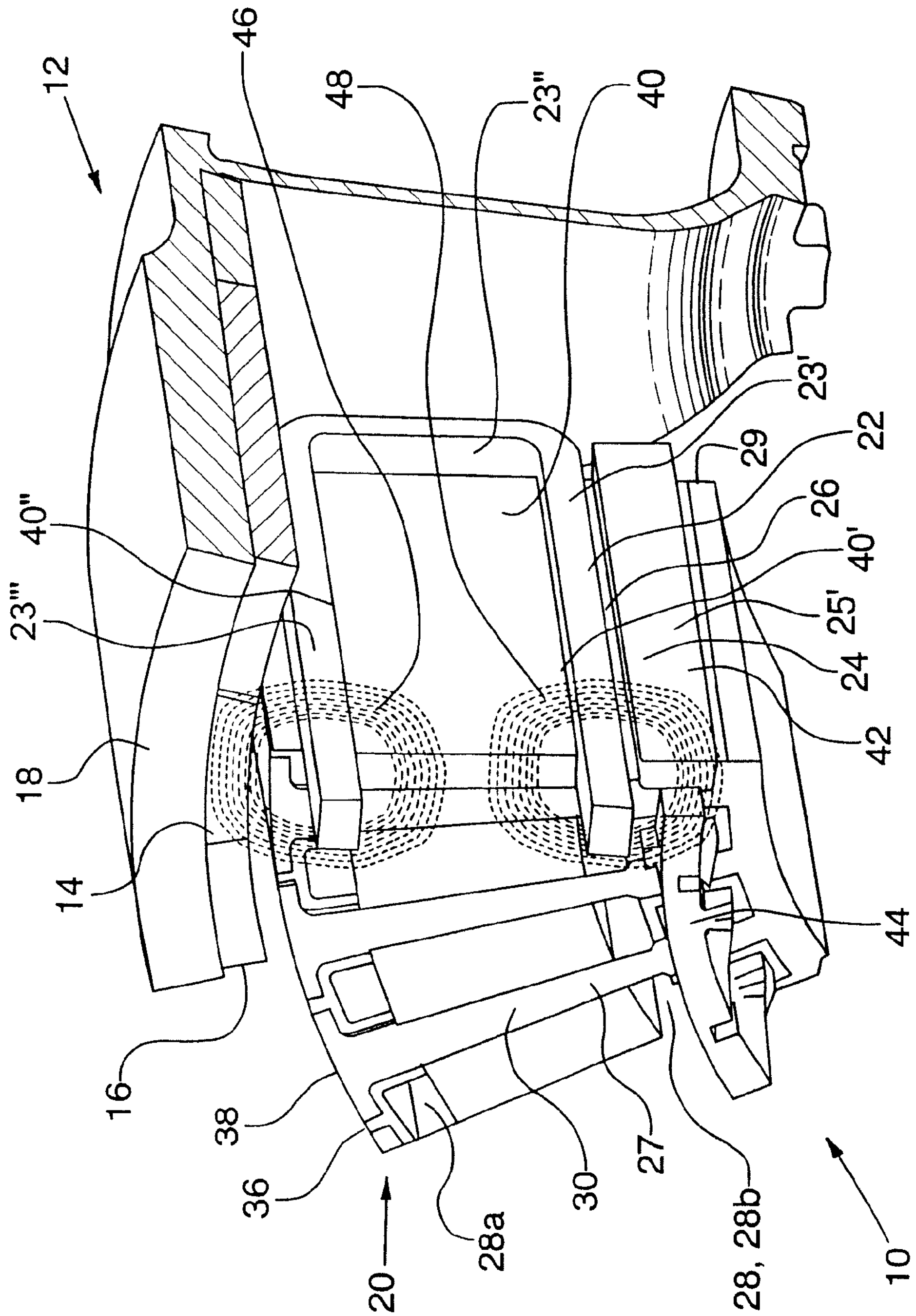


FIG.4D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23'
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40'
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44
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28, 28b
27
30
28a
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36
38
16
14
18
23'''
40"

FIG.4E

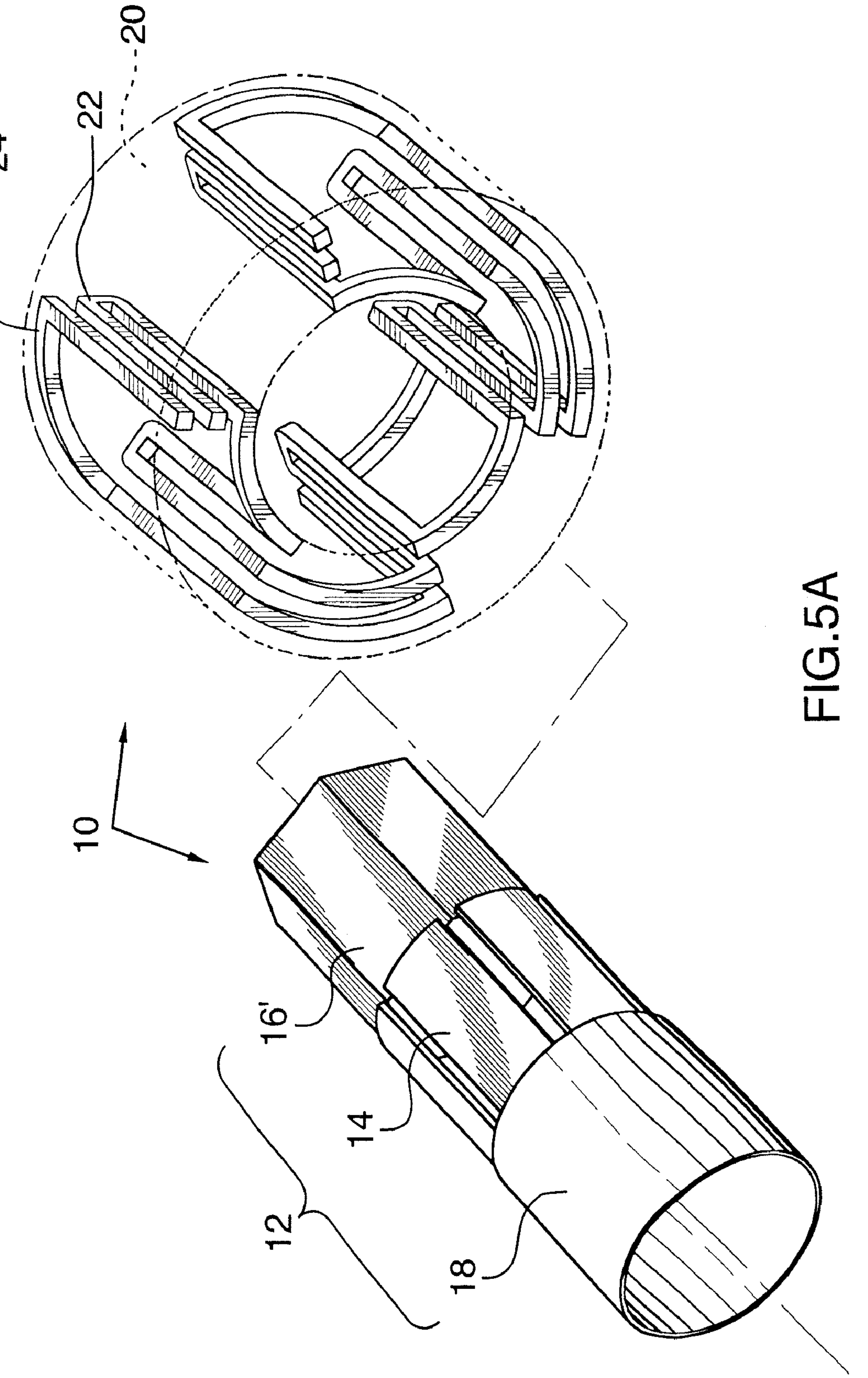


FIG.5A

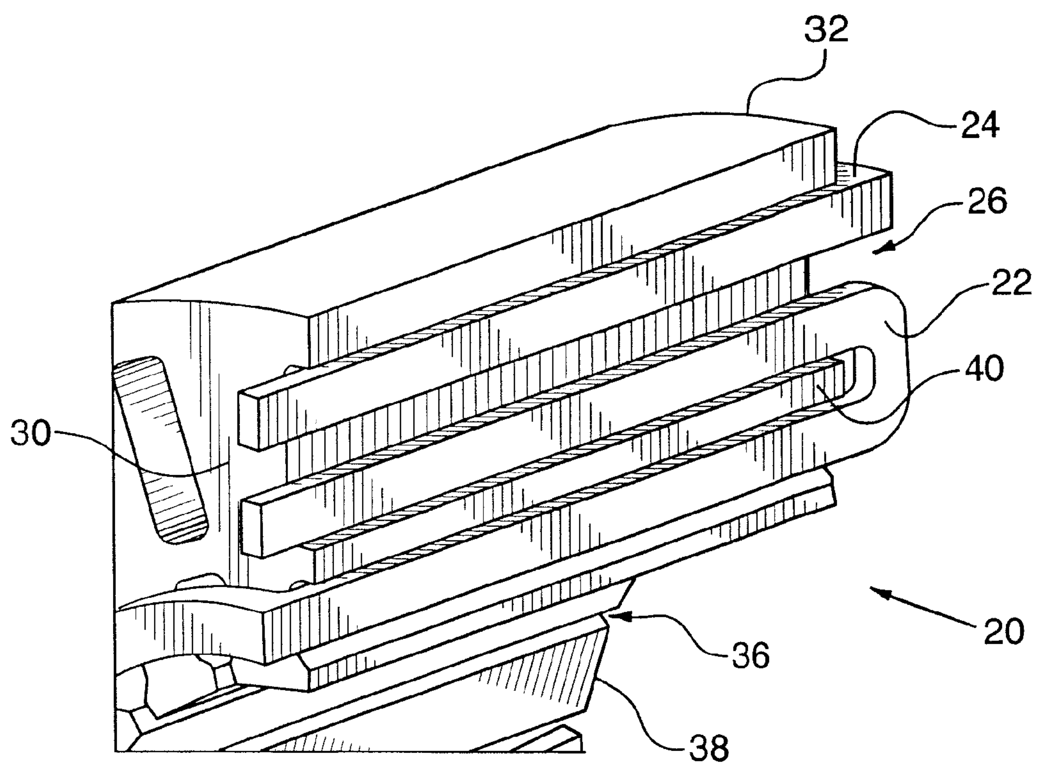


FIG. 5B

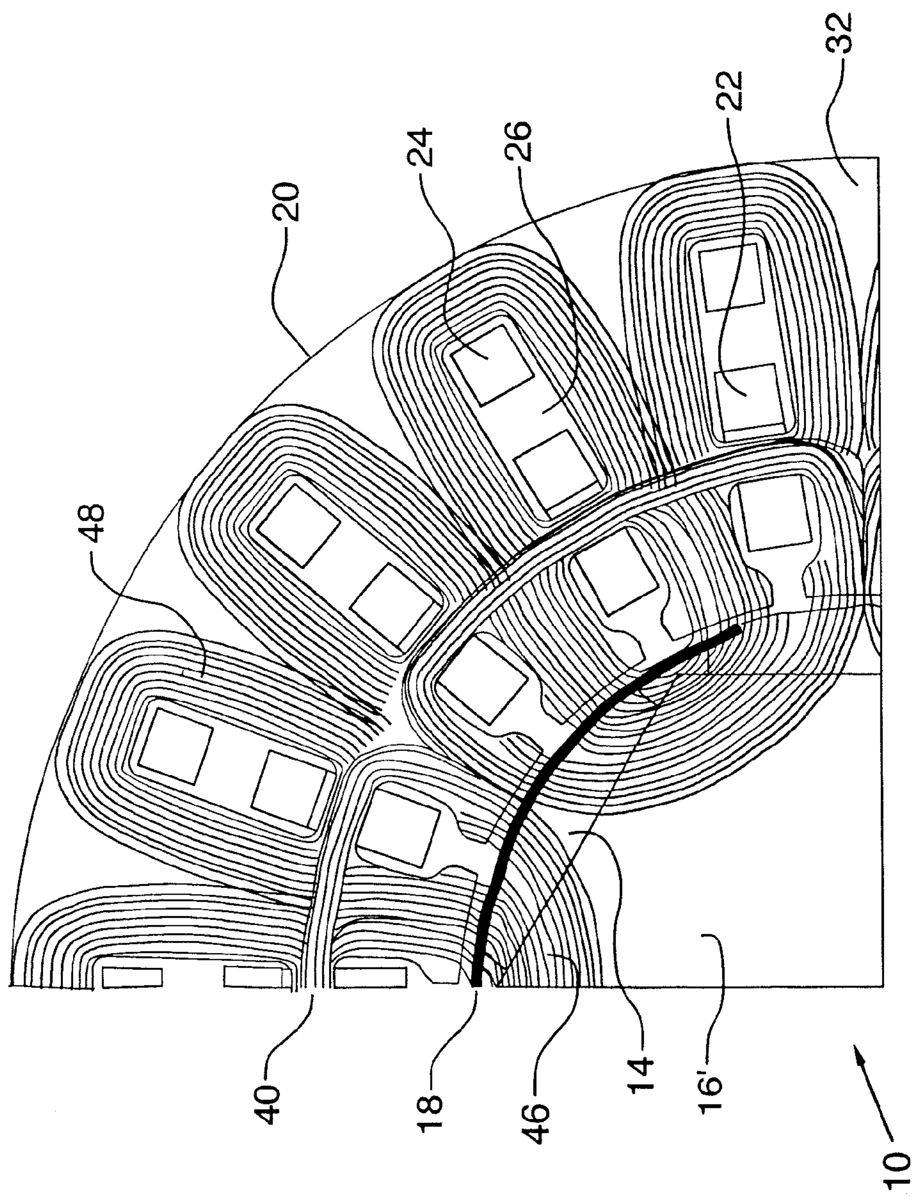


FIG.5C

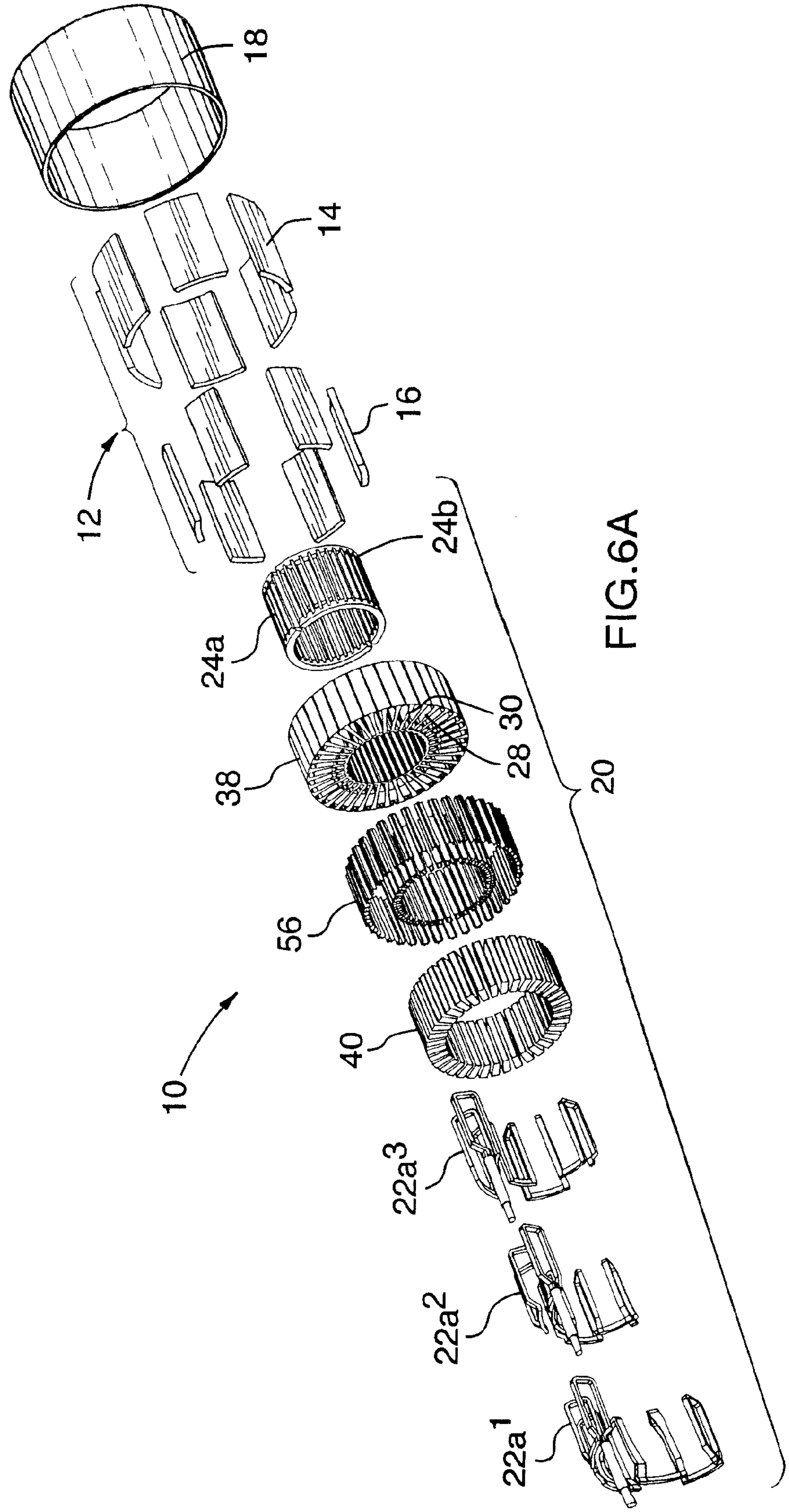
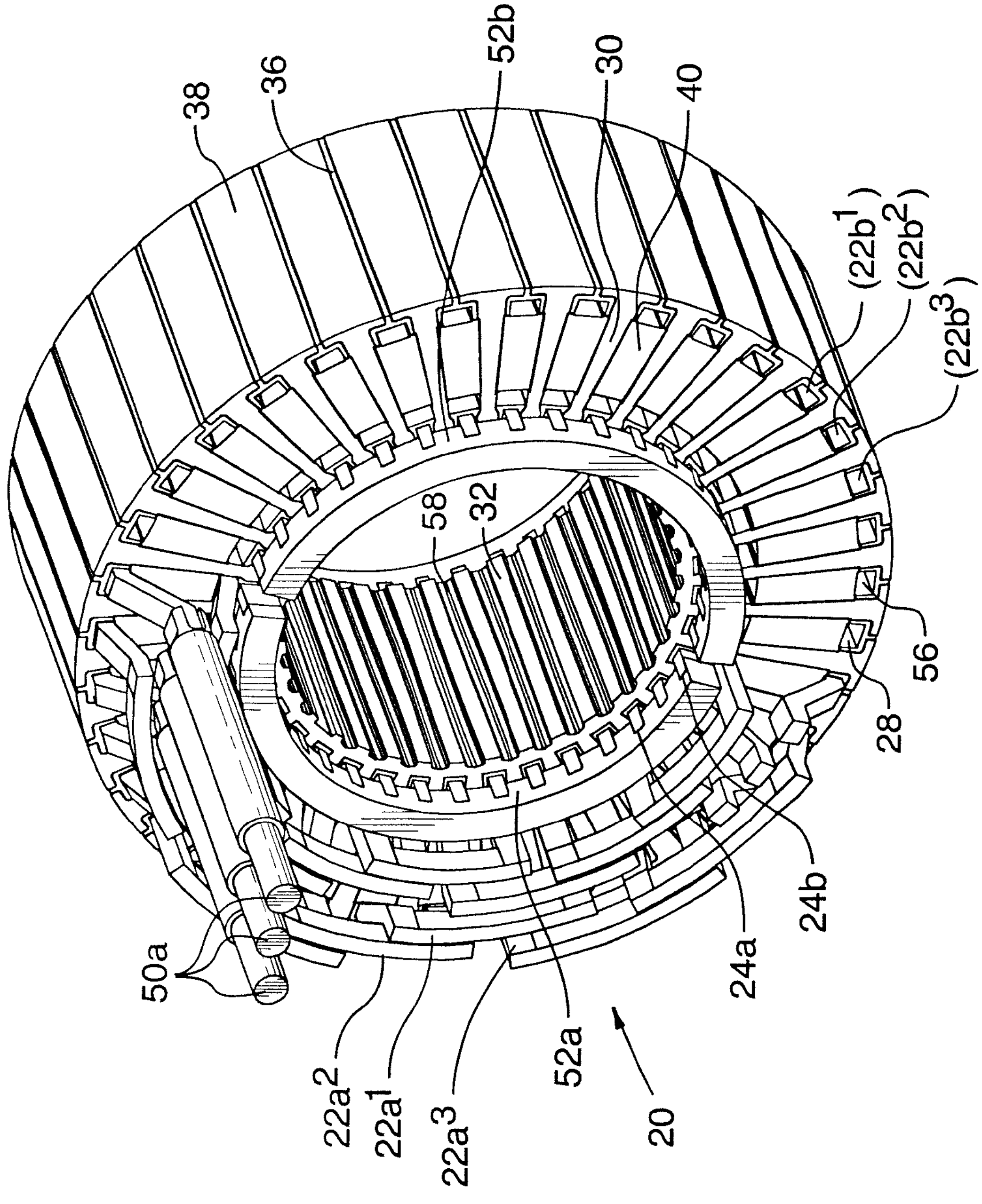


FIG.6A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(22b2)
(22b3)
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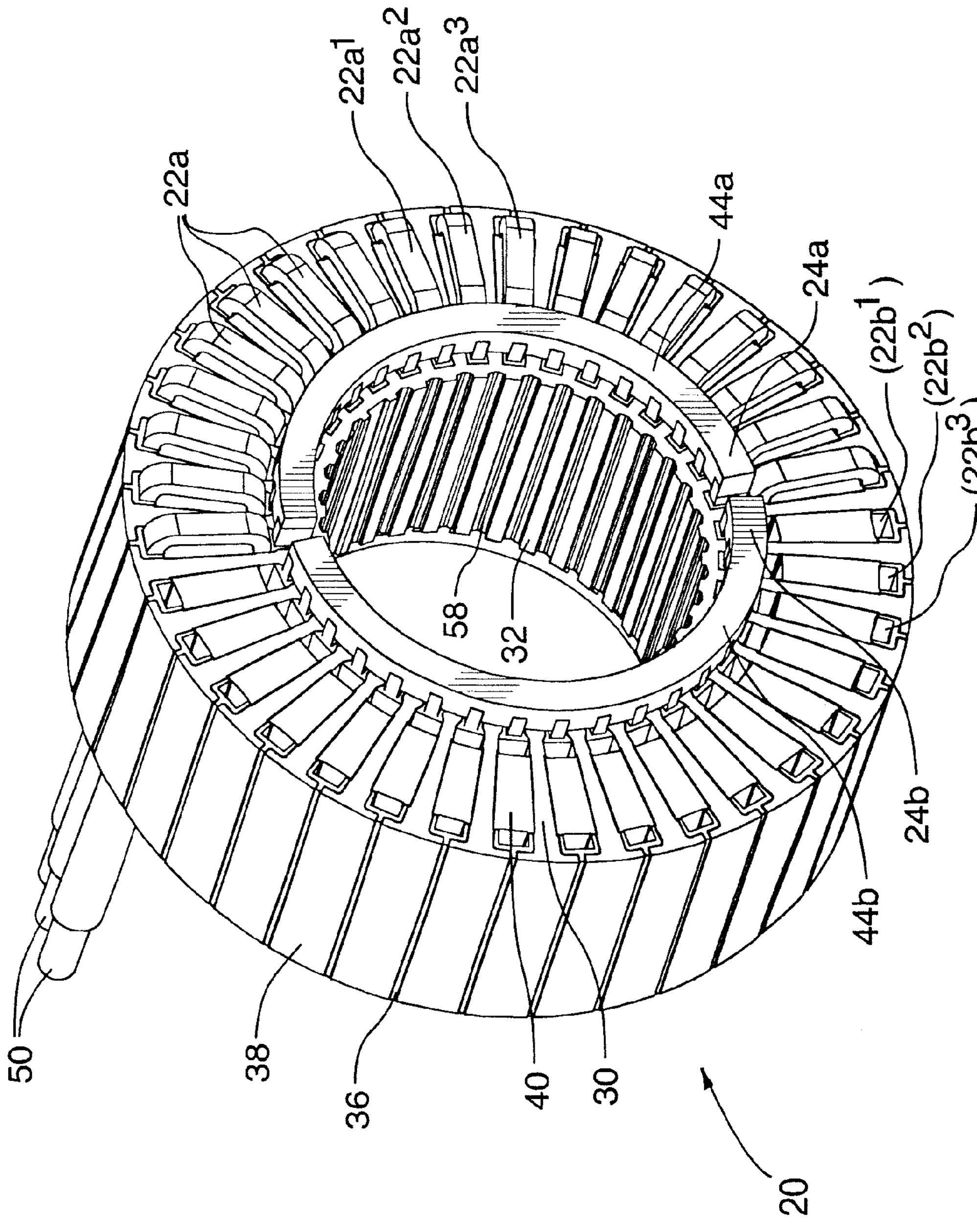
22a2
22a1
22a3
20

FIG.6B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44b
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FIG.6C

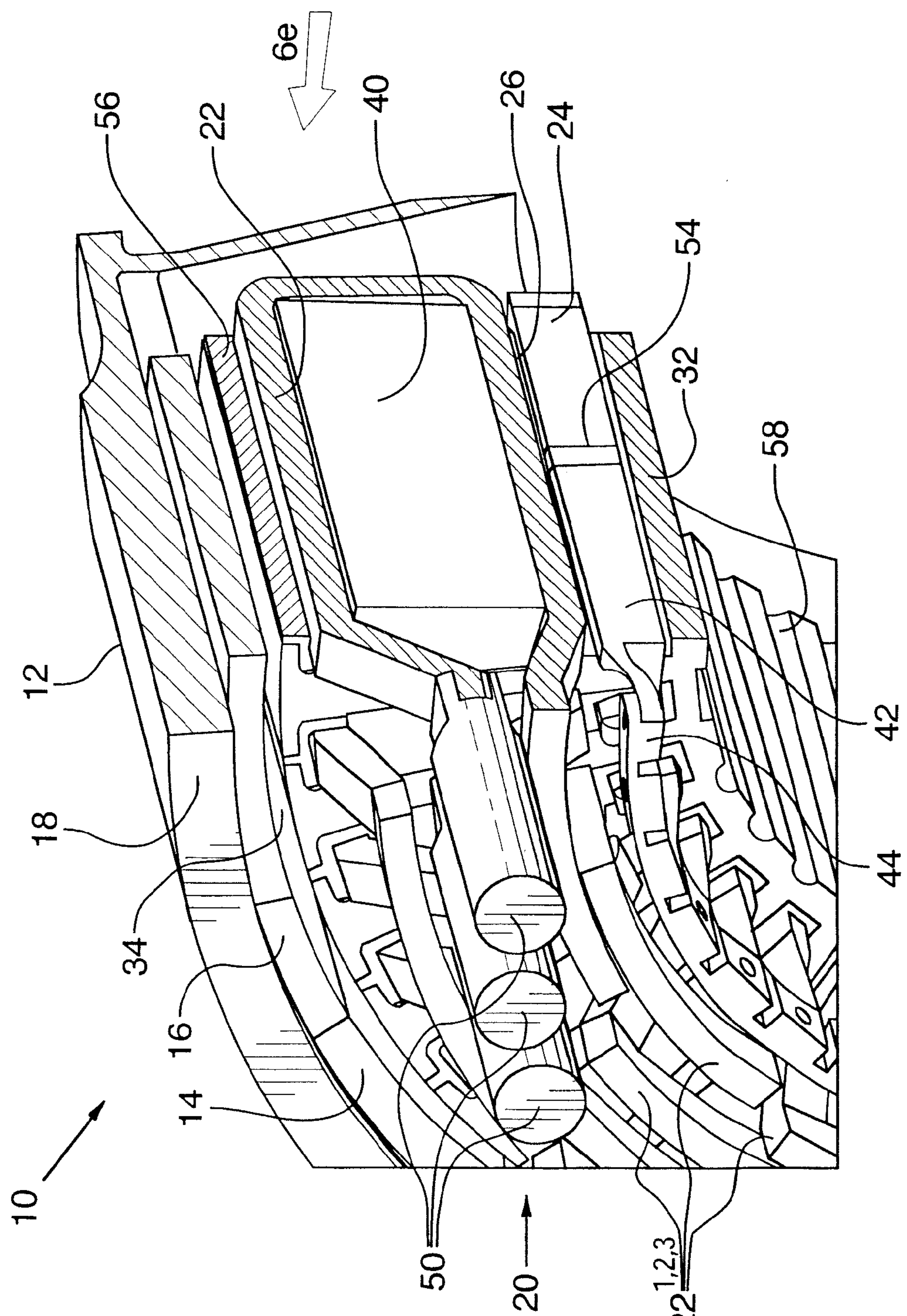
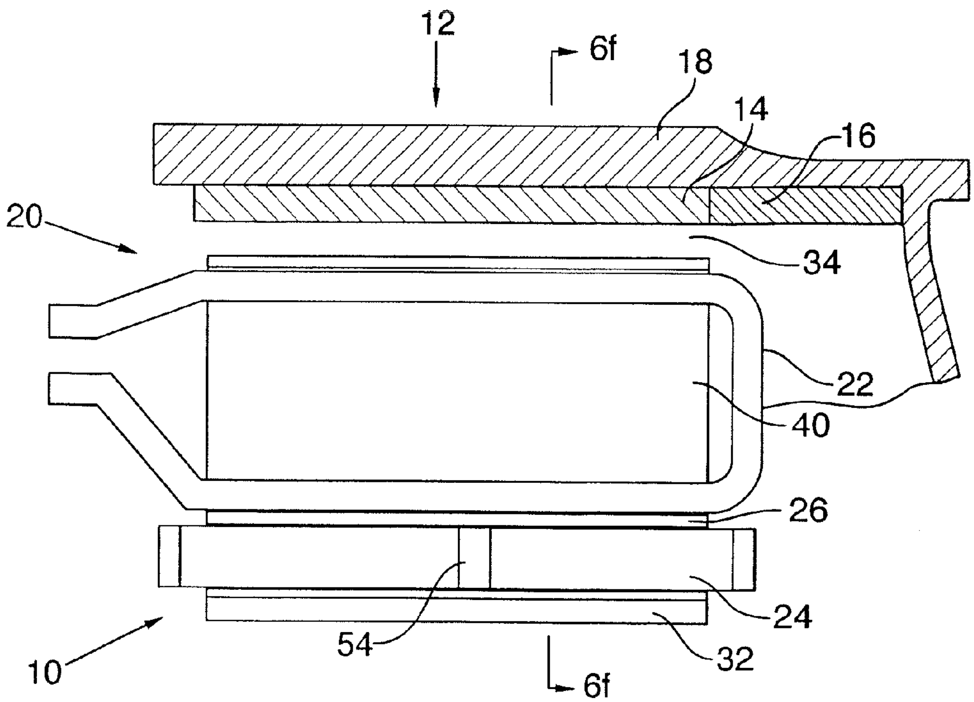


FIG.6D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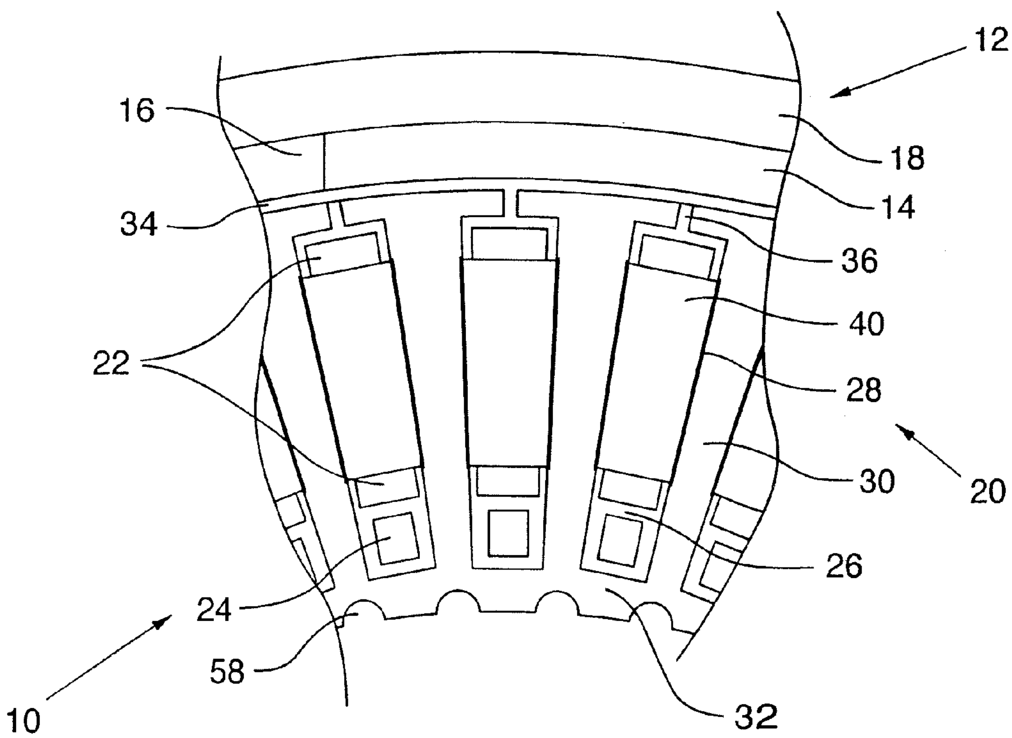
32
6f

FIG.6E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32

FIG.6F

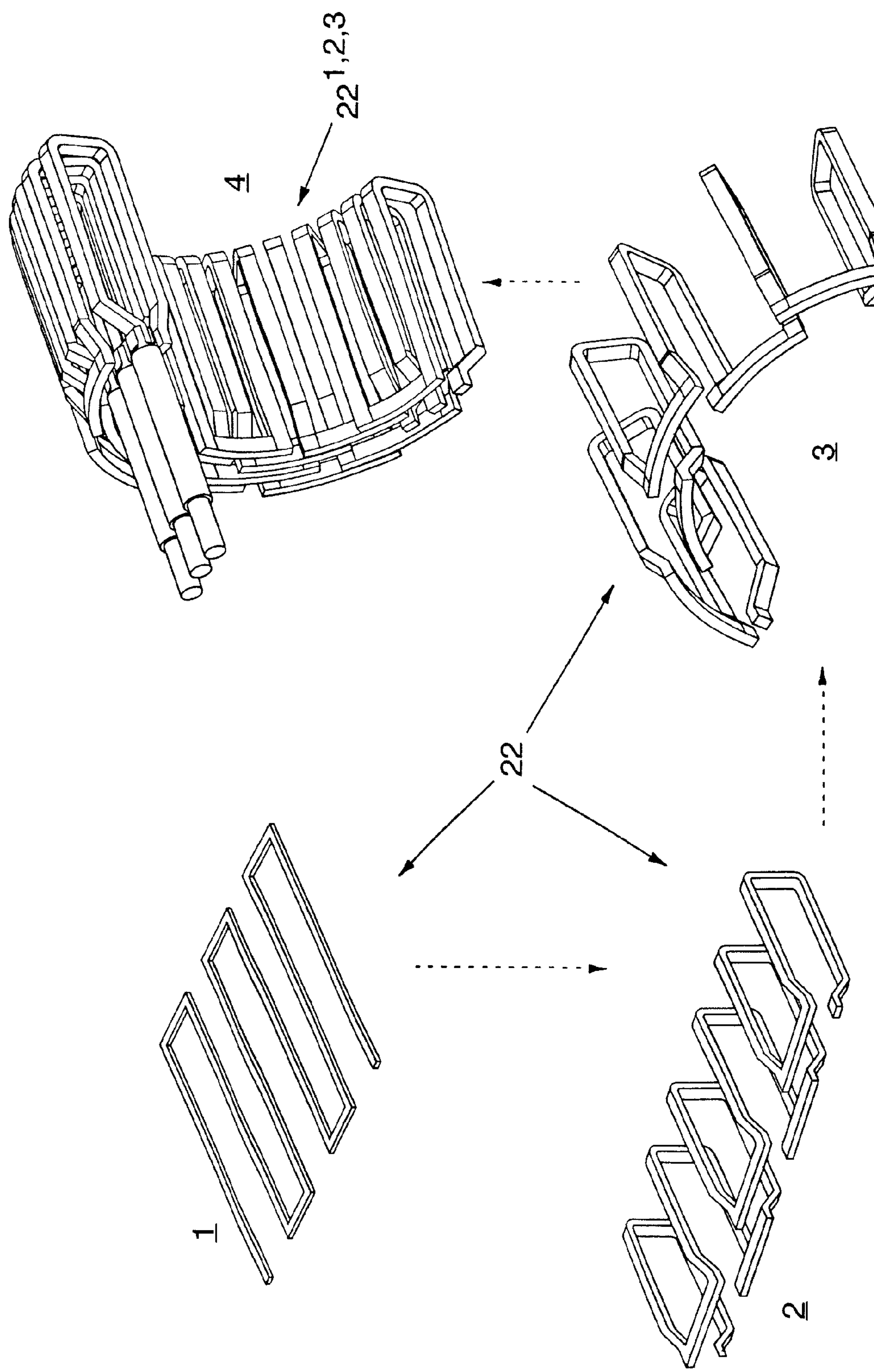


FIG.7A

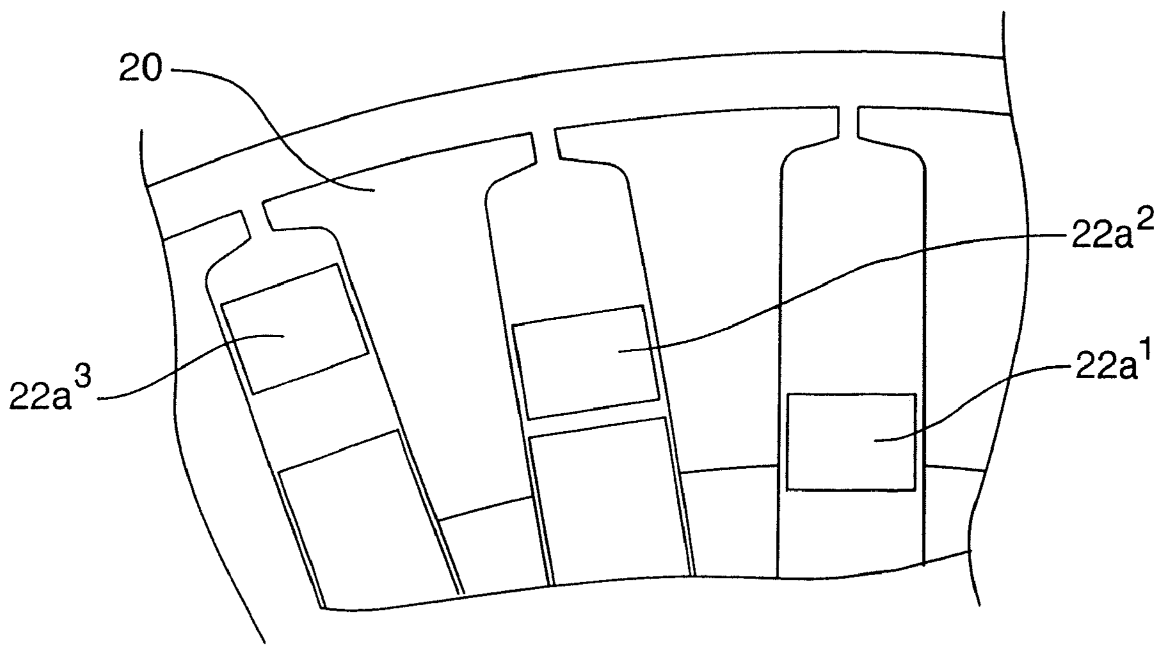


FIG.7B

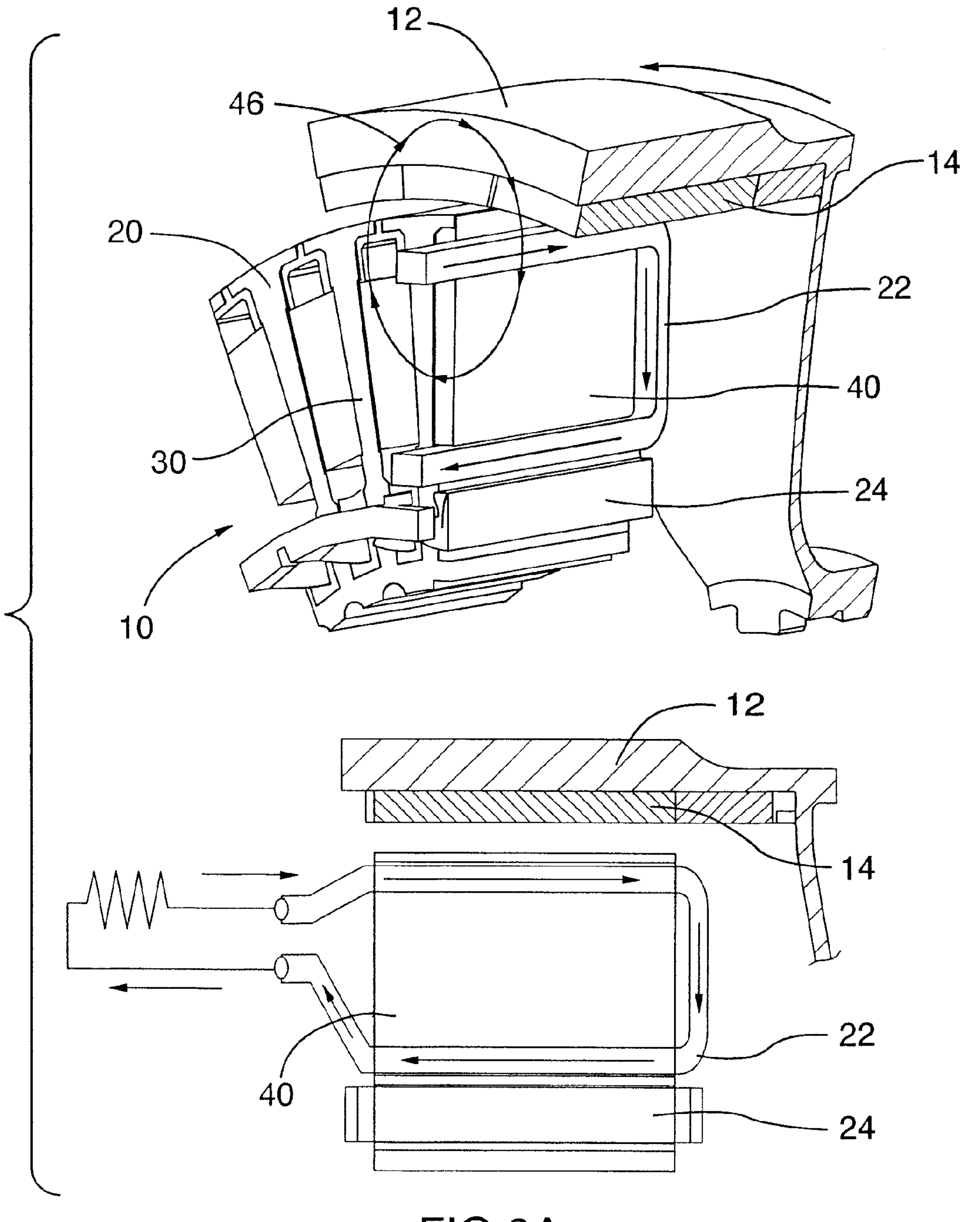


FIG.8A

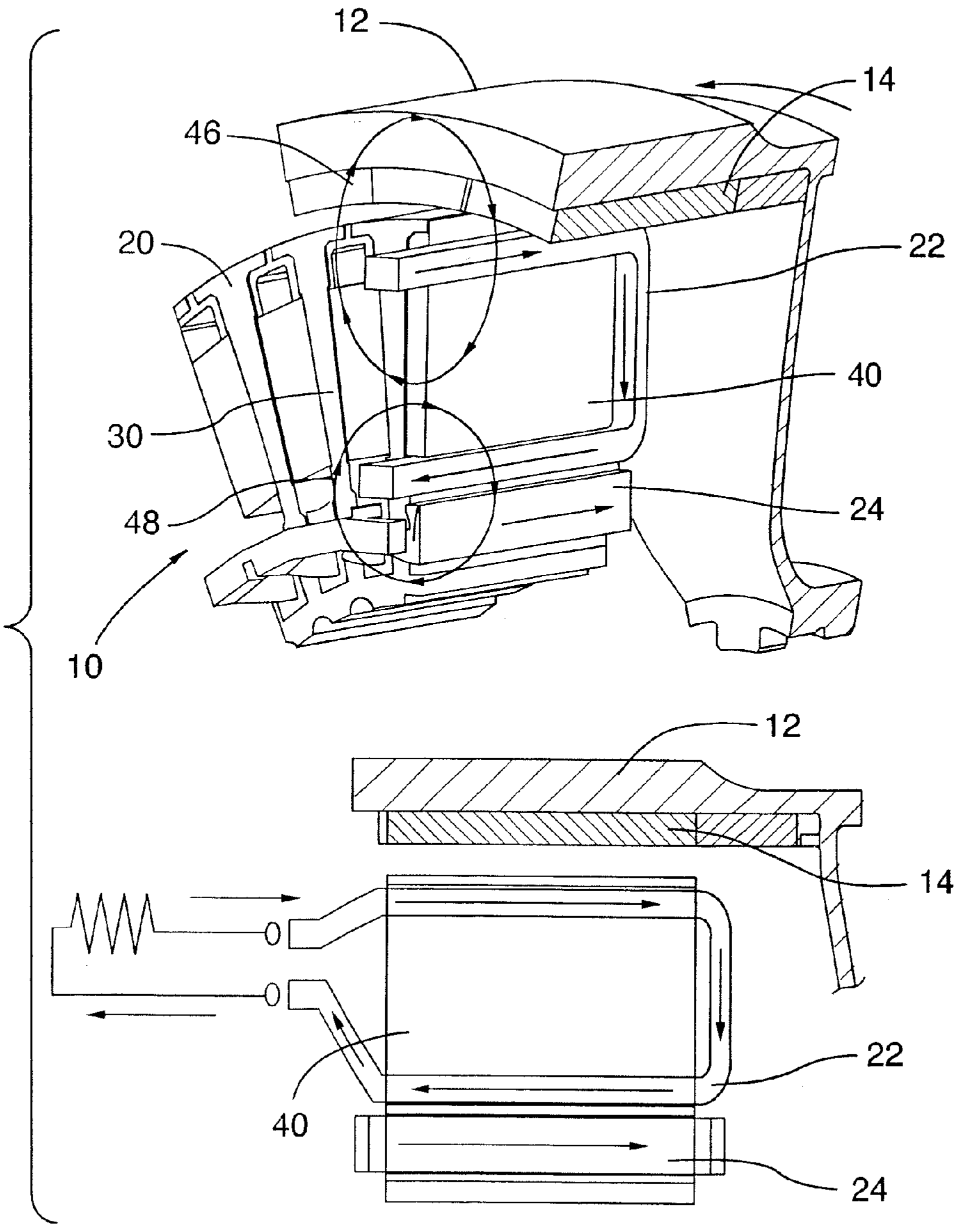


FIG.8B

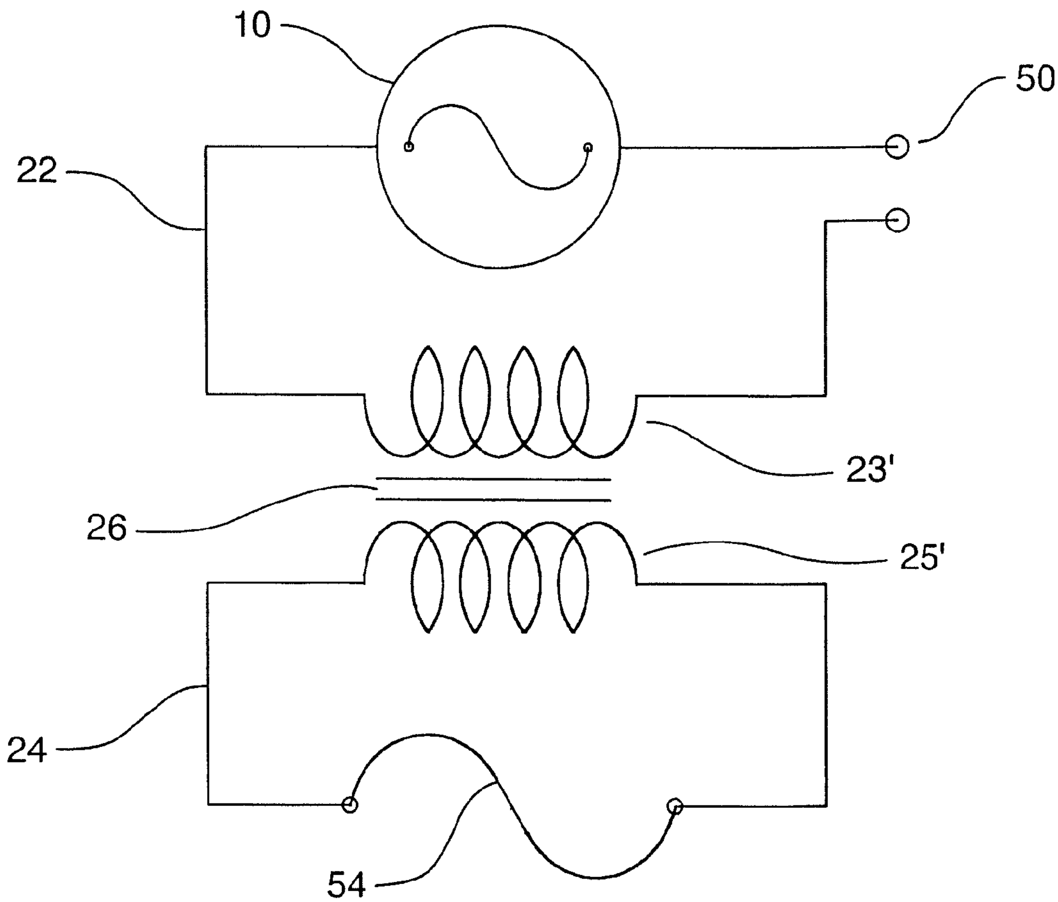


FIG.9

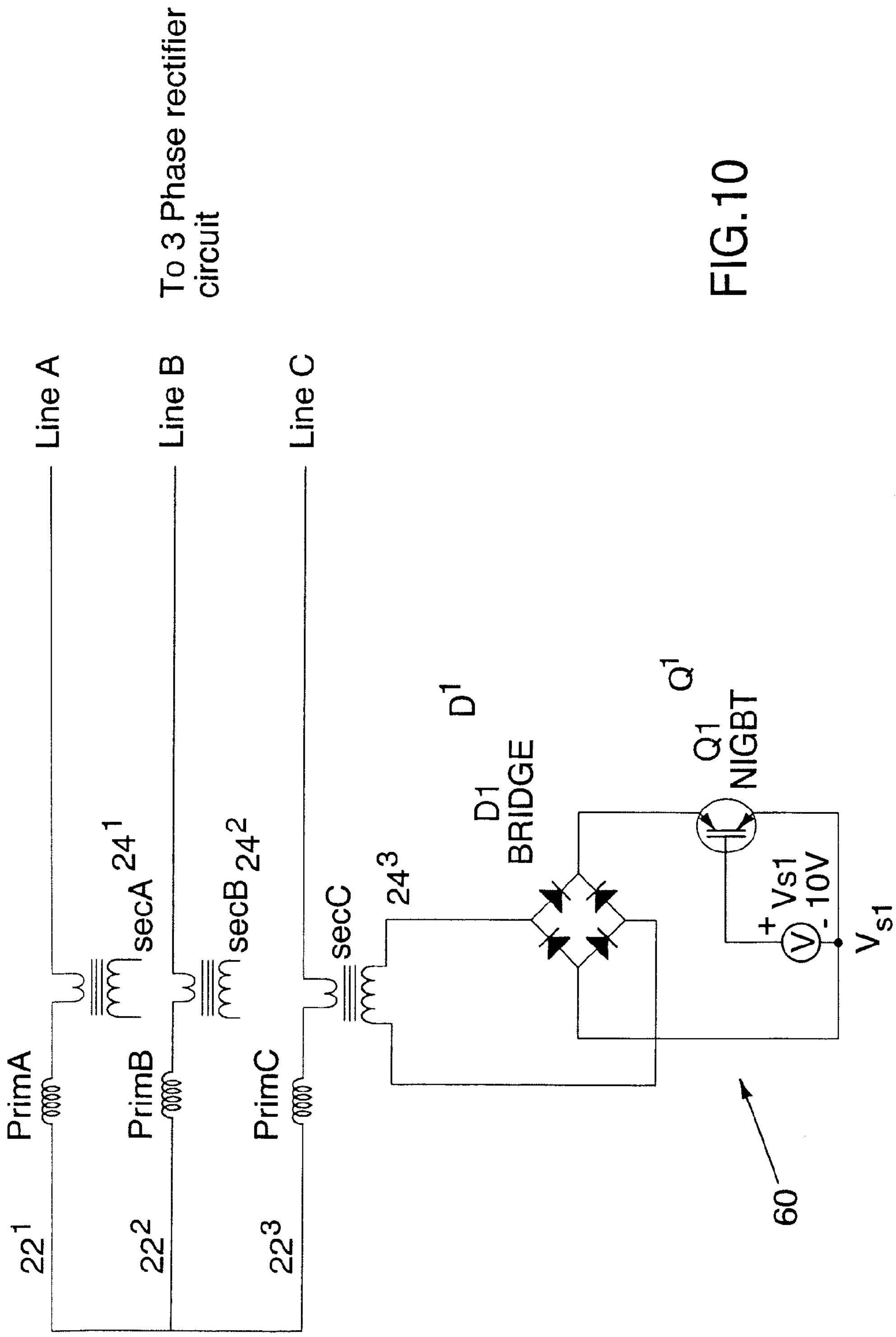

To 3 Phase rectifier circuit
Line A
Line B
Line C
PrimA
PrimB
PrimC
22^1
22^2
22^3
secA
secB
secC
24^1
24^2
24^3
D1
BRIDGE
D^1
Q1
NIGBT
Q^1
+ Vs1
- 10V
V_{s1}
60

FIG.10

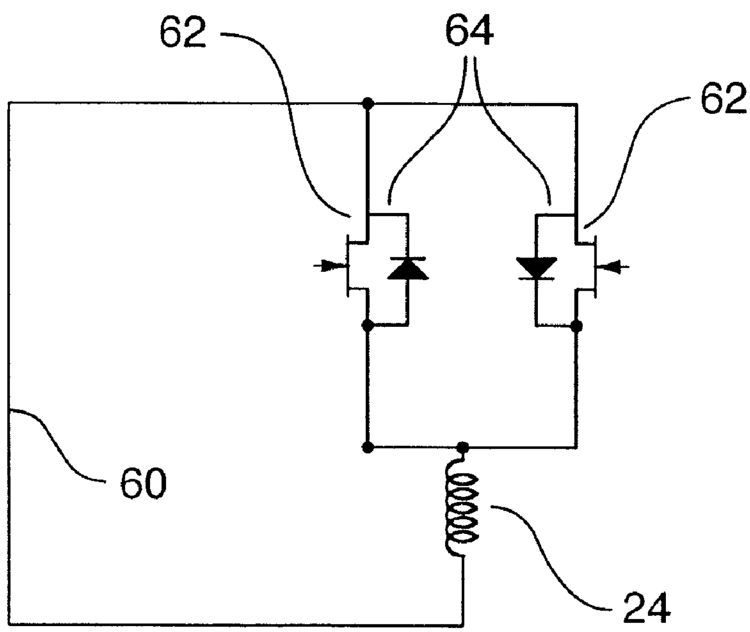


FIG.11A

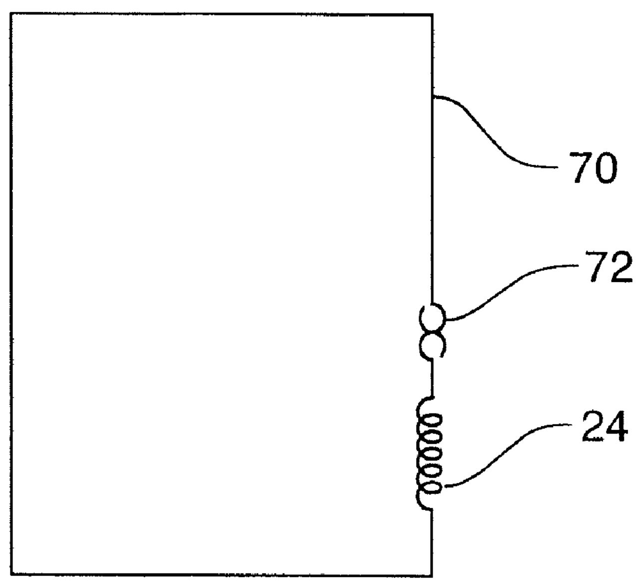


FIG.11B

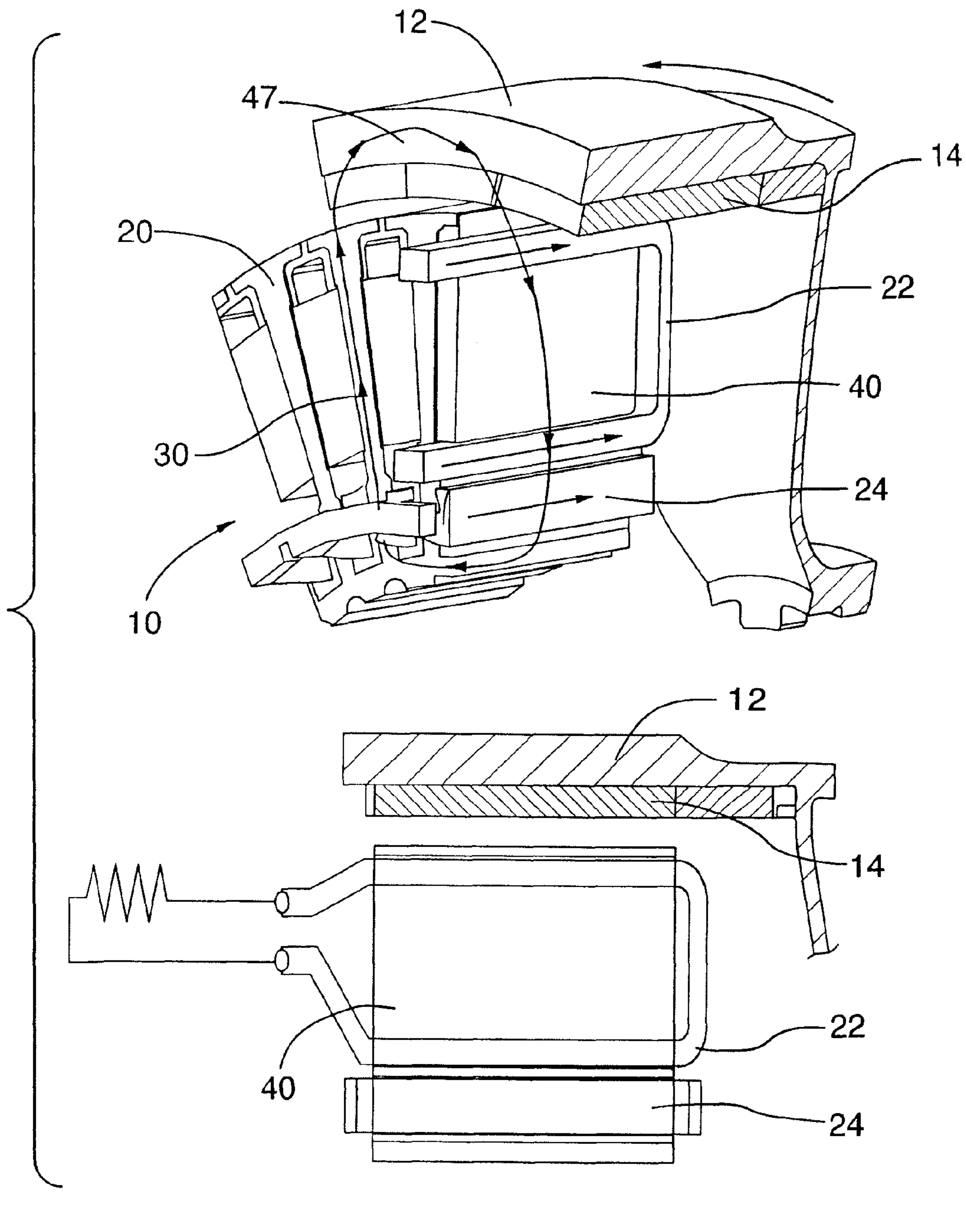


FIG.12A

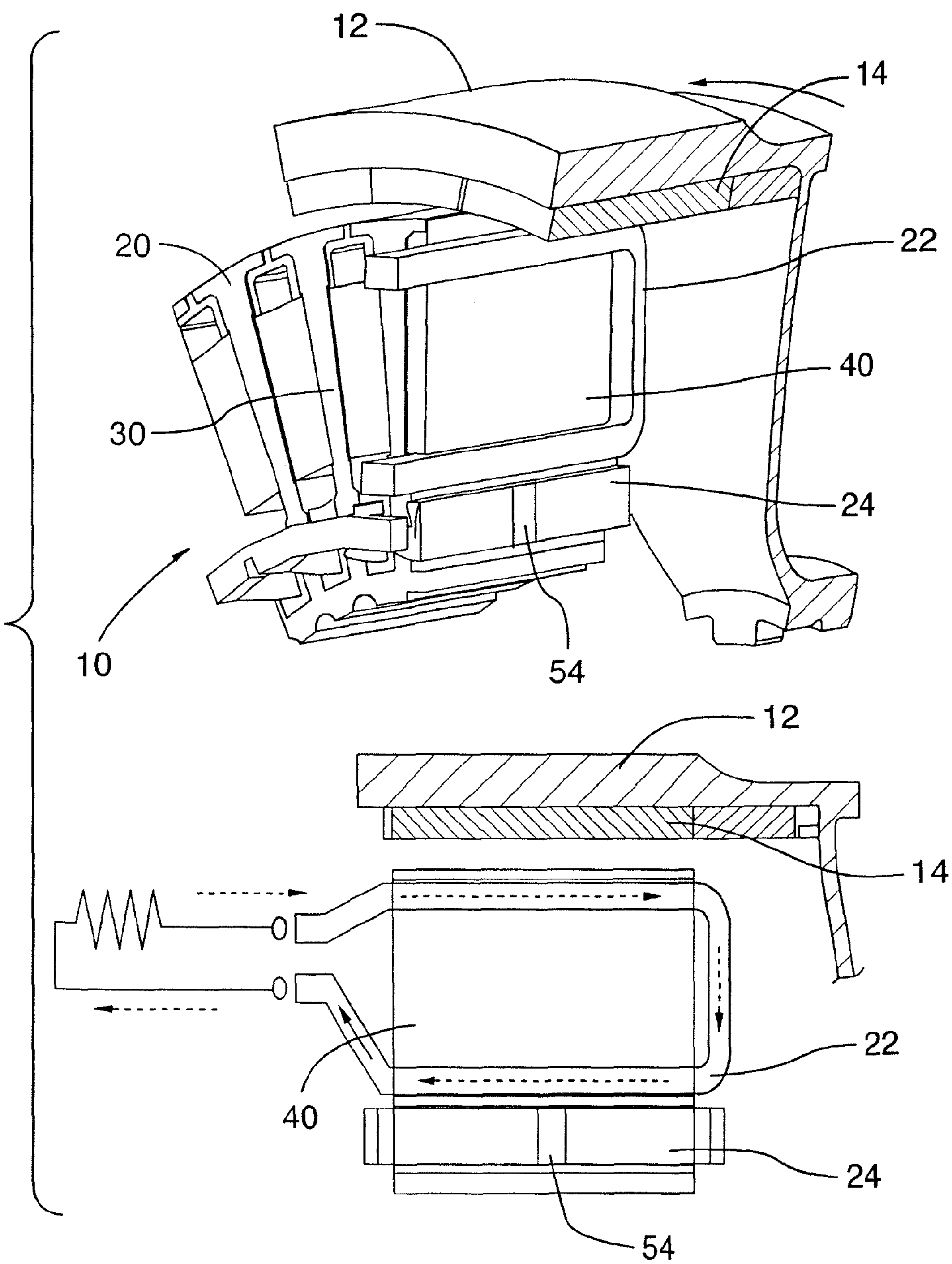


FIG.12B

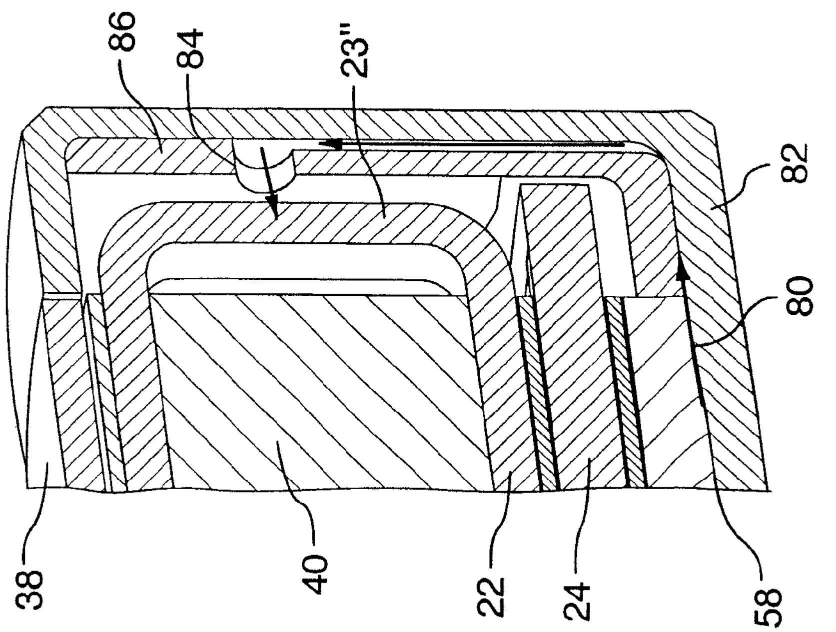


FIG.13B

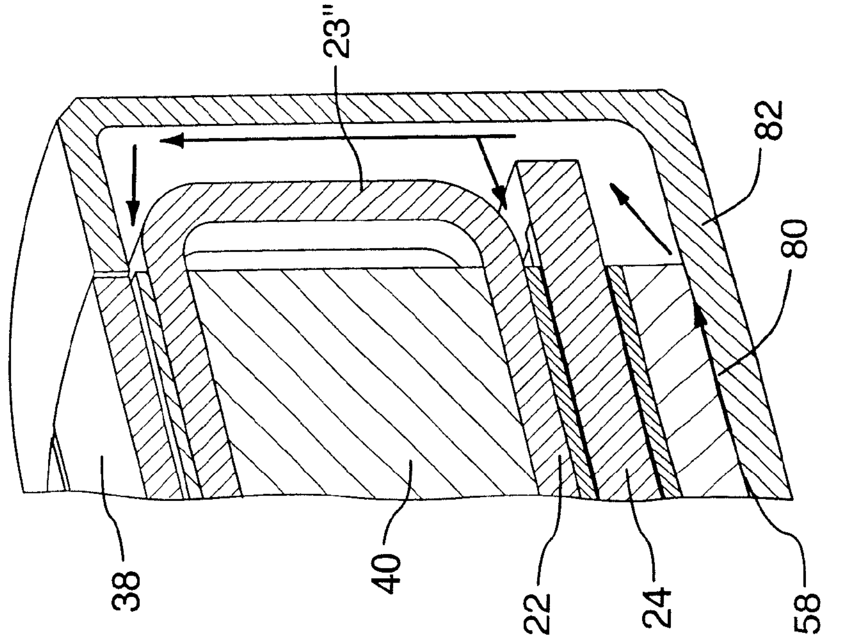
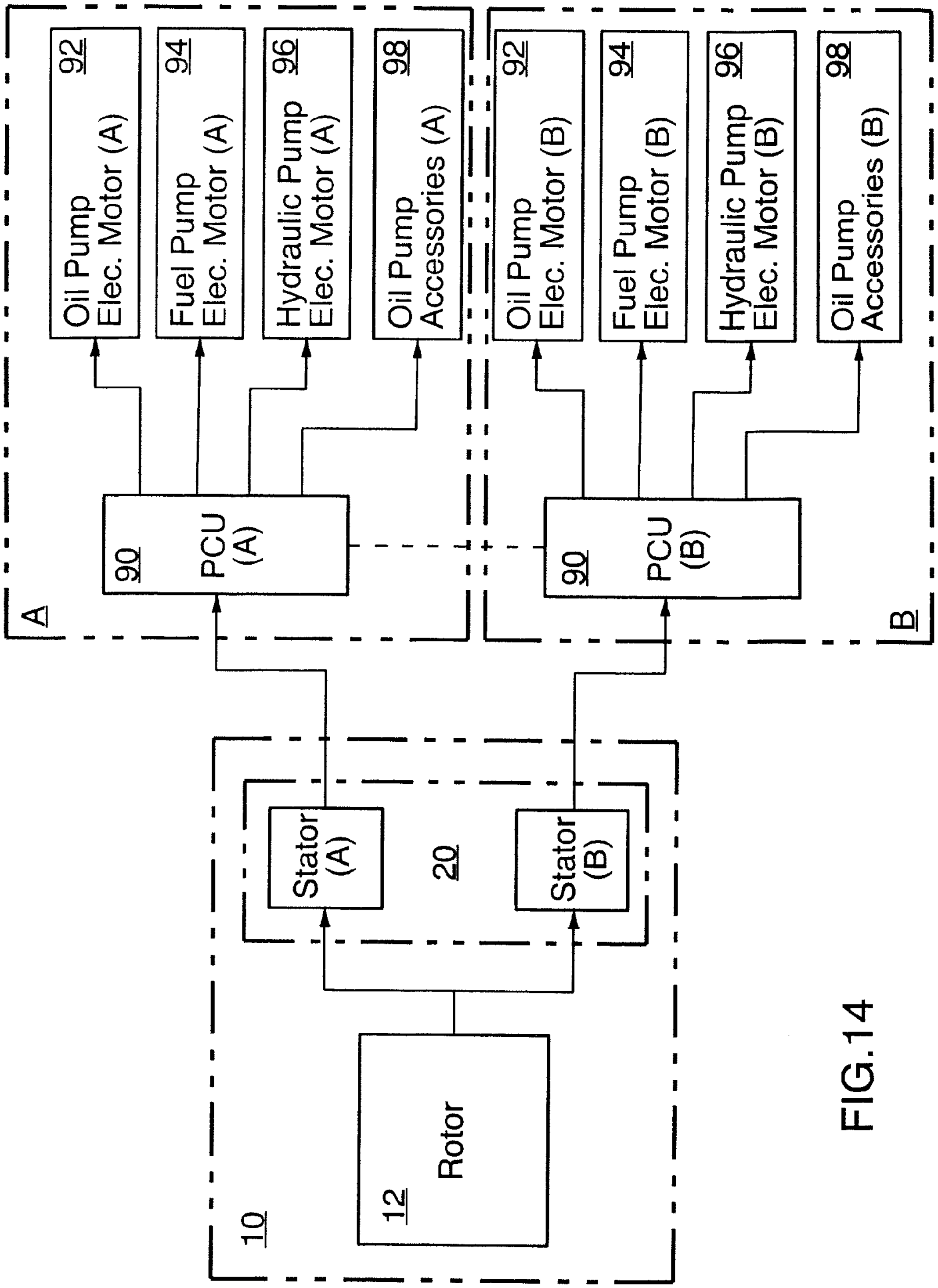


FIG.13A



A
90
PCU (A)
92
Oil Pump Elec. Motor (A)
94
Fuel Pump Elec. Motor (A)
96
Hydraulic Pump Elec. Motor (A)
98
Oil Pump Accessories (A)
B
90
PCU (B)
92
Oil Pump Elec. Motor (B)
94
Fuel Pump Elec. Motor (B)
96
Hydraulic Pump Elec. Motor (B)
98
Oil Pump Accessories (B)
10
12
Rotor
20
Stator (A)
Stator (B)

FIG.14

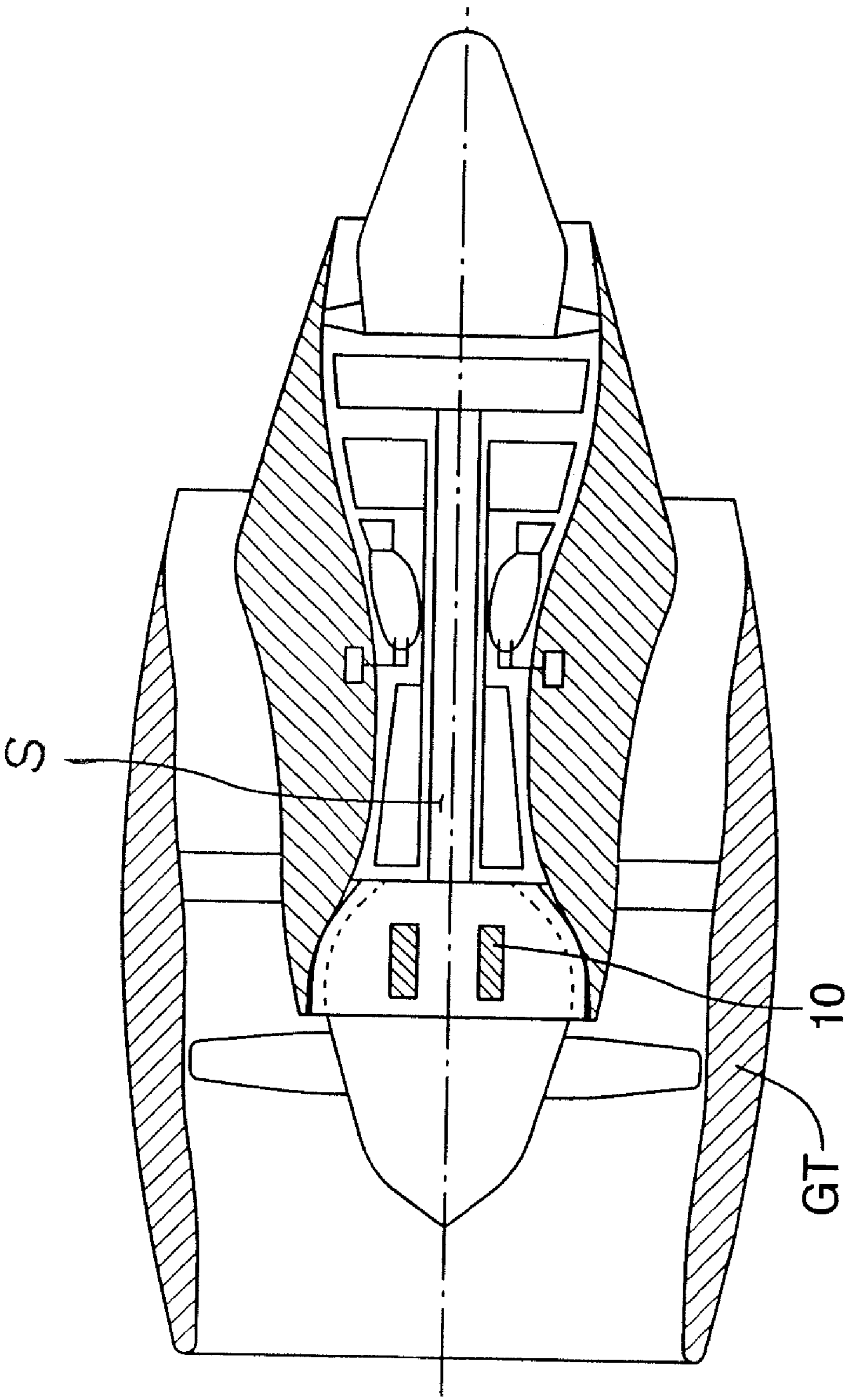


FIG.15

ARCHITECTURE FOR ELECTRIC MACHINE

CROSS-REFERENCE TO RELATED U.S. APPLICATIONS

The present application is a continuation of allowed U.S. patent application Ser. No. 12/509,636 filed Jul. 27, 2009, which is a divisional of the U.S. patent application Ser. No. 11/941,396 filed Nov. 16, 2007, now U.S. Pat. No. 7,583,063, which is a divisional of the U.S. patent application Ser. No. 11/531,854 filed Sep. 14, 2006, now U.S. Pat. No. 7,312,550, which is a continuation of U.S. patent application Ser. No. 11/159,290 filed Jun. 23, 2005, now U.S. Pat. No. 7,126,313, which is a divisional of U.S. patent application Ser. No. 10/444,952 filed May 27, 2003, now U.S. Pat. No. 6,965,183, all of which are hereby incorporated by reference.

TECHNICAL FIELD

The invention relates to electric machines such as alternators and motors and, more particularly, to a novel architecture for such machines.

BACKGROUND OF THE ART

Referring to FIGS. **1**A and **1**B, a typical permanent magnet (PM) machine according to the prior art is shown at **100**. Prior art PM machine **100** has a rotor **102**, with permanent magnets **104** mounted thereto by a retaining ring **106**, which is mounted on a rotatable shaft **108**. Rotor **102** is adjacent a stator **110** having a plurality of windings **112** interspersed between a plurality of teeth **114** mounted to a back iron **116**. (For ease of illustration, the adjacent elements of windings **112** in FIG. **1**B are shown unconnected.) As is well understood, PM machine **100** may operate in a generator/alternator mode or a motor mode. When operated in a generator/alternator mode, an external torque source forces rotation of the shaft (and thus the rotor and the magnets), and the interaction of the magnets and the windings causes a magnetic flux to loop the windings in the slots. As the rotor rotates, the magnetic flux in the stator structure changes, and this changing flux results in generation of voltage in the windings, which results in an output current that can be used to power electrical devices, or be stored for later use. When operated in a motor mode, a voltage from an external source is applied to the stator windings which causes current flow in the windings and results in a magnetic flux to be set up in the magnetic circuit formed by the teeth and back iron. When current is supplied in an appropriate manner to the windings, the rotor can be made to rotate and thus produce usable torque. The operation of such machines is thus well understood.

Such PM machines can have an "inside rotor" configuration as shown in FIGS. **1**A and **1**B, or an "outside rotor" configuration as shown in FIGS. **2**A and **2**B. The reference numerals in FIGS. **2**A and **2**B correspond to the corresponding features described with reference to FIGS. **1**A and **1**B. In the "outside rotor" configuration, however, rotor yoke **108'** replaces rotor shaft **108**. For ease of illustration, the adjacent elements of the windings in FIG. **2**B are also shown unconnected.

Irrespective of whether operated in an alternator or motor mode, the magnetic flux path in these prior art PM machines is as partially and simply depicted in FIG. **3**, the flux path as indicated by the arrows **118**, and the poles and virtual poles denoted by an "N" or an "S". It is this magnetic flux **118** which induces a voltage in the alternator winding **112** (or in the case of a motor, creates the magnetic attraction with the permanent magnet **106** to cause rotor rotation), as described above.

Prior art PM machines (and particularly PM alternators) suffer from at least two limitations which has limited their usefulness somewhat, namely: (1) the output of the PM alternator may only be controlled within the machine (i.e. varied) by varying the rotor speed (assuming a fixed geometry machine), and (2) if a short circuit or other internal fault occurs in the machine, the internal fault current can become extremely destructive to the machine, particularly in high power applications. With reference to the first drawback, this intrinsic feature particularly limits the usefulness of a PM generator in circumstances where the rotor rotation speed cannot be independently controlled. It would therefore be desirable to improve the controllability of PM machines, generally.

PM machines offer certain attractive advantages for use in high speed applications, and particularly as an integrated starter-generator (ISG) for a propulsive or prime-mover gas turbine engine, in which the PM machine is mounted directly to a turbine shaft of the engine. This shaft, of course, is driven at whatever speed is required for the running of the gas turbine engine (typically anywhere in the range of 0-50,000 rpm) and thus the shaft speed cannot be varied to suit the controllability limitations of the PM machine, but rather is dictated by the mechanical output requirements of the engine. Therefore, although the ISG designer will know the average steady state speed of the turbine shaft at cruise, can thus design an PM alternator system to provide sufficient electrical output necessary to power the aircraft systems at cruise (where the engine typically spends most of its operation cycle), accommodations must be made for take-off (where the turbine shaft may be turning at twice cruise speed, doubling alternator output) and landing approach (where turbine shaft speed may be half of cruise speed, halving alternator output). The problem is an order of magnitude greater for certain military applications, where cruise speed is rarely maintained for any length of time. The prior art therefore poses optimization problems to the ISG designer, where critical over-power and under-power scenarios must be managed to achieve a satisfactory design.

There are other drawbacks inherent prior art designs, which result in complicated mechanisms and fabrication techniques. U.S. Pat. No. 6,525,504 to Nygren et al. shows one example of a relatively complicated solution to the control of certain aspects of the operation of a PM machine used in high voltage power generator applications. The device offers only limited control over operation of the machine, and its complexity makes it unsuitable for higher reliability and lighter weight applications such as, for example, aircraft applications.

Accordingly, there is a need to provide an improved PM machine which addresses these and other limitations of the prior art, and it is an object of this invention to do so.

SUMMARY OF THE INVENTION

In one aspect, the present invention provides a method for operating a gas turbine engine, comprising the steps of: providing the engine, the engine having a main shaft drivingly connected to a multiple power output channel electric machine, the machine having a rotor and a stator, the stator having a plurality of non-overlapping sectors, each sector having a set of stator windings associated therewith, said sets of stator windings being electrically independent of one another, the stator sectors and associated windings each providing one of said multiple power output channels; providing an electrical distribution system electrically connected to said power output channels of the machine, the channels connected to the electrical distribution system in parallel relative to one another; operating the engine to rotate the rotor and thereby generate electricity; in normal machine operation, combining the power output channels to provide a single power output to the electrical distribution system; and in the event of a fault, shutting down at least one channel associated with said fault while continuing operation of a remainder of said channels to provide power output to the electrical distribution system.

In another aspect, the invention provides an alternator comprising a rotor, a stator having at least one stator winding having a plurality of end turns exposed at an axial end of the stator, a fluid cooling jacket substantially surrounding the stator and the end turns, and an insert disposed intermediate the end turns and the cooling jacket, the cooling jacket communicating with a fluid coolant supply, the insert having jets for directing fluid coolant from the cooling jacket to the end turns, the insert comprised of at least one of copper and aluminium to thereby reduce stray inductance of the end turns

Still other inventions are disclosed in this specification and attached figures, as well.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the present invention and to show more clearly how it may be carried into effect, reference will now be made by way of example to the accompanying drawings, showing articles made according to preferred embodiments of the present invention, in which:

FIG. **1**A is a cross-sectional view of a typical permanent magnet (PM) machine according to the prior art;

FIG. **1**B is an exploded isometric view of the prior art device of FIG. **1**A;

FIG. **2**A is a cross-sectional view of a typical PM machine according to the prior art having an "outside rotor" configuration;

FIG. **2**B is an exploded isometric view of the prior art device of FIG. **2**A;

FIG. **3** is a cross-sectional view similar to FIG. **1**A, schematically showing magnetic flux paths;

FIG. **4**A is a cross-sectional view of a PM machine according to the present invention;

FIG. **4**B is an exploded isometric view of the device of FIG. **4**A;

FIG. **4**C is a rear isometric view of a portion (i.e. a few adjacent loops) of the primary winding of the device of FIG. **4**A;

FIG. **4**D is an isometric view of the secondary winding of the device of FIG. **4**A;

FIG. **4**E is an enlarged isometric view of a portion of the rotor and stator of the device of FIG. **4**A, with a portion broken away to reveal detail therein and schematically showing some magnetic flux paths in the device;

FIG. **5**A is an exploded isometric view of a second embodiment of a PM machine according to the present invention, with the stator shown in ghost lines to reveal the winding detail therein;

FIG. **5**B is an enlarged isometric view of a portion of the stator of the device of FIG. **5**A, with a portion broken away to reveal detail therein;

FIG. **5**C is an enlarged cross-sectional partial view of the device of FIG. **5**A, schematically showing magnetic flux paths in the device;

FIG. **6**A is an exploded isometric view of a third embodiment of a PM machine according to the present invention;

FIG. **6**B is an isometric view of the stator of the device of FIG. **6**A;

FIG. **6**C is a rear isometric view of the stator of FIG. **6**B;

FIG. **6**D is an enlarged isometric view of a portion of the rotor and stator of the device of FIG. **6**A, with a portion broken away to reveal detail therein;

FIG. **6**E is a partial cross-sectional view of the portion of the rotor and stator shown in FIG. **6**D;

FIG. **6**F is a cross-sectional view along the lines ***6f*-*6f*** in FIG. **6**E;

FIG. **7**A is an isometric schematic representation of a method for making primary windings in accordance with the present invention;

FIG. **7**B is much-enlarged cross-section of a portion of a stator showing the windings of FIG. **7**A;

FIG. **8**A is an enlarged isometric view and a cross-sectional view similar to FIGS. **6**D and **6**E, respectively, schematically representing electrical and magnetic activity on start up of the present invention;

FIG. **8**B is an enlarged isometric view and a cross-sectional view similar to FIG. **8**A, respectively, schematically representing electrical and magnetic activity immediately after the moment in time represented in FIG. **8**A;

FIG. **9** is a schematic of an equivalent electrical circuit of one phase the device of FIG. **6**A;

FIG. **10** is a schematic of an embodiment of a secondary winding control circuit;

FIGS. **11**A and **11**B are schematics of other examples of secondary winding control circuits;

FIG. **12**A is an enlarged isometric view and a cross-sectional view similar to FIGS. **6**D and **6**E, respectively, schematically representing electrical and magnetic activity of another embodiment of the present invention employing a low Curie point material;

FIG. **12**B is an enlarged isometric view and a cross-sectional view similar to FIGS. **6**D and **6**E, respectively, schematically representing electrical and magnetic activity after the secondary winding fuse of the present invention blows;

FIG. **13**A is an enlarged isometric cross-sectional view of a portion of the stator of another embodiment of the present invention;

FIG. **13**B is an enlarged isometric cross-sectional view of a portion of the stator of an alternate design for the embodiment of FIG. **13**A;

FIG. **14** is a schematic of an aircraft accessory system employing a multi-channel version of the present invention; and

FIG. **15** shows a gas turbine engine incorporating the present invention, with a portion of the engine broken away to reveal a cross-section thereof.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

A permanent magnet (PM) machine according to the present invention is depicted in at **10** in FIGS. **4**A to **4**E. Referring first to FIGS. **4**A and **4**B, PM machine **10** has a rotor **12** which includes a plurality of permanent magnets **14** retained by a yoke **16** and retention sleeve portion **18**. Machine **10** also has a stator **20** which includes at least a primary winding **22** and at least a secondary winding **24** (for clarity, only one of each such winding is shown), separated in this embodiment by a winding air gap **26** and disposed in radial slots **28** between a plurality of adjacent teeth **30** in a back iron **32**. (For ease of illustration in FIG. **4**B, the adjacent elements of secondary winding **24** are shown unconnected.) The winding air gap serves as insulation and may be replaced by other suitable insulation. A rotor air gap **34** separates rotor **12** and stator **20** in a typical fashion, and a stator tooth gap **36** separates adjacent teeth **30** at a rotor interface surface **38** of stator **20**. Primary winding **22** and secondary winding **24** are thus electrically isolated from one another. Stator **20** also includes a core or "bridge" portion **40** bridging adjacent pairs of teeth **30** and passing between adjacent portions of primary winding **22**, as will be described in more detail below.

The materials for PM machine **10** may be any deemed suitable by the designer. Materials preferred by the inventor are: samarium cobalt permanent magnets, maraging steel (preferably 250 or 300) retention sleeve, aluminum yoke, copper primary and secondary windings, a suitable electromagnetic material for the stator teeth and for the back iron.

Referring to FIGS. **4**C and **4**E, primary winding **22** of the embodiment of FIG. **4**A consists of a conductor which enters a first end **27** of a slot **28***a* on a first side **40'** of bridge **40**, and a first leg portion **23'** of winding **22** travels down slot **28***a*, an end turn portion **23"** of winding **22** crosses bridge **40** at the second (i.e. other) end **29** of slot **28***a* and a second leg portion **23'''** travels back along slot **28***a* and exits slot **28***a* from the first end **27**, but on a second side **40"** of bridge **40** (i.e. opposite to the first side **40'** the winding entered). Primary winding **22** then continues along the first end **27** of the stator to the next appropriate slot **28***b* and again enters from the first end **27** of slot **28***b*, but preferably from the second side **40"** of bridge **40** (i.e. the same side of bridge **40** as it exited the last slot **28***a*). Primary winding **22** then travels down slot **28***b*, loops around bridge **40** at the second end **29** of slot **28***b*, then proceeds back up slot **28***b* and exits the first end **27** of slot **28***b*, and is now again on the first side **40'** the bridge piece, and so on. Primary winding **22** is thus positioned in the desired slots **28** in stator **20**. This particular pattern both facilitates assembly (as will be discussed further below) and provides an orderly arrangement for primary winding **22**, and also beneficially assists winding separation within PM machine **10** (see FIG. **7**B).

Referring to FIG. **4**D, secondary winding **24** in the embodiment of FIGS. **4**A-**4**E is a shorted winding to provide a squirrel cage configuration. Secondary winding **24** thus has a plurality of legs **42** extending between end rings **44**.

Referring to FIG. **4**E, a close-up partial isometric section shows the relative arrangements of primary winding **22** and secondary winding **24** (only a portion of one primary winding **22** is shown for clarity). In operation, as will be described in greater detail below, the interaction of magnets **14** and windings **22**, and windings **22** and **24**, creates magnetic flux within PM machine **10**. Referring to FIG. **4**E, a primary magnetic flux path or magnetic circuit **46** and a secondary magnetic flux path or magnet circuit **48** are set up within PM machine **10**, as are represented schematically in FIG. **4**E. The secondary magnetic flux path is isolated from the rotor and rotor magnetic circuit.

Primary magnetic circuit **46** includes rotor **12**, rotor air gap **24**, bridge **40** and the portion of stator teeth **30** between rotor **12** and bridge **40**. Primary magnetic circuit encircles primary winding **22** and, in use (as described further below) either causes or is caused by a current flow in primary winding **22**, depending on whether machine **10** is operated as an alternator/generator or motor, respectively. Secondary magnetic circuit **48** includes bridge **40**, back iron **32** and the portion of stator teeth **30** between back iron **32** and bridge **40**. Secondary magnetic circuit encircles secondary winding **24**. Secondary winding **24**, as will be described further below, is provided for control purposes and preferably, therefore, not connected to an output circuit of machine **10**.

Referring again to FIG. **4**A, stator **20**, bridge **40** and slot **28** together define two slots or openings **28'** and **28"**, with one opening **28'** for the primary winding only, and another opening **28"** for the primary and secondary windings. The primary magnetic circuit encircles opening **28'** while the secondary magnetic circuit encircles opening **28"**. In FIG. **4**A, the opening **28'** is radially closer to the rotor than the other opening **28"**. Within the slot **28**, bridge **40** extends a portion of the distance from the radially innermost portion of slot **28** to the radially outermost portion of slot **28** to thereby define openings **28'** and **28"**. The designer will select the size of the bridge, as well as the rest of the stator dimensions, based at least in part on the desired properties of the magnetic circuits in the machine to yield the desired machine performance, etc. Referring to FIG. **4**E, bridge **40** also preferably extends the entire distance from stator faces **27** to **29** and thus is adjacent the primary winding **22** along the length of legs **23'** and **23"**. Leg **23'** is preferably substantially parallel to winding **24** along its leg **25'** extending the length of opening **28"**.

Referring to FIGS. **5**A-**5**C, a second "inside rotor" embodiment of the present invention is shown. The same reference numerals are used to denote the analogous elements described with reference to FIGS. **4**A-**4**D. The skilled reader will also appreciate the relative similarities and differences in construction and operation of typical "outside" vs. "inside" rotor configurations, and thus these will not be discussed further here. Aspects of the second embodiment not specifically described below may otherwise be assumed to be made in accordance with the description of the analogous element described above.

Referring to FIGS. **5**A and **5**B, the second embodiment of the present invention is another multi-winding, multi-phase configuration. In other words, there are multiple primary windings **22** and secondary windings **24**, preferably one for each phase. For clarity, only one phase is depicted. Though only the windings of one phase will be described below, preferably the description will apply to the windings of all phases.

Referring first to FIG. **5**A, each phase of primary winding **22** consists of a conductor which, in a manner similar to that described above, enters a first end **27** of a slot **28***a* on a first side **40'** of bridge **40**, travels down slot **28***a*, crosses bridge **40** at the second (i.e. other) end **29** of slot **28***a* and travels back along slot **28***a* and exits slot **28***a* from the first end **27**, but on a second side **40"** of bridge **40** (i.e. opposite to the first side the winding entered). Primary winding **22** then continues along the first end **27** of the stator to the next appropriate slot **28***b* and again enters from the first end **27** of slot **28***b*, but preferably from the second side **40"** of bridge **40** (i.e. the same side of bridge **40** as it exited the last slot **28***a*). Primary winding **22** then travels down slot **28***b*, loops around bridge **40** at the second end **29** of slot **28***b*, then proceeds back up slot **28***b* and exits the first end **27** of slot **28***b*, and is now again on the first side **40'** the bridge piece, and so on. Primary winding **22** is thus positioned in the desired slots **28** in stator **20**.

In this embodiment, each phase of secondary winding **24** consists of a conductor which enters one end **27** of the slot **28***a* occupied by the primary winding **22** of that phase and then exits slot **28***s* from the opposite end **29** and continues to the next appropriate slot **28***b* (preferably the next slot occupied by this phase of primary winding **22**, as depicted in FIG. **5**A), and so on.

Referring to FIG. **5**B, the relative arrangements of primary winding **22**, secondary winding **24** and bridge **40** can be seen within stator **20**. Referring to FIG. **5**C, a schematic representation of the primary and secondary magnetic circuits flux paths **46** and **48**, respectively, is shown when PM machine **10** is in use.

A third embodiment of the present invention is disclosed in FIGS. **6**A-**6**F. Referring first to FIGS. **6**A and **6**C, this embodiment is an outside-rotor, 3-phase, dual "channel" PM machine, depicted with one set (i.e. "channel") of primary windings **22** absent (for clarity), as will be described in more detail below. The same reference numerals are used in FIGS. **6**A-**6**F to denote the analogous elements described with reference to the embodiments above, and thus these elements will not be redundantly described here but rather addressed only as required. Aspects of the third embodiment which are not specifically described below may be assumed therefore to be otherwise made in accordance with the description of the analogous elements above.

As mentioned briefly above, and for reasons which will become more apparent below, in this embodiment, stator **20** of PM machine **10** is conceptually divided into an "a" half and a "b" half, and thus windings **22** and **24** will be described in terms of primary windings "**22***a*" and "**22***b*" and secondary windings "**24***a*" and "**24***b*". Other features associated with windings **22** and **24** may also be described as "a" or "b" specific. Primary windings **22***b* are not depicted in FIGS. **6**A-**6**C for clarity, but may be assumed to be otherwise identical to primary windings **22***a*.

Referring to FIG. **6**A, in this embodiment three primary windings **22***a* are provided, namely primary windings $\mathbf{22}a^1$, $\mathbf{22}a^2$ and $\mathbf{22}a^3$, to provide the desired 3-phase configuration. Each primary winding **22***a* is provided with its own primary terminal **50***a* (see FIG. **6**B) for ease of connection to an associated primary circuit (not shown). Secondary windings **24***a* and **24***b* each have squirrel cage-type arrangement (i.e. with legs **42** and end rings **44**) and have secondary terminals **52***a* and **52***b*, respectively, for ease of connection to an associated secondary circuit. Referring to FIGS. **6**D and **6**E, preferably (as will be described in greater detail below) each leg **42** of secondary windings **24** includes a current-limiting device such as a fuse or breaker element **54**. Stator **20** has a plurality of passages **58** defined on its inner periphery to act as an oil transfer mechanism, as will also be described in more detail below. Referring again to FIG. **6**A, preferably paper spacers **56** are placed between primary windings **22** and stator **20**, and between secondary winding **24** and stator **20**, for insulation purposes.

Bridges **40** are preferably non-integral with stator **20**, and thus inserted as an assembly as depicted schematically in FIG. **6**C, which advantageously permits the designer to select different materials for bridge **40** and stator **20**. For example, a bridge material may be chosen to alter the magnetic or performance characteristics of machine **10**, as will be discussed in greater detail below. Non-integral bridges **40** may also beneficially facilitate machine assembly, as explained further below.

Referring in particular to FIGS. **6**A-**6**C, as mentioned this embodiment has a "multi-channel" architecture, in that a plurality of fully independent "sets" of primary and secondary windings are provided. In this case, two such sets are provided (i.e. sets "a" and "b" described briefly above), namely primary windings **22***a* and **22***b* (primary winding **22***b* is not shown, for clarity) and secondary windings **24***a* and **22***b*. This multi-channel architecture permits a plurality of motor/alternators to exist within the same stator, and which may either be operated conjunctively, or independently, as desired. For example, in normal machine operation, the outputs of the winding sets may be combined to provide a single output, but in the event of a fault which requires one winding set to be shut down, the remaining winding set(s) may continue operation unaffected. This feature thus permits more than one motor/generator to exist within the same machine (as is discussed in greater detail below), thereby providing redundancy which may very valuable in applications where a complete shutdown would be catastrophic.

Stator **20** has a tooth gap **36** preferably provided in accordance with the applicant's U.S. Pat. No. 7,119,467, the contents of which are incorporated into this disclosure by reference. Though not shown specifically in this disclosure, but as incorporated by reference from the applicant's patent, tooth gap **36** is not necessary in the stator face adjacent the rotor (i.e. near **28***a*, as in FIG. **4**E), but rather slots **28** may open to the opposing face (i.e. the face opposing the stator's 'rotor face'—i.e. nearer to **28***b* in FIG. **4**E) or slots **28** may have no such openings adjacent either **28***a* or **28***b*, but rather having openings only at faces **27** and **29**.

Primary windings **22** and secondary winding **24** are preferably each composed of single conductor provided in a single turn configuration. This single conductor, single turn configuration is preferred because it reduces the probability of a short circuit within the winding. Primary windings **22** are preferably stamped or otherwise provided from sheet metal and then pre-bent into a desired shape prior to insertion into the stator. An example series of fabrication steps are shown schematically in FIG. **7**A. Advantageously, bridge **40** may be inserted into the windings before insertion into the stator, and this removable bridge portion and stator architecture permits the windings to be completely pre-assembled before being inserted into the stator, thereby improving manufacturability. Referring to FIG. **7**B, primary windings **22** are also preferably installed in stator **20** such that they are individually radially separated from one another to provide increased anti-short circuit protection between adjacent windings.

Referring to FIGS. **6**C and **6**D, in this embodiment wherein bridges **40** are non-integral with stator **20**, primary windings **22** may be "pre-wrapped" around bridges **40** prior to assembly into teeth **30** of stator **20**. When a whole-number of turns around bridge **40** are made by primary winding **22** (in this case, one turn is made), primary winding **22** enters and exits slot **28** of stator **20** between from the same side, as described above. This design feature advantageously permits primary windings **22** to be pre-assembled with bridges **40** (and spacers **56**, as desired) prior to insertion into slots **28** of stator **20**. This permits traditional winding machines (and their associated manufacturing and tolerance difficulties) to be avoided altogether in the present design.

Referring to FIG. **8**A, in use, whether in a motor or alternator mode, the interaction of magnets and primary winding **22** causes a primary flux path **46** to be set up which runs down a first portion (i.e. the upper end) of tooth **30**, across bridge **40**, and back up a corresponding first portion of an adjacent tooth **30**, and then to and through the rotor to complete the loop, as depicted by the solid arrows in FIG. **8**A. This primary flux path causes (or is the result of, depending on whether PM machine is operated as a motor or an alternator) current to pass through primary winding **22** (in a closed primary circuit). Referring to FIG. **8**B, this current flow through primary winding **22** causes a secondary flux path **48** to be set up through a second portion (i.e. the lower end) of teeth **30**, through back iron **32**, back up through the corresponding second portion of an adjacent tooth **30** and then back through bridge **40** to close the secondary loop. This secondary magnetic circuit causes a secondary current to flow through secondary winding **24** (in a closed secondary circuit)

The magnetic flux in secondary path **48** thus loops the portion of secondary winding **24** opposite primary flux path

46, and the interaction of primary winding 22 and secondary winding 24 thus sets up a secondary magnetic circuit in machine 10. It can clearly be seen, therefore, that the magnetic flux path(s) of the present invention are entirely different than is present in a typical prior art PM machine. As will be described in greater detail below, these characteristics of the present invention present many advantages to a PM machine designer.

When used as an alternator, a PM machine will generate voltage and current which may be used as required, or stored for later use. Often, a conditioning step of some description is required to convert the raw output of the alternator into a more useful form (typically by varying the voltage, current and/or frequency and perhaps also rectify the output into DC current). As discussed in the Background, in a gas turbine integral-starter generator (ISG) application, in normal operation in an alternator mode, variations in engine speed and load results in an ISG output current and voltage which requires conditioning before the generated electricity is useable by on-board aircraft systems such as electric oil pumps, fuel pumps and other accessories. Therefore, means may be provided outside PM machine 10 to control and condition the machine output (i.e. preferably the output of primary winding 22).

However, when operated as an alternator, the present invention also permits the output the primary winding(s) 22 to be controlled to a certain extent through a manipulation of at least the current secondary winding(s) 24, as will now be described.

Referring again to FIGS. 8A and 8B, it will be appreciated that, in essence, the present invention set ups a transformer-type relationship between primary winding 22 and secondary winding 24, as is schematically represented FIG. 9 by a simple equivalent circuit. In the preferred embodiments depicted in FIGS. 4A to 6F, the equivalent "transformer" is a 1:1 transformer, i.e. the number of turns in primary winding 22 equals the number of turns in secondary winding 24 (here, each has only one turn). In such a "transformer", the following relationship exists between the primary and secondary windings:

$$I_{PRIMARY} * V_{PRIMARY} = I_{SECONDARY} * V_{SECONDARY}$$

Thus, the magnetic flux developed within secondary magnetic circuit is proportional to the current flow in primary winding(s) 22 and inversely proportional to the magnetic coupling within secondary magnetic circuit. The magnetic flux in secondary magnetic circuit is proportional to the magnetic coupling, and inversely proportional to the current flow in secondary winding 24 (i.e. the current induced in the secondary winding causes the secondary flux to be cancelled). Therefore, the current flowing in secondary winding 24 directly influences the current generated in the primary winding 22 by the rotating magnetic system of PM machine 10, and the current flow is a function of the current flow in the primary windings. The secondary windings 24 are inductively coupled only to the primary winding 24 (excluding leakage, etc.), and thus the secondary winding 24 and secondary magnetic circuit 48 are only influenced by the flux in the primary magnetic circuit 46 set up by the primary winding 24 (except in the case of a low Curie point bridge, of the type describe further below, when the bridge is at or exceeds the bridge material's Curie point temperature).

This aspect of the present invention permits the designer to use the secondary winding to manipulate the output of primary winding 22, and thus secondary winding 24 may be used as a source of control PM machine 10. Means for controlling the operation of PM machine are thus available within the machine itself, as the "control" current may be generated within PM machine 10, that is in secondary winding 24. In some instances, therefore, no external source of control current may be required. The novel architecture of the present invention therefore lends itself to many novel possibilities for control systems for the machine, a few examples of which will now described.

In one example control scheme, the output (i.e. from a primary winding 22) of PM machine 10 in an alternator mode may be controlled by mechanical means by directly influencing the current in the secondary winding 24. Referring again to FIGS. 6D and 6E, a current limiting device 54, such as a fuse element, is preferably provided in one or more legs 42 (preferably all legs) of secondary winding 24. Referring to FIGS. 8A and 8B, as mentioned, current in secondary winding 24 is a function of current in the primary winding 22. Thus, as current in the primary winding rises (such as in the case of an internal fault such as a short circuit) so, too, will the current in the secondary winding. Referring to FIG. 12B, in use, when the current in secondary winding 24 exceeds a certain threshold, a fuse element 54 would "blow", thereby creating an open-circuit in secondary winding (i.e. no secondary current) and, by reason of the electrical inter-relationship between the primary and secondary circuits, the output current of primary circuit will be limited. With no current flow in the secondary winding, the flux in primary magnetic circuit 46 induces in a significant flux in secondary magnetic circuit 48. Consequently inductive reactance is increased, which can be used limit maximum output current to a maximum synchronous impedance of machine 10. (Prior to opening of the fuse, when secondary current is allowed to flow in the secondary winding, the resulting secondary flux is in the opposing direction and thus tends to cancel the secondary flux. Hence, the operation of machine 10 is relatively unaffected by the presence of the secondary until the secondary circuit opens.) This permits the control of the machine's impedance and offers PM machine 10 intrinsic thermal protection against a short-circuit in primary winding 22 when operating in an alternator mode. Any suitable fuse may be used.

Prior to opening of fuse 54 (i.e. in normal machine operation), secondary winding 24 as disclosed in the embodiment of FIGS. 6A-6F operates in a simple short-circuited squirrel cage arrangement, and thus will have no perceptible effect on primary winding 22. In other words, when secondary winding 24 is fully short circuited, PM machine 10 maybe operated in a manner substantially in similar to prior art machines.

In a second example control scheme, current in the secondary winding 24 can be influenced by electronic means to control the current in primary winding 22. Direct electronic control of current in secondary winding 24 can be achieved by an impedance or other control system, such as the examples depicted in FIGS. 10, 11A and 11B which provide proportional type or other control adjustments of the current in secondary winding 24, to thereby control the current in primary winding 22.

FIG. 10 shows an example of a simple arrangement for solid state secondary winding electronic control circuit 60 for control secondary winding 24 for machine 10. The main elements are D_1 Bridge rectifier, and Q_1 IGBT device (Insulated Gate Bipolar Transistor). The device Q_1 could also be substituted by another type of device, such as a power MOSFET or other switching device. In this example, multiple secondary windings 24^1, 24^2, 24^3 (e.g. as in the example of a multiphase machine having a secondary winding for each phase) preferably each have similar circuits, e.g. as 60 is depicted in FIG. 10, which could be controlled by a single control system. V_{s1}, the control voltage, is used to switch Q_1

'on' or 'off' and, as such, may be used to control the average DC current flow in the D_1 rectifier bridge and, consequently, the AC current flow in secondary winding **24**. In this arrangement, secondary winding **24** preferably has multiple turns (relative to primary winding **22**) such that the current being switched by the Q_1 device would be stepped-down to only a fraction of the current flow in primary main winding **22** to thereby permit low current control circuitry connected to secondary winding **24** to control a high current machine output from primary winding **22**. (The switched voltage at Q_1 would generally still be higher than the primary machine voltage, but it will be understood that this is still practical since Q_1 devices are available which operate at over 1500V). This control arrangement is useful as a voltage regulator when the output of machine **10** (i.e. the output of primary winding **22**) is to be rectified for use as a DC supply or further conditioned as desired. In use, the current induced in the secondary is affected and controlled by the elements in the secondary circuit, and this control permits the current and/or voltage of the primary to be affected as desired to control the operation and behaviour of PM machine **10**.

Many other control schemes are also possible. Referring FIG. **11**A, a different secondary winding electronic control circuit **60** is shown, in which the output of secondary winding **24** fed in parallel through parallel diode **62** and transistor **64** pairs (in this case the transistors are NJFETs) to permit the secondary current to be modulated to thus control the primary winding **22** output. Referring to FIG. **11**B, a second embodiment of a secondary winding control circuit **70** is shown, in which the output of secondary winding **24** fed to a thermally-sensitive switch **72**. Still other control schemes are possible, as will be appreciated by one skilled in the art upon consideration of this disclosure.

In a third example control scheme, the current in secondary winding **24** can be influenced by varying the magnetic coupling in the secondary magnetic circuit to thereby control the primary winding current. For example, referring again to the figures the configuration and material selection for components such as stator teeth **30**, back iron **32** and bridge **40** will also vary the magnetic properties of the secondary magnetic circuit, thus permitting the designer to "control" the performance of PM machine **10**. In one example, described further below, the secondary magnetic circuit includes a low Curie point material such as ferrite, when the machine operates with the secondary magnetic circuit at or above the Curie temperature the effect or influence of the secondary winding would be greatly reduced.

As discussed above, non-integral bridge pieces **40** may provide benefits for the assembly of PM machine **10**. Also, as briefly mentioned, the provision of a non-integral bridge permits the designer to select a different material for bridge **40**. For example, additional short-circuit control can be provided to PM machine **10** in accordance with the teachings of the applicant's U.S. Pat. No. 6,313,560 (the '560 patent), the contents of which are incorporated by reference into this disclosure. The '560 patent teaches that materials with a low Curie temperature (referred to as low Curie point materials in this description), such as ferrite, can be beneficially used in electric machines to provide thermal protection in the event that a fault causes normal operating temperatures to be exceeded. This concept may also be applied in the present invention, as will now be described.

Referring again to FIGS. **6**A-**6**F, preferably bridges **40** are made of different material than teeth **30**, which thereby permits the designer to alter the behaviour of the primary and secondary magnetic circuits. Most preferably, bridge **40** is made of a low Curie point material of the type described in the '560 patent, such as ferrite.

Referring now to FIG. **12**A, in use, in such a thermally-protected embodiment primary winding **22** is preferably closely thermally coupled to bridge **40** pieces to permit a fast and effective control of the machine in the fault condition. In the event of a fault that raises the temperature of a bridge **40** to or above the Curie point of the ferrite bridge material, bridge **40** begins to lose its ability to conduct magnetic flux, and thus (eventually, as temperature increases) becomes "invisible" to the magnetic circuit in stator **30**. The primary and secondary magnet circuits are thus joined into one circuit (reference **47**), as magnetic flux (eventually) no longer crosses bridge **40**, or flux is at least greatly reduced.

In fact, preferably, the low Curie point material is selected such that when the Curie point of bridge **40** is reached, bridge **40** doesn't completely stop magnetic flux from passing therethrough (and thus doesn't completely "shut down" the primary current down, but rather as the Curie point is reached and exceeded, the amount of magnet flux passing though the bridge is progressively reduced, thereby acting just to "turn down" the primary current, rather than shut it off completely. The amount the current is "turned down" by bridge **40** is controlled by the amount of magnetic "short circuit" experienced as a result of reaching the bridge material Curie temperature, and is thus affected not only by bridge **40** material, but also by (a) tooth pitch, (b) back iron thickness, (c) tooth length, and (d) back iron material, among other things. The designer may use this knowledge to control the "turn down" behaviour of PM machine **10** in the event a machine fault occurs.

To enhance the effectiveness of a low Curie point embodiment of the present invention, a close thermal coupling between the windings and the low Curie point material of bridge **40** is advantageous and thus preferred. This close coupling may be achieved by close contact between primary winding **22** and bridge **40**, and/or may be enhanced by the use of bonding material between the windings and the low Curie point material.

Advantageously, the use of a low Curie point bridge material can provide thermal protection to PM machine **10** in fault situations where the current in secondary winding **24** is not high enough, for example, to blow a fuse **54** and yet continued operation of machine **10** could result in damage to the machine. Thus, the use of a low Curie point material in conjunction with the present invention can permit intrinsically redundant safety systems to be incorporated.

Another significant advantage of PM machine **10** is that, when a low Curie point material is employed as described, if the internal fault is a short in a loop (or loops) of the winding, the described low Curie point embodiment can permit only the faulty loop(s) to be shut down or turned down, leaving the operation of the rest of the winding essentially unaffected. The bridge and stator arrangement, in conjunction with the independent ferrite bridge portions, in effect forms a plurality of serially-connected by otherwise independent alternators within PM machine **10**.

A low Curie point material may also be used in the secondary circuit for control purposes. For example, if a low Curie point material (such as ferrite) were used in the secondary magnetic circuit of the present invention, for example in the back iron, the design could permit the current in the primary circuit to be increased as the low Curie point material in the secondary circuit is heated above its Curie temperature. This may be a beneficial feature, depending on the performance criteria or specification for a particular application for PM machine **10**. For example, this feature may be used to increase output to a cooling system such that the machine, operated as an alternator, both provides cooling power and controls temperature.

Referring to FIGS. **13**A and **13**B, the present invention may be provided including a cooling system including a coolant **80** (preferably oil) within PM machine **10**. Oil is circulated through passages **58** inside a stator jacket **82** around and along the primary and secondary windings to assist in cooling them. In FIG. **13**B, an oil jet **84** in an insert **86** directs oil onto the end turn of the primary winding. If the insert **86** is made of aluminum or copper, the stray inductance of the end turn is also reduced, thereby reducing the overall machine impedance.

Accordingly, control schemes such as those disclosed above may be employed individually or may be combined as desired to permit several control features to exist contemporaneously within the PM machine. As prior art fixed-geometry PM machines typically are not controllable in any way other than by the speed at which they are operated, this controllability feature of the present invention is of significant value to the PM machine designer, particularly in those applications where the rotational speed of the machine cannot itself be used to control machine output. The present invention also offers a robust and reliable design suitable for aerospace applications.

In essence, the present invention provides a type of internal current-limiting transformer (in the described embodiments, a 1:1 transformer, but other ratios are possible) built into the magnetic structure of the machine. The "primary" is connected electrically in series with the main output feeders of the alternator, and the "secondary" is configured preferably as a short circuit, which will become an open circuit, by means of a fuse, or other circuit interrupting or current limiting means, above a certain pre-selected temperature. Typically, the pre-selected threshold temperature will be the maximum safe sustained operating temperature of the machine, above which the machine is susceptible to thermal damage (e.g., say about 300° C. when typical electric machine construction materials are used). When the secondary becomes open circuit, current flow in the primary is significantly reduced as a result of the inductive reactance of the "transformer" under no load conditions, which thereby results in an increase in the machine impedance. Preferably, the increase in machine impedance is a significant one (e.g. doubling the machine impedance), such that the short circuit current in the primary is effectively limited to a value equal to the maximum power rating of the machine. The advantage of using this "transformer" type arrangement is that each stator slot may be protected by its own "transformer-breaker", and thus the voltage that is being fused is only a fraction (e.g. $1/6^{th}$ in a dual-channel 3 phase machine of the type described further below) of the total generated voltage. Consequently, the breaker/fuse in the secondary will be less likely to experience an arc when the circuit is opened.

The 'transformer' of the present invention may also be remote from the stator, such that a portion of the primary and some or all of the secondary are disposed external to the stator.

The net effect of the low Curie point embodiment described above is that two thermal protection schemes may be implemented in the machine, namely (1) a low Curie point type over-temperature protection scheme, which provides intrinsic and automatic reversible (i.e. non-permanent) overload protection to prevent permanent damage to the machine for moderate to severe temperature overloads, and (2) a high temperature protection scheme which will automatically react in the event that (i) the first-mentioned mechanism does not sufficiently control the short circuit current within the time desired, and/or (ii) in situations where the short circuit resistance(s) in the machine is (are) very low.

As discussed above, the present invention also includes a "multi-channel" design which can, among other things, offer inherent redundancy useful in aerospace applications. Referring to FIG. **14**, a PM machine **10** of the type described with reference to FIGS. **6**A-**6**F above in essence provides a single rotor rotating relative to multiple (in the described case, two) independent stators. Thus, rotor **12** rotates relative to a "virtual" stator **20***a* (the portion with primary windings **22***a*) and also relative to a "virtual" stator **20***b* (the portion with primary windings **22***b*). This, PM machine is a two-in-one machine in this case. The output of these two "machines" may then be combined, which permits the option of operating the "two machines" as one. PM machine **10** is then preferably connected to fully redundant accessory systems, which may include redundant power conditioning units (PCU) **90**, oil pumps **92**, fuel pumps **94**, hydraulic pumps **96** and other electrically-run accessories **98**. In a gas turbine ISG application, this dual- or multi-channel design permits a fully redundant system (system A+system B, in FIG. **14**) to provided with a minimum of hardware, thereby minimizing weight and space and increasing reliability. As well, since generator efficiency is proportional to I^2 losses, it is often preferable to run two "machines" like this, each at ½ of the output current, rather than one machine a full output current. Further, power from the two "machines" may be shared, if desired, between the PCUs with the appropriate connections, etc., to permit redundancy in the case of a "machine" or PCU failure.

The present invention is particularly well suited, among other things, to prevent overheating problems of an internally short circuited permanent magnet arrangement that is driven continuously, such as in the case of an internal fault in a machine **10** driven by a shaft 'S' in gas turbine engine 'GT', as depicted in FIG. **15**. The invention also permits a certain level of control to be attained over an alternator which is driven at variable speeds (i.e. driven by an operating propulsive aircraft gas turbine).

The above description is meant to be exemplary only, and one skilled in the art will recognize and changes may be made to the embodiments described without departing from the scope of the invention disclosed. For example, the machine may be single or multi-phase, single or multi-channel. The windings may have single or multi turns per slot, the number of turns of primary windings does not have to equal the number of turns of secondary winding, the number of turns of a winding not necessarily have to be a whole number, the number of primary windings does not have to equal the number of secondary windings, as one or more windings in a slot may perhaps be present in a slot. A variety of winding types may be used (squirrel cage, lap, etc.), and the windings may be any conductor(s) (i.e. single conductor, more than one wire, insulated, laminated, etc.) or may be superconductors. In multiphase machine, there may be zigzag, delta, or Y-connected windings in accordance with known techniques. There need not be an air gap between the primary and secondary winding, as long as the windings are electrically isolated from one another.

The rotor can be electromagnetic (i.e. permanent magnet not necessary), and may be provided in an outside or inside configuration, or any other suitable configuration. The bridge may be provided in one or more slots, and may be integral or non-integral with the rest of the stator. A secondary bridge may also be provided, in the form of the back iron, for example, if the secondary winding(s) are wound around the back iron. Other secondary bridge configurations are also possible.

Secondary winding may also be used for control purposes in motor mode. Other portions of the stator and rotor, such as back iron for example, may be provided of a low Curie point material to achieve the benefits of the present invention. Still other modifications which fall within the scope of the present invention will be apparent to those skilled in the art, in light of a review of this disclosure, and such modifications are intended to fall within the equivalents accorded to the appended claims. In this application, it is to be understood that the term 'alternator' is used generically to mean a device used for creating electricity, and is not intended therefore to be limited to a device for generating an output alternating current.

What is claimed is:

1. A stator assembly for a multi-phase electric machine, the assembly comprising:

a stator having a plurality of radially-extending slots around a periphery of the stator, and

a multi-phase winding set comprising at least three phase windings each configured for carrying an alternating current signal of a distinct phase relative to the other phase windings, the at least three phase windings disposed regularly around the stator in selected stator slots, each stator slot carrying only one of said at least three phase windings, the at least three windings extending circumferentially from respective slot to respective slot adjacently to one another along a common face of the stator, the at least three windings extending adjacently to one another along the common face at different radial distances relative to the stator, the radial distances being selected to provide a radial air-gap separation between adjacent phase windings.

2. The stator assembly of claim **1** wherein each phase winding extends through its respective slot at a radial distance different than the other phase windings.

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