ELECTROMAGNETIC MACHINES

Filed Nov. 14, 1966 7 Sheets-Sheet 1

Fig. 1

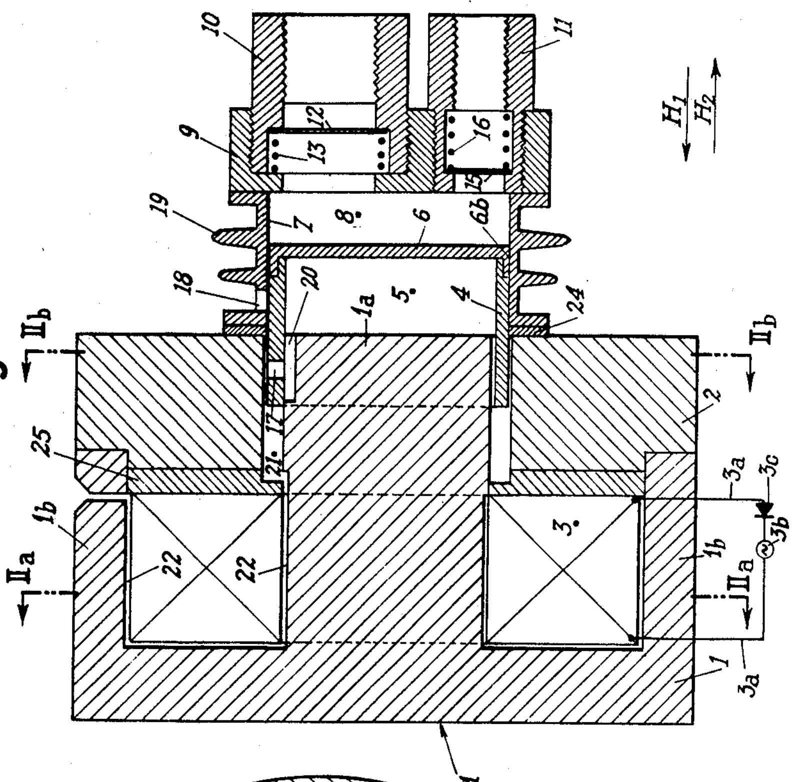
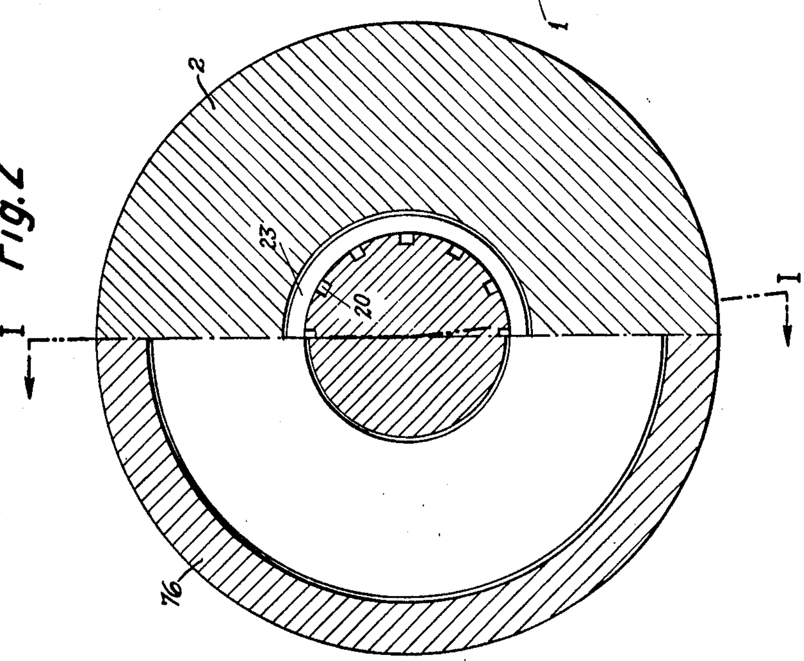
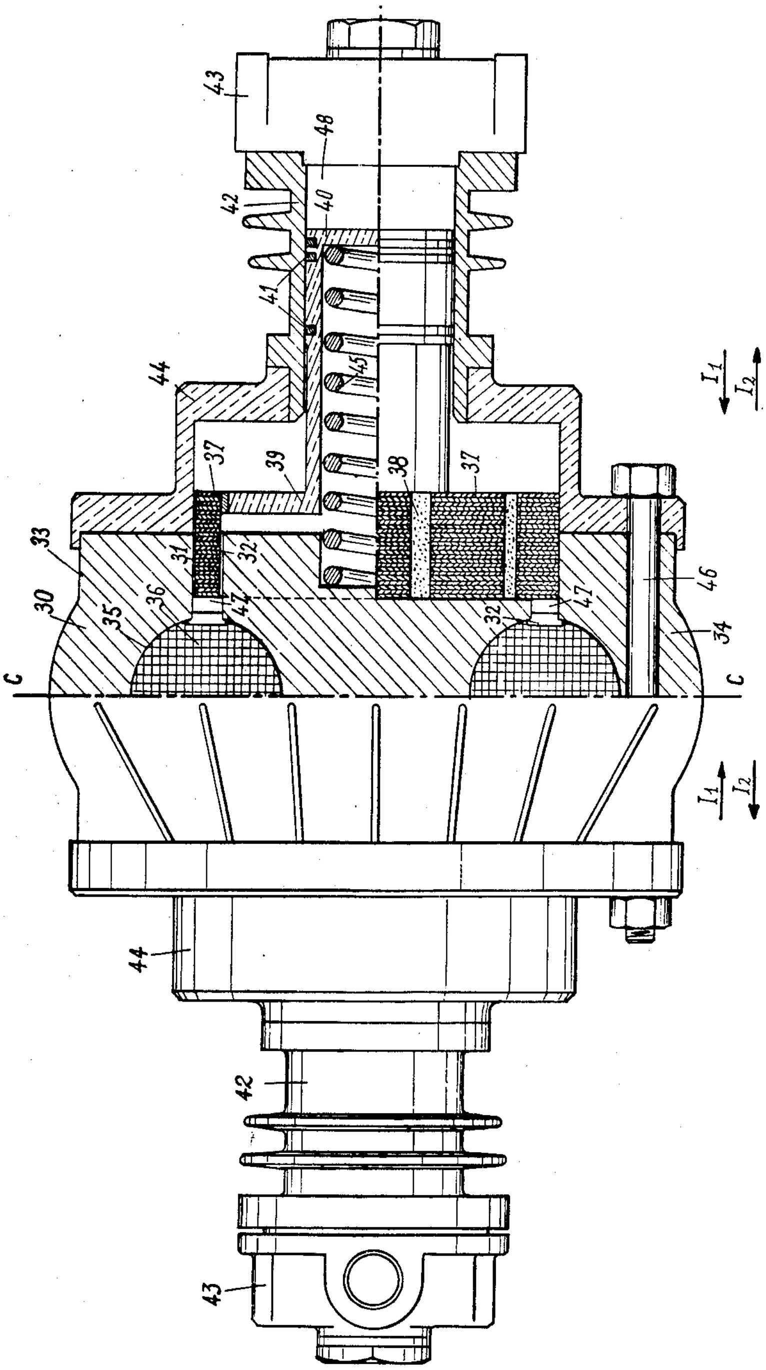


Fig. 2

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38
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I_1
I_2
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31
32
30
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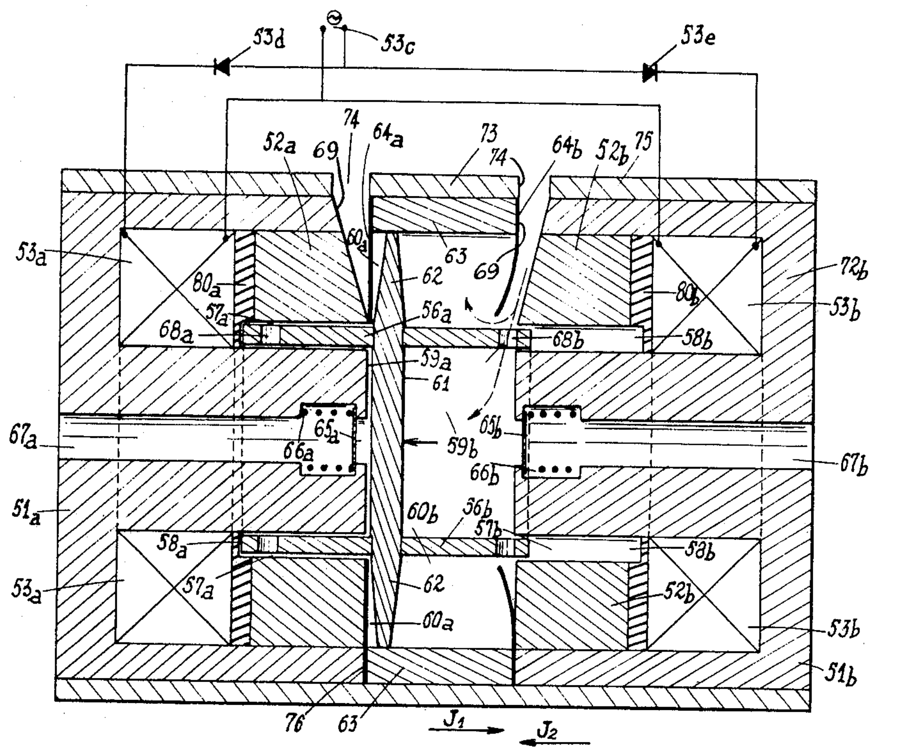
36
47
32
47
46
34
c
c
I_1
I_2
44
42
43

Fig. 3

Fig. 4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57a
56a
80b
53b
68a
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59a
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65a
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66b
51a
60b
56b
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60a
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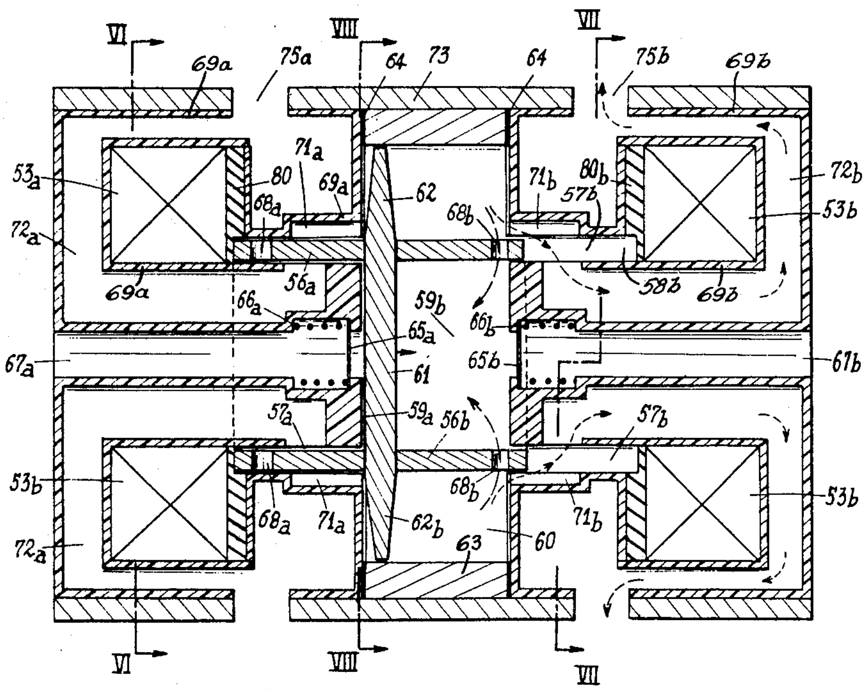
76
63
J1
J2

Fig.5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VII
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66a
65a
59b
66b
65b
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67b
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59a
56b
57b
53b
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72b
58b
69b
53b
VI
VIII
VII

Fig.6

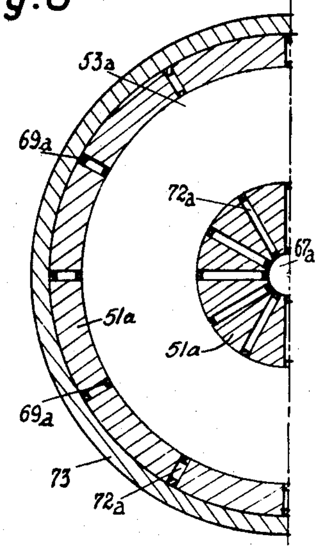


Fig.7

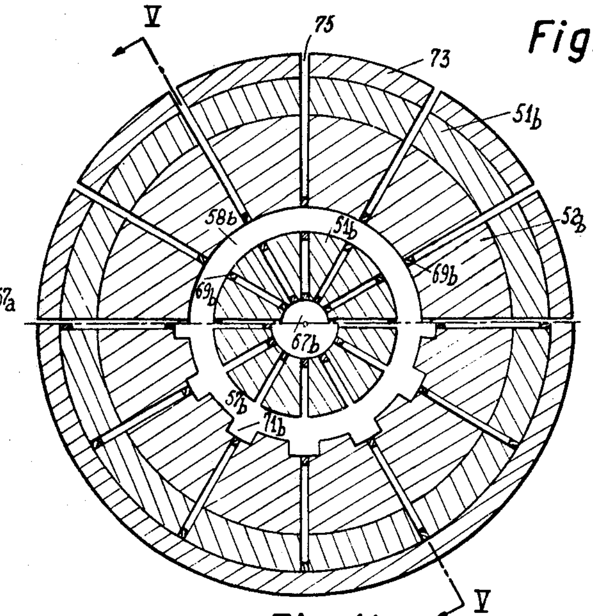


Fig. 8

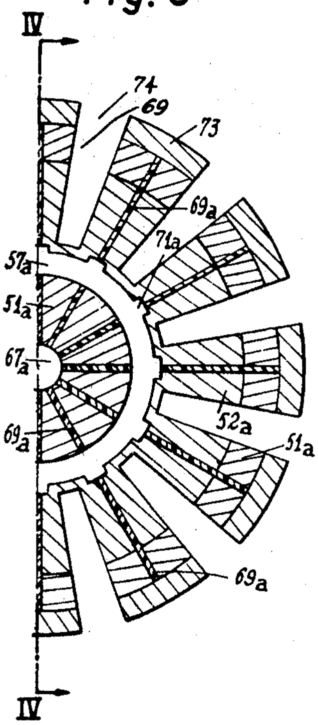


Fig.11

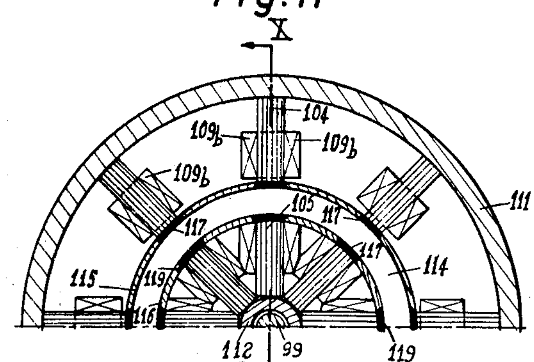


Fig.12

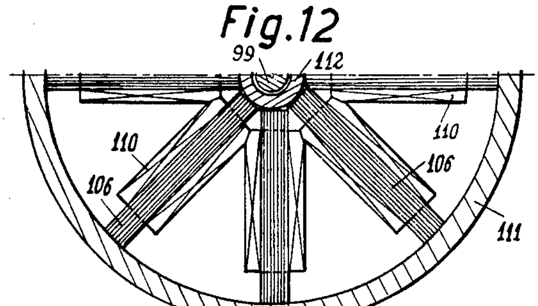


Fig. 14

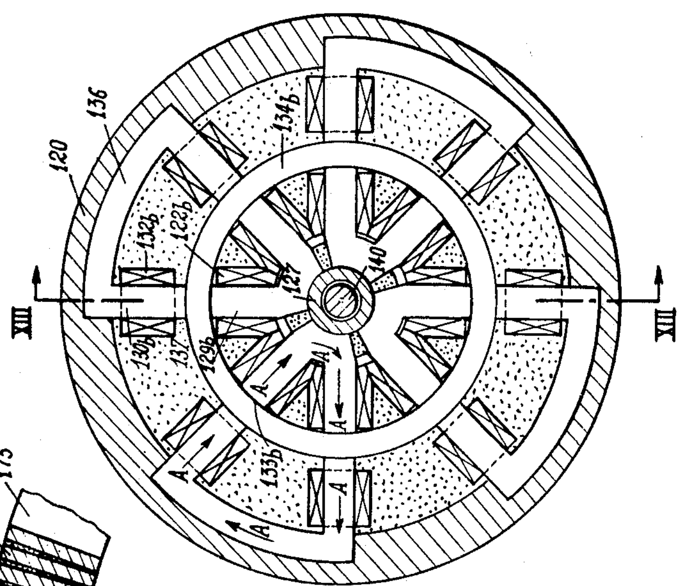


Fig. 15

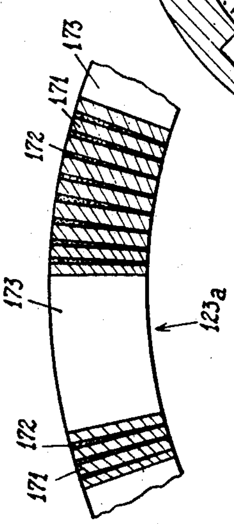


Fig. 9

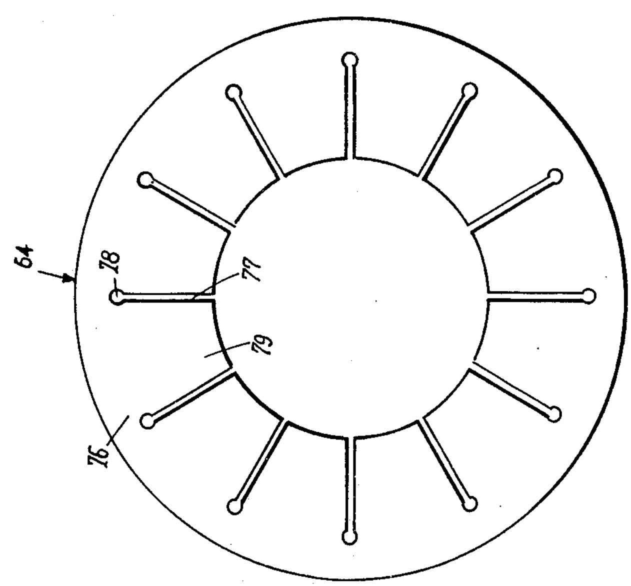
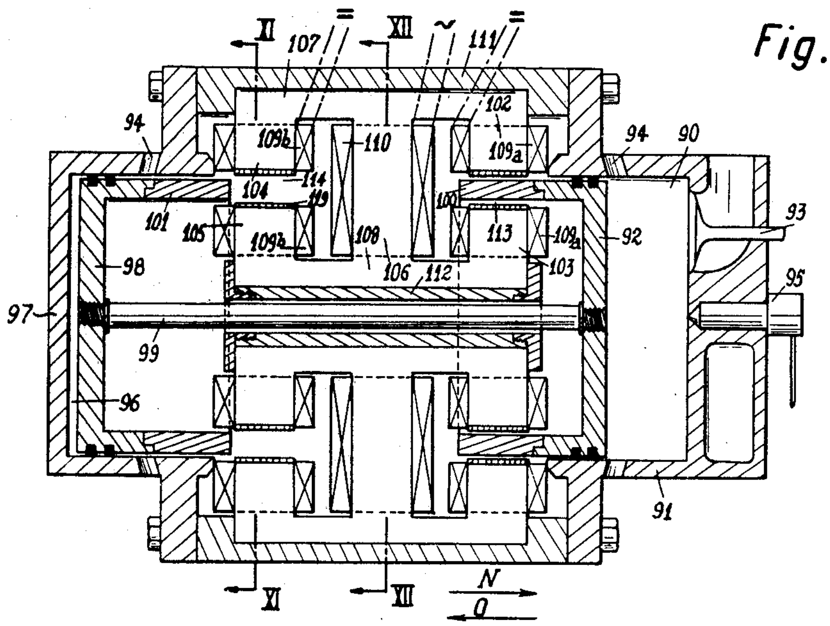


Fig.10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109a
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113
109a
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98
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96
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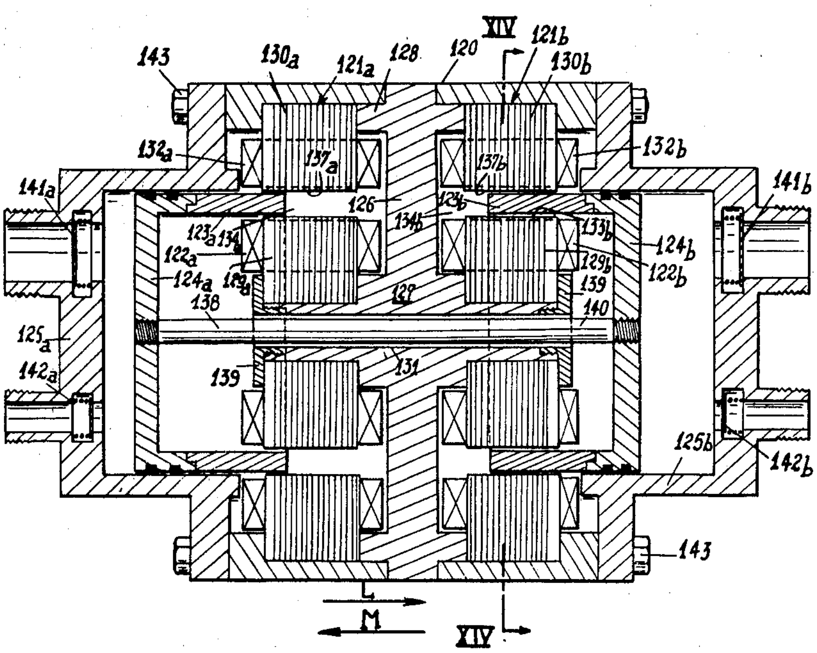
N
O

Fig.13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137a
137b
132b
141a
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141b
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127
139
140
125a
142a
131
125b
142b
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M

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ELECTROMAGNETIC MACHINES

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U.S. Cl. 310—15 12 Claims

ABSTRACT OF THE DISCLOSURE

A reciprocating electric motor comprises at least one magnetic circuit including a fixed core part which includes spaced, cylindrical, co-axial pole surfaces defining an annular air gap and at least one coil associated with the fixed part and connected to a source of electrical energy which generates a magnetic field across the air gap. A magnetic, weakly electrically conductive armature is mounted for reciprocating movement into and at least partly out of the air gap, the magnetic armature being of tubular cylindrical form.

This invention concerns electro-magnetic variable reluctance machines, that is machines that comprise an electro-magnetic circuit comprising a fixed circuit and an armature of magnetic material which is a relatively poor conductor movable relative to the fixed circuit the movement being rectilinear.

In this type of machine the electro-magnetic force arises from the tendency of the magnetic armature to move into that position giving the maximum flux in the magnetic circuit which is composed of the fixed circuit and the armature, this latter closing the fixed magnetic circuit, apart from operational clearances.

This invention concerns especially the structure and assembly of such machines.

Electro-magnetic machines having linear movement and variable reluctance in a magnetic cirruit are already known. Among these the most interesting comprise an armature in a metal preferably a poor conductor but possessing good magnetic characteristics, sliding with a clearance practically independent of the stroke in an air gap in which the lines of force are transverse relative to the direction of movement. An arrangement of this type gives a very high force per unit of mass of the magnetic armature for a given current, this force varying little with the stroke except at the ends where it suddenly becomes zero and at the centre where it suddenly changes sign for a small variation of stroke. These properties are particularly advantageous for the construction of sliding electromagnetic driving or driven machines and in particular for a linear reciprocating electric motor which can be used to drive the piston of a pump, the magnetic armature, preferably a poor conductor, being connected to this piston and being alternatively drawn into the air gap of the magnetic circuit under the action of a magnetic field created by successive electrical impulses feeding a coil, and on the other hand drawn out of this air gap, either by elastic means or by a second magnetic circuit acting on the same moving assembly. In this latter case the circuits fed alternatively by electric impulses dephased by 180°, may each comprise an armature, the two armatures being rigidly connected.

Variable reluctance machines are also known operating in a reverse manner from the preceding, in which the piston and the cylinder form a reciprocating combustion engine, the piston driving at least one armature which causes the reluctance of a magnetic circuit to vary alternatively, and having a movement perpendicular to the lines of force created in the air gap by an excitation coil or magnet.

These machines may comprise one or more cylinders working together.

In all the machines of these types described to date the air gap in which the armature moves has a parallelepiped form and special means must be provided for guiding the armature while allowing it to move without metallic contact with the faces of the poles. This guiding is specially important because a small clearance between the armature and the poles is necessary to obtain maximum efficiency, and because any departure of the armature away from its axial position of symmetry results in the plane surface of the armature being attracted to the point where it sticks to the plane face of the pole, and thus in a considerable lateral force being applied to the armature parallel to the field, and consequently in serious friction losses, in lateral vibrations of the armature and even in the impossibility of correct operation.

Another difficulty with known solutions is that of correctly aligning the axis of the armature and the axis of the driven mechanism, for example the axis of the cylinder in the case of the machines comprising pistons described above. It is therefore, necessary to provide an appreciable operational clearance which results in a reduction of efficiency and of power.

A further well-known difficulty is the tendency of the poles to move towards each other under the influence of the considerable electro-magnetic forces of attraction which requires the use of mechanical means to maintain constant the distance between the poles and, therefore, the lateral clearance of the magnetic armature.

Furthermore, the parallelepiped forms of the magnetic armature, preferably a poor conductor, and of the circuits and therefore the form of the fixed magnetic circuit, do not lend themselves easily to inexpensive quantity production in view of the tolerances required for reliable and satisfactory operation.

Finally, the fixed magnetic circuit of previous realisations only partially surrounds the coil, part of the turns of the latter thus being geometrically placed relative to the circuit to the direction of movement and to the armature such that the current passed therethrough is only of little effect.

The object of the present invention is to achieve machines having variable reluctance and a field perpendicular to the movement of the armature which overcome the disadvantages referred to above. Another object of the invention is to achieve for such machines a simple, accurate and cheap construction and easy assembly.

According to the invention, the electro-mechanical energy converting machine of the type comprising at least one magnetic circuit with a fixed part comprising a coil supplied from a source of electrical energy and with a moving part constituting a magnetic electrically weakly conducting armature moving in the field created between the pole surfaces of the fixed magnetic circuit and transversely with respect to said field, the said armature having rectilinear movement and being directly coupled to an operating slide, is characterised in that said magnetic armature has a tubular cylindrical structure, in that said pole surfaces are also cylindrical and in that at least one part of said fixed magnetic circuit is located within said armature for at least a part of the stroke of said magnetic armature.

By "operating slide" is understood here the organ producing mechanical work if the machine is an electric motor or the organ driving the movable armature if the machine is used as an electric generator.

The poles and the armature having a cylindrical structure can only make line contact and not over the whole and surface of the poles; as a result the lateral force acting on the armature, when it departs slightly from the central position in the air gap, cannot reach serious value.

Furthermore, as the external surface of the air gap is formed by a closed cylindrical tube, it is well able to resist crushing which practically eliminates movement of the poles towards each other.

Machines according to the invention may in the first place form driving machines in which the armature drives an operating slide and thus form reciprocating electric motors such as actuators, electro-compressors, electro-pumps and reciprocating electric motors. The invention also refers to the realisation of electric generating machines such as motor alternators, motor pulse-generators, etc.

According to an advantageous embodiment of the invention the fixed magnetic circuit and the armature have sections in directions orthogonal to the direction of movement which are circular. Considerable resistance to deformation arising from the magnetic attraction of the poles is thus obtained. At the same time this structure lends itself well to rapid, precise and inexpensive machining.

The circular section cylindrical structure also gives symmetrical temperature distribution when the machines warms up during operation, thus reducing distortion when hot, allowing clearances to be reduced and the unit power of the machine to be increased.

According to an advantageous characteristic of the invention, the magnetic circuit completely envelops the coil which is formed by a toroid of revolution co-axial with the circuit. The mean distance between one turn and the circuit thus reaches a very low value and each segment of a turn remains perpendicular to the movement of the armature. This results in a major reduction of flux leakage and the quantity of copper necessary to obtain a given power can be considerably reduced (for example divided by two in certain cases).

Another advantageous characteristic of the invention consists in providing a certain number of non-conducting volumes traversing from side to side and from the exterior to the interior the parts forming the magnetic circuit. These non-conducting volumes preferably have their axial planes passing through the axis of the cylinder and form separations between the magnetic sheets of the fixed or moving parts of the magnetic circuit. This disposition avoids the formation of annular eddy currents which in the case of the moving armature can be sufficiently intense almost to suppress the magnetic attraction in the air gap.

These non-conducting volumes can be used in the case of machines of a certain size as cooling air circulation ducts in the circuit.

Preferably the cylindrical static and moving parts are made using stampings having a profile corresponding to the section of the said circuits on a plane passing through the axis. These stampings are assembled by casting a non-magnetic and non-conductive material, such as for example epoxy resin, into the spaces which separate them.

According to another advantageous characteristic of the invention the elements forming either the static or the moving part of the electro-magnetic circuit are assembled by means of a single piece comprising coaxial bores in which such elements are inserted. Thus the axis of the machine and so the alignment of the parts are precisely fixed which allows very small clearances to be used, ensuring precise guiding avoiding lateral hunting of the moving parts. Thus a particularly simple machine may be realised which is easy to machine and assemble with precision and speed.

Another preferred characteristic of the invention consists in covering at least one of the faces of the air gap with a film of non-magnetic anti-friction material such as polytetrafluoroethylene, which completely prevents any contact between the poles and the armature even along a line contact and which practically eliminates lateral forces on the armature.

Finally, in the case of larger size, and therefore more complex machines, it is also intended that the magnetic circuit should be formed by means of an assembly of a certain number of elements of simple geometric form, which facilitates assembly. This method has the particular advantage of allowing the form or the quality of the metal used in the different parts of the magnetic circuit to be adapted to the values necessary to obtain optimum performance.

Thus the thickness of the laminations used for the poles may differ from that for the rest of the machine.

The attached drawings, given as examples and not in any limiting sense, show particular embodiments of the invention.

FIG. 1 shows a first industrial embodiment on axial section I—I of FIG. 2.

FIG. 2 shows sections of FIG. 1 respectively on II*a*—II*a* on the left hand side and II*b*—II*b* on the right hand side, the armature having been removed.

FIG. 3 is a variant of the first embodiment shown partly as an external view, and partly in section, the moving parts being in half section.

FIG. 4 shows the third industrial embodiment on axial section IV—IV of FIG. 8.

FIG. 5 is an axial section of the same machine on V—V of FIG. 7.

FIG. 6 is a part section on IV—IV of FIG. 5.

FIG. 7 is a section on VII—VII of FIG. 5.

FIG. 8 is another part section on VIII—VIII of FIG. 5 after removal of valve.

FIG. 9 is a plan view of a valve blade from the preceding embodiment.

FIG. 10 is an axial section of a fourth embodiment on X—X of FIG. 11.

FIG. 11 is a half section on XI—XI of FIG. 10.

FIG. 12 is another half section on XII—XII of FIG. 10.

FIG. 13 is an axial section on XIII—XIII of FIG. 14 of a variant of FIG. 10.

FIG. 14 is a section on XIV—XIV of FIG. 13.

FIG. 15 is a partial transverse section, large scale, of part of the armature of the preceding embodiment.

In the first industrial embodiment shown in FIGS. 1 and 2 the machine comprises a fixed magnetic circuit preferably manufactured from sintered material, which combines high induction saturation, high permeability and high resistivity which sensibly prevents eddy currents. For example, a composition comprising 70% pure iron oxide and manganese oxide and whose grain size is of the order of 10 microns could be used advantageously. This circuit comprises a magnetic core **1** forming a first pole piece and including a solid central cylinder **1*a*** and an external annular cylinder **1*b***. On the magnetic core **1** is centered the second pole piece **2** of circular cylindrical section. On the central cylinder **1*a*** is mounted the single magnetising coil **3** which is thus surrounded by the magnetic circuit and which is of toroidal form, which gives a good efficiency, low flux loss and low manufacturing cost. The coil **3** is fed by successive electric impulses provided by conductors **3*a*** from a source **3*b*** of alternating current (for example at 50 cycles), this circuit further comprising a rectifier **3*c*** such as a diode, allowing only one out of the alternations to pass.

Between these two pole pieces slides the cylindrical section magnetic armature **4** perpendicular to the radial magnetic field created in the cylindrical annular air gap **21** and with residual clearance less than ⅕ of this air gap, the armature being made in a magnetic material (that is with high saturation induction) and which is furthermore arranged to have an appreciable electrical resistance in respect of currents circulating along an annular path. In particular these conditions can be fulfilled by using a sintered magnetic material having high permeability and high resistivity. The armature **4** when it slides, causes the reluctance of the magnetic circuit to vary, it limits a cushion volume **5** and forms an extension of a compressor piston **6** whose external surface **6***b* guides the moving assembly in a compressor cylinder **7** defining the compressor volume **8**. The radial clearance of piston **6** in cylinder **7** is preferably less than half the magnetic clearance between the armature and the surface of the poles. This limits the transverse magnetic force which acts upon the armature when it leaves its axial position, to a small value. In this version the operating slide is formed by piston **6**.

The moving assembly is thus especially simple to machine and manufacture. The ratio between the air gap and the residual clearance, which is greater than 5, results in a high flux variation and thus in high unit power. The compresor is closed by a cylinder head **9** in which valve housings **10** and **11** are screwed, the housings carrying the suction valve **12** (and its spring **13**) and the delivery valve **15** (and its spring **16**). The annular armature **4** has ports **17** which at the end of the stroke are opposite ports **18** drilled in cylinder **7**, so as to ensure the distribution of cooling air pumped by the under face of piston **6**. Cylinder **7** is also provided with cooling fins **19**. Channels **20** supply cooling air through the air gap **21** to the air jacket **22** surrounding the coil **3**. A non-magnetic spacer **24** is interposed between the cylinder **7** and the pole piece **2** and ensures their respective centering. Another non-magnetic spacer **25** is interposed between the coil **3** and the pole piece **2**. In the case of small machines without cooling air circulation the spacer **25** may hermetically seal the volume containing coil **3** which is thus protected against corrosive gases or liquids from the other half of the machine.

The machine thus arranged is of the type which delivers fluid during the return stroke, that is, the electro-magnetic energy created by the excitation of coil **3** is first entirely transformed into spring energy in cushion **5** in the form of compressed air.

Operation is as follows: When the current emitted by the source **3***b* is in the direction which the diode **3***c* allows to pass, coil **3** is excited. Since the central cylinder **1***a* forms one of the poles of the machine the other pole being formed by the annular pole piece **2** the current creates a radial flux in the air gap **21**. The annular magnetic armature **4** thus tends to move into the position of minimum reluctance and enters into the air gap **21**. At the beginning of this power stroke (in direction H_1) the suction valve **12** opens and the fluid is drawn into the compressor volume **8**. Communication between the atmosphere and cushion **5**, which occurs when ports **17** and **18** coincide, closes and the cooling air contained in cushion volume **5** is delivered through channels **20** and the air jacket **22** to atmosphere, thus providing the cooling of the annular armature **4**, the coil **3** and the core **1**.

Armature **4** then closes channel **20** and the air contained in the cushion volume **5** is compressed, thus storing spring energy. At the end of the power stroke valve **12** closes, the excitation of coil **3** decreases very rapidly and the moving assembly is returned towards the right, in direction H_2, by the energy of the compressed air contained in cushion volume **55**. The fluid contained in the compressor volume **8** is compressed and then delivered through delivery valve **15** in the same way as in a conventional machine. The structure of the compressor itself differs very little from that of a conventional compressor, particularly in its essential parts (cylinder, piston, cylinder head, valves) which is advantageous and economical for mass production manufacture. At the end of the stroke cushion **5** is at a lower pressure then atmospheric pressure which results in the admission of fresh air into this volume when ports **17** and **18** coincide.

The characteristics of the structure intended for the pole pieces, the armature and the coil of the machine ensure the advantages of economy of material, thermal symmetry resistance to the movement of the poles towards each other, and good centering of the static and moving parts as explained above.

Furthermore, since all the electro-magnetic energy is transformed at the end of the power stroke into pneumatic energy which is accumulated in cushion **5**, the return forces are considerable and the duration of the return stroke is shorter than in an embodiment in which delivery occurs during the power stroke. The unit power is higher and the price of the machine is lower than in the case of a machine driving during its power stroke but the efficiency is slightly lower.

According to a variant of the first industrial embodiment above, shown in FIG. 3, two machines of the type just described above are placed back to back and a unit twice as powerful is obtained. Furthermore, if a single coil and a double magnetic circuit are used the machine remains the same but with a single magnetic part and two mechanical compressor parts, each identical with the preceding embodiment, these parts having a symmetrical movement which permits operation without vibration.

The magnetic circuit **30**, which is symmetrical on plane C—C, comprises on each side annular poles **31** and **32** of revolution defining the annular air gap **47**. The magnetic circuit is formed from two identical parts **33** and **34**, in which an annular channel is hollowed on the face opposite the poles, in the form of a circular section toroid **35**. A magnetised coil **36** is located in this channel **35** and is fed by successive electrical impulses as in the preceding variant.

The magnetic armature **37** is formed of lamination separated in planes orthogonal to the axis of movement (for example by varnished sheets of annular sector shape) and also on planes passing through the axis of movement, so as to reduce the losses and parasitic forces due to eddy currents. The longitudinal separation of the laminations are further used as grooves for anti-friction material **38**, such as polytetrafluoroethylene, formed as bands.

The magnetic armature **37** is attached to the skirt **39** of compressor piston **40**, which has a different diameter and is of non-magnetic material.

The piston **40** which can be equipped with sealing means **41**, slides in cylinder **42**, closed by cylinder **43** carrying the suction and delivery valves of any known type and not shown.

The compressor volume **48** is defined by piston **40**, cylinder **42**, and cylinder head **43**. A non-magnetic spacer **44** separates the cylinder from the magnetic circuit and ensures their respective centering. A spring located in piston **40** ensures the return of the latter to the top dead point.

The assembly mounted on the other side of plane C—C is exactly symmetrical with that already described.

The two parts **33** and **34** of the magnetic circuit and the two spacers **44** are assembled by tie rods **46**.

Operation is as follows: While an electrical impulse is supplied to coil, **36** the latter magnetises the two magnetic circuits **33** and **34** and the two armatures **37** are drawn into the two annular air gaps **47** following I_1 by the lines of force passing from poles **31** to poles **32**.

During movement towards the centre of the machine, piston **40**, attached to the armatures, draws the fluid into the compressor volumes **48** and at the same time compress springs **45**.

At the end of the electrical impulse, springs **45**, giving back the energy stored during the power stroke, push pistons **40** away from the centre in direction I_2 while compressing the fluid in volume **48** and delivering it to the exterior through the delivery valves.

In view of the fact that the movement of the two pistons during the impulse takes place towards the centre of the machine, thus in opposite directions and speeds, and that the masses of the two moving parts are equal, the machine is balanced and there is no vibration, which is advantageous for large machines.

The two preceding embodiments thus provide two machines, one having twice the power of the other while using the same parts for the compressor assembly (cylinder, cylinder head, pistons, springs, armature).

In both cases the machines thus formed are much more simple to construct and to assemble than normal electro-compressors or electro-pumps sets. Their space and their weight are very small.

In the third industrial embodiment represented in FIGS. 4 to 9 the machine is entirely of revolution and is symmetrical with respect to the central plane. It comprises (FIG. 4) two magnetic cores **51***a*, **51***b* in which are mounted two pole pieces **52***a*, **52***b* thus completing the two static magnetic circuits which are assembled by means of the external cylinder **73** of non-magnetic material whose axis precisely determines the axis of the machine. The magnetic circuits are excited by coils **53***a*, **53***b* supplied from an alternating source **53***c* across inverted diodes **53***d*, **53***e* mounted in parallel. The piston skirts **61** comprise two magnetic armatures **56***a*, **56***b*, relatively poor conductors sliding in the annular air gaps **57***a*, **57***b* whose external extremities **58***a*, **58***b* form return cushions. The skirts **56***a*, **56***b*, piston **61** and magnetic cores **51***a*, **51***b* define two compressor volumes **59***a*, **59***b*. A peripheral extension of piston **61** forms a ventilation piston **62** sliding in the non-magnetic cylinder **63** and thus defining two ventilation volumes **60***a*, **60***b*, which avoids complicating the machine by an external source of ventilation. Volumes **60***a* and **60***b* are fed through single piece suction valves **64** formed from a disc of spring steel whose external part **76** (FIG. 9) is trapped between cylinder **63** and pole piece **51** and whose annular central part is cut away to form a certain number of blades **79** by slots **77**, themselves rounded at their ends **78**.

External air passes through ports **74** drilled in the cylindrical casing **73** and through the channels **69** formed in the cores **51***a*, **51***b* and the pole pieces **52***a*, **52***b*.

Air passes from the ventilation volume **60***a* or **60***b* in skirt **56***a* or **56***b*. The compressed air is delivered through the delivery valve **65***a* or **65***b*. This is advantageously located in the central pole piece **51***a* or **51***b* with its return spring **66***a* or **66***b*. The air is then evacuated through the axial drilling **67***a* or **67***b*. Channels **71***a*, **71***b* and, **72***a*, **72***b* and **75***a*, **75***b* form the cooling air circuit, communicate with the atmosphere through posts **75***a*, **75***b* in the casing **73**, and act as laminations to avoid annular eddy currents. The walls of the channels **71***a*, **71***b*, **72***a* and **72***b* are formed of molded plastic, such as an epoxy resin. Joints **80***a* and **80***b* of flexible non-magnetic material ensure complete separation of the electric part from the pump part which is advantageous in case of corrosive fluids.

Operation is as follows: When coil **53***b* is excited skirt **56***b* is drawn into air gap **57***b* in direction J_1. Valve **64** opens and allows external air to enter under the action of the depression created in volume **60***a* by the movement of the piston **62** to the right in direction J_1. Valve **65***a* closes under the action of spring **66***a*. Pistons **61** and **62** compress the air contained in volumes **59***b* and **60***b*. This air is delivered through canals **71***b* and **72***b*, cooling the delivery valve and the core. Fresh air entering through the valve **64***a* cools skirt **56***a* directly, then towards the end of the stroke, ports **68***a* open, the external fresh air flows directly into the compressor cylinder **59***a* owing to the depression created in this volume by the movement of the piston **61**. In parallel, the air compressed in volume **59***b* is delivered through valve **65***b* and axial channel **67***b*. Also during this end of stroke, skirt **56***b* closes volume **58***b* which forms a cushion return means and closes off channel **71***b* which transforms volumes **60***b* and **58***b* into a cushion return means. The return stroke in direction J_2 is entirely symmetrical.

FIGS. 4 and 5 indicate the direction of movement of the movable armature by an arrow and the circulation of compression and cooling air by broken lines.

In this moving assembly the hottest parts due to contact with hot compressed air are those where the heat given out by electro-magnetic effects is least, and reciprocally, which results in uniform expansion. It may also be noted that the structure described prevents any movement of the pole piece towards one another which might reduce the air gap and require excessive clearance under stationary conditions. In the same way this structure reduces thermal distortion of the assembly to a minimum and provides the best guarantee of maintaining the symmetry with respect to the axis which is essential for obtaining symmetrical electrical and pneumatic forces, and therefore stability and a high efficiency for the machine. The assembly is very compact, has high unit power and comprises very few wearing parts. Its manufacture in quantity is inexpensive.

The fourth industrial embodiment, illustrated in FIGS. 10 to 12, is an application of the invention to a motor alternator (internal combustion electric generating set) and forms an improvement in the structure of electrical generating equipment of which the principle is already well-known. The structure proposed is more especially intended for machines having higher unit power than those already described (above one kw. for example).

It comprises a combustion volume **90** defined by a cylinder head **91** and piston **92**. On the cylinder head are exhaust valves **93** and inlet ports **94** and a means of introducing and igniting fuel **95** of a type already known. A return cushion volume **96** symmetrical with volume **90** with respect to the electro-magnetic part situated in the centre, is defined by a cylinder head assembly **97** and a piston **98**. A non-magnetic rod **99** connects pistons **92** and **98**.

The cylinder piston skirts **100** and **101**, of circular section, are formed by the assembly of moving armatures of a certain number of independent magnetic circuits having three branches preferably arranged radially. These circuits comprise interrupted branches **102**, **103** on the one hand and **104**, **105** on the other, which carry excitation coils **109***a* and **109***b* situated in the immediate neighbourhood of the air gap, which increases the power and the efficiency, and the common branch **106** which carries the power coil **110**. Coils **109***a* tend to cause magnetic flux to circulate between pole pieces **102**, **103** and the same thing applies for the coils **109***b* in respect of the pole pieces **104**, **105**. Lateral members **107** and **108** join these three branches.

Non-magnetic and non-conducting casings **111** and **112** provide the centering of the assembly. The external and internal parts of the stator are defined by cylindrical rings, carrying magnetic plates **117** and **119** placed opposite the poles and in one piece with the rest of the rings which are of non-magnetic material, acting as strengthening rings and preventing the poles from moving towards each other.

The operation already known is as follows: The moving assembly is projected in direction O by the force of the combustion which takes place in volume **90** and this compresses the fluid contained in the cushion volume **96** which, at the end of the stroke, returns the moving assembly in direction N.

Coils **109***a* and **109***b* are excited (as shown in FIG. 10) by direct current supply such that the corresponding flux in branch **106** cancels itself out in the absence of any armature.

When skirts **100** and **101** are introduced alternatively into the air gaps **113** and **114** alternating current is obtained from coil **110** in the normal way already known.

The resulting electrical generating set has high unit power, easy assembly, and inexpensive manufacture in large quantities. The separation into several coils results in an armature having a greater diameter and thus in machines of a higher unit power than those of the first embodiment.

According to fifth industrial embodiment shown as electric compressor (FIGS. 13 to 15) the machine comprises a central casing **120** containing a number of magnetic circuits **121***a,* **121***b* and of coils **122***a,* **122***b,* **132***a,* **133***b,* two skirts formed of annular armatures **123***a,* **123***b* attached to two pistons **124***a,* **124***b* and two cylinders **125***a,* **125***b.*

FIG. 15 shows in detail the structure of a sector of armature **123***a* formed for example in laminations **171** assembled with sheets **172** of epoxy resin, the groups of laminations **171** being separated by spacers **173** of epoxy resin cast between these laminations. The number of stacks of laminations corresponds to the number of poles (8 in the example considered).

The central casing **120** is made of a non-magnetic non-conducting material and comprises a central disc **126** solid with an internal boss **127** and an external sleeve **128** projecting equally relatively to the two faces of disc **126.** Sleeve **127** is cut away axially to receive the inner pole piece **129***a,* **129***b.* Sleeve **128** is cut away to receive outer pole piece **130***a,* **130***b.* These various pole pieces are equally spaced and aligned radially. This assembly comprises the magnetic circuits **121***a,* **121***b.* On the inner pole pieces **129***a,* **129***b* are mounted the magnetising coils **122***a,* **122***b* and on the outer pole pieces **130***a,* **130***b* other magnetising coils **132***a,* **132***b.*

The number of inner pole pieces **129***a,* **129***b* depends on the dimensions of the machine. FIG. 14 shows an embodiment comprising 8 radial pole pieces, joined in pairs by their bases by means of sleeve **127** and equally spaced radially. The extremities **133***a,* **133***b* of the pole pieces constitute the poles and form the inner part of the cylindrical air gaps **134***a,* **134***b.*

The outer pole pieces **130***a,* **130***b* are arranged radially as extensions of the inner pole pieces **129***a,* **129***b.* These pole pieces are also joined in pairs. The parts of each pair are connected at their outer extremities by members **136** forming the arcs of a circle.

The inner ends **137***a,* **137***b* of the pole pieces **129***a,* **129***b* form the poles and form also the outer part of the air gaps **134***a* and **134***b.*

The magnetic circuit is thus formed by four circuits of triangular contour (FIG. 14). These magnetic circuits can be made from sintered material or in the form of laminated sheets **144** as indicated in FIG. 13. In this case, the end sheets are preferably thicker to resist the attraction of armatures **123***a,* **123***b.* The inner and outer surfaces of air gaps **134***a,* **134***b* are covered with a thin coating of polytetrafluoroethylene or other similar non-magnetic, non-conducting, anti-friction material.

Coils **122***a* and **132***a* on one hand **122***b,* **132***b* on the other are fed alternatively, similarly to coils **53***a,* **53***b,* on FIG. 4. Furthermore the associated coils **122***b* and **132***b* are so connected that the magnetic flux circulates in the same direction A (FIG. 14) in the corresponding pole pieces **129***b,* **130***b.* The same arrangement is adopted for the coils of the other group.

The axial canal **131** of sleeve **127** is threaded at each end to receive the caps **139** through which passes a rod **140** whose ends are screwed into the pistons **124***a* and **124***b* so that they move as one unit.

The assembly of the annular armatures **132***a,* **132***b* which form the skirts of pistons **124***a,* **124***b* is so arranged that the stacks of laminations **171** are situated in alignment with pole pieces **133***a,* **137***a* or **133***b,* **137***b.*

Each piston **124***a,* **124***b* is equipped with piston rings or other sealing means and slides in the corresponding cylinder **125***a,* **125***b* which are equipped with suction valves **141***a,* **141***b* and delivery valves **142***a,* **142***b.*

The two compressor assemblies are thus situated outside the magnetic assembly so that a very rigid machine can be achieved since the massive electro-magnetic part is in the centre.

The assembly of the static part of the machine is carried out by first placing the coils on the inner and outer pole pieces of the fixed magnetic circuits which are then inserted axially into the central casing **120** and held in place by the caps **139** and by the dove tail shape of the members **136** inserted into the casing **120.**

Thus the static parts are easily and accurately positioned in the casing. The whole of the static part is then located with a non-conducting non-magnetic material of epoxy resin type (indicated in FIG. 14 by random dots) which renders it sufficiently rigid to avoid distortion due to the magnetic attraction between the poles and to withstand severe operational conditions without damage.

The air gap is suitably protected during this operation. A coating of polytetrafluoroethylene or other material having a low coefficient of friction is then applied to the air gap and thus prevents any contact between the annular armatures **123***a,* **123***b* and the surfaces of the poles, and thus any appreciable lateral force towards the poles, which would be the consequence of contact between the armature and the poles. Pistons **124***a,* **124***b* arc then attached to annular armatures **123***a,* **123***b* then to rod **140,** such that when armature **123***b* fully occupies air gap **134***b,* the other armature **123***a* is ready to enter its corresponding air gap **134***a.*

Finally, cylinders **125***a,* **125***b* are fitted over the pistons and assembled with screws **143.**

Operation is as follows:

Electrical impulses alternatively feed coils **122***a,* **132***a* of the first half of the machine, then coils **122***b* and **132***b* of the second half.

When coils **122***a,* **132***a* are excited, armature **123***a* is drawn into the corresponding air gap and the other armature is drawn out of its air gap, the moving assembly moving in direction L. At the end of the stroke, when armature **123***a* completely fills air gap **134***a* the electrical impulse is cut off and coils **122***b,* **132***b* of the other half are excited in their turn, drawing armature **123***b* into its air gap **134***b* and the moving assembly in direction M. The moving assembly thus has a reciprocating movement during which the pistons draw in, compress and deliver air in cylinder **125***a,* **125***b,* by means of corresponding valves.

What I claim is:

1. An electro-mechanical energy converting machine comprising at least one fixed electromagnetic circuit having spaced apart cylindrical and coaxial pole surfaces defining an annular cylindrical air gap, a field coil on the fixed magnetic circuit adapted to generate a magnetic field across the air gap, means to reduce the flow of eddy currents that tend to travel along annular paths concentric with the air gap in the fixed magnetic circuit, an operating piston incorporating a tubular cylindrical magnetic armature mounted for reciprocating movement along a path disposed transversely to the magnetic field, the magnetic armature disposed coaxially with the pole surfaces of the fixed magnetic circuit, a part of the fixed magnetic circuit being located within the armature for at least part of the stroke of the armature, the armature formed to be a poor conductor of eddy currents to minimize the flow of eddy currents therein, an operating cylinder having an inner surface that is coaxial with the pole surfaces, the operating piston sliding along the inner surface of the cylinder to guide the piston and center the armature in the air gap, and means including supporting structure for centering the cylinder on the axis of the cylindrical air gap so that the maximum possible displacement of the armature from its axial position in the air gap is less than half the residual clearance between the armature and the pole surfaces, the residual clearance being less than one-fifth the distance separating the pole surfaces.

2. A machine according to claim **1,** wherein the operating piston comprises the piston of an air compressor.

3. A machine according to claim **1,** wherein the operating piston comprises the piston of a heat engine.

4. A machine according to claim **3,** in which is provided two fixed magnetic circuits each of which includes an annular cylindrical air gap, each of the magnetic circuits carrying at least one magnetizing coil, two tubular cylindrical magnetic armatures respectively movable in the air gaps of the fixed magnetic circuits, and a third common magnetic branch of the two magnetic circuits carrying a coil for the generation of alternating current.

5. A machine according to claim **1**, wherein the operating piston comprises the piston of a reciprocating pump.

6. A machine according to claim **1**, in which is provided means forming cooling passages in the machine, and the operating piston includes a central part and an outwardly extending part, the outwardly extending part functioning as a piston of a pump that insures circulation of a cooling fluid through the cooling passages in the machine.

7. A machine according to claim **1**, wherein said centering means includes a cylindrical bore, the bore centering the fixed magnetic circuit with respect to the operating cylinder.

8. A machine according to claim **1**, in which is provided a cylindrical ring formed partly of magnetic material and partly of non-magnetic material to hold pole pieces of the fixed magnetic circuit in place and prevent any variation in the dimensions of the air gap under the influence of magnetic attraction forces.

9. A machine according to claim **1**, which includes a plurality of fixed magnetic circuits extending radially from the axis of the machine, each of the circuits including at least one coil whose axis is perpendicular to the axis of the magnetic armature, and said coil being located adjacent to the air gap.

10. A machine according to claim **1**, in which is provided an operating cylinder located on each side of the fixed magnetic circuit, each of the operating cylinders centering one of the operating pistons rigidly joined to the tubular cylindrical magnetic armature, the fixed magnetic circuit having two coaxial annular air gaps in which the two magnetic armatures and operating pistons are mounted to move in opposite directions.

11. A machine according to claim **1**, in which two magnetic armatures extend axially in opposite directions from and form part of the operating piston.

12. A machine according to claim **1**, wherein the fixed magnetic circuit includes first pole pieces extending substantially radially from the air gap inwardly, the pole pieces being joined at their bases and bearing on an axial sleeve, and second pole pieces extending substantially radially from the air gap outwardly in line with the first pole pieces and interconnected by annular cores engaged by an external casing.

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