672548

This invention relates to electric machines of the variable-reluctance type.

Such a machine generally comprises two cooperating parts movable relatively to one another, and one of which will herein be termed stator (even though it is not necessarily stationary), and the other will be termed the moving part. The moving part may be either reciprocable or rotatable with respect to the stator, and in the latter instance constitutes a rotor. The stator part comprises one or more pairs of

10   electromagnetic poles while the moving part comprises magnetic portions projecting towards the stator poles and adapted, during the relative movement between the stator and moving part, to pass closely adjacent to the stator poles and define narrow airgaps therewith. The relative movement of the magnetic portions past the stator teeth produce variations in reluctance in the operation of the machine.

While the relative movement of the moving part with respect to the stator is usually one of rotation, in the usual case where the machine is an electric motor or generator,

20   movements of reciprocation are also sometimes used as in electromagnetically operated pumps and other reciprocatory devices.

In the construction of variable-reluctance machines, as in the majority of rotary electric apparatus in general, it is common practice to avoid bringing the material, e.g. iron, in the magnetic circuits close to saturation, in an attempt to maintain the efficiency ratio of the machine at a desirably high level. Usually the machine is so designed that the permeability of the iron is higher than about 100

30   throughout the major portions of the machine, except adjacent

*

the polar areas where a lower permeability value within a range of say 10 - 25 is maintained.

In a variable-reluctance machine the electromagnetic torque and hence the power output is proportional to the product of the magnetic field generated by the stator poles and the magnetic flux or magnetizing force of the magnetic projections of the moving part. To increase the torque therefore, it would evidently be desirable to increase the flux in the projections and hence maintain the material thereof

10   close to saturation. Heretofore, however, it has not been found feasible to construct machines of the specified type in which the magnetic projections were saturated, or in fact had a permeability value of less than about 10.

It is an object of this invention to provide an improved variable-reluctance electric machine in which the power output for a given dimensioning of the machine, and specifically the power/mass ratio, will be substantially increased over what has been heretofore thought possible, without any decrease in the efficiency ratio.

20   In accordance with the invention, there is provided a variable-reluctance electric machine wherein the magnetic portions of the moving part cooperating with the stator poles, are substantially saturated. By this it is meant that the permeability of said portions is in a range of from about 2 to about 10, and preferably no greater than about 8. At the same time the remaining magnetic portions of the machine are kept substantially unsaturated, by which it is meant that the permeability therein is greater than about 12, and preferably greater than about 15.

30   The basic feature of the invention residing in the

afore-mentioned reduction in the magnetic permeability of

the magnetic portions of the moving part cooperating with

the stator poles, as compared to the range of values currently

used, may be achieved through various means. Thus said portions

may be formed from a suitably selected magnetic material

different from that constituting the stator and the remainder

of the moving part. However, in accordance with a preferred

form of the invention usable instead of or concurrently with

the foregoing measure, the average density of the magnetic

10   material in said portions is reduced, as by interspersing in

said projections portions thin sheets of iron with sheets or

spaces of non magnetic material, e.g. air.

A variable-reluctance machine according to the

invention is preferably so constructed that the maximum

magnetic field present at the stator poles is at least four

times, and preferably considerable more times, the field

value required to saturate the magnetic portions or teeth of

the moving part, and the design is such that the average

magnetic induction in said teeth is substantially one half

20   the maximum value of induction provided in the remaining

parts of the machine. However, the ratio of the induction

in the teeth to the maximum induction in the remaining magnetic

circuits in the machine may depart substantially from the said

value 1/2, e.g. may lie within a range of from 40 to 60 %,

or from 15 to 85 %.

The magnetic teeth of the moving part of a machine

according to the invention is preferably made from a material

having a substantially rectangular characteristic, e.g. pure

iron.

In a preferred embodiment of the invention, the

30   stator is provided with at least two similar pairs of poles

and the stator and rotor are so constructed that the angular extent of a rotor tooth substantially equals the combined angular extent of one stator pole plus the spacing between adjacent stator poles.

Exemplary embodiments of the invention will now be described with reference to the accompanying drawings, given by way of illustration but not of limitation, and wherein:

Fig. 1 is a simplified cross sectional view, on
line I-I of Fig. 2, of a bipolar synchronous motor constructed in accordance with the invention;

Fig. 2 is a corresponding longitudinal section on line II-II of Fig. 1; and

Fig. 3 is a view similar to Fig. 1 showing a four-pole alternator according to the invention.

The variable-reluctance rotary machine shown in Figs. 1 and 2 is a synchronous motor, and comprises a stator 1 formed with the symmetrical pair of poles 2a and 2b each carrying a field winding 3, and a rotor 4 secured on a rota-
table shaft 5 and formed with the symmetrical pair of polar projections or teeth 6a, 6b, cooperating with the stator poles. The dimensioning is such, according to well-known practice in machines of the general class to which the invention relates, that the radial width e of the airgap defined between the stator poles and rotor teeth is a very small fraction, preferably not greater than 1/100, of the radial extent of the rotor teeth 6a, 6b.

The construction of the machine in the aspect of it visible in Fig. 1, is generally conventional. However,
the invention provides certain constructional features, now

to be described, whereby the torque developed by the synchronous motor shown will be considerably increased over the range heretofore attainable, ceteris paribus, and will in fact approximate the maximum possible torque, while retaining a satisfactory efficiency ratio. In attaining this dual objective, the invention provides means for, on the one hand, maintaining the rotor teeth 6a, 6b substantially at magnetic saturation, i.e. with a low magnetic permeability, while, on the other hand, keeping the magnetic circuits of the stator and remaining

10   portions of the rotor in a condition remote from saturation, i.e. with a substantial permeability value, at least greater than about 15.

For this purpose in the embodiment shown the stator 1 is formed as a stack of sheets 7 of silicon steel or the like high-permeability material, wherein the maximum flux density (adjacent the polar surfaces) may equal e.g. 23,000 gauss, corresponding to a permeability of 15. The rotor 4 on the other hand is made as a set of axially spaced strips or sheets or high-purity iron separated by spacer disks 10

20   which do not extend radially as far out as the rotor tooth portions 6a, 6b, so that the iron strips in said portions are separated by airgaps. The spacer disks may be made from a magnetic material such as silicon steel. A simple calculation will show that with the stator and rotor constructed as just described, the above specified conditions relating to high saturation in the rotor teeth coupled with low saturation in the stator and remainder of the magnetic circuits of the machine, can be readily attained.

The maximum induction or flux density in the silicon-

30   steel stator sheets 7 as obtained adjacent the polar surfaces,

is selected equal to C = 23,000 gauss, corresponding to the
permeability value of 15 previously selected. The average
induction or flux density B for saturating the rotor teeth
63, 6b is then selected at a value of about 0.5 C, which is
an optimum ratio as will later be explained, i.e. a value of
about 11,500 gauss. Assuming the saturation flux density of
the high-purity iron from which the rotor is made is 21,500
gauss, then to obtain the desired average flux density of 11,500
gauss just mentioned in the rotor teeth, it is necessary that
10   the volume of the iron strips 8 in the rotor teeth should
represent a fraction of 11,500/21,500 of the total volume of
said teeth, i.e. 53% of such total volume. Assuming pure iron
strip of 0.5 mm gauge is used in making up the rotor, then the
air spaces between the adjacent strips 8 should be 0.5 x
(47/53) = 0.44 mm wide, this being obtained by using spacer
disks 10 having a thickness of 0.44 mm.

        In the operation of the machine described, when
the field windings 3 of the stator are energized with current
of a value to generate a magnetic field of 11,500 oersteds
20   adjacent the stator poles 2a and 2b, the average flux density
in the rotor teeth is substantially equal to the sum of the
flux density in the airspaces defined between the stator pole
surfaces and the smaller-radius cylindrical surface portions
of the rotor, i.e. 11,500 gauss, plus the average saturation
flux density in the teeth, i.e. 11,500 gauss also, or a total
of 23,000 gauss. The flux density in the stator poles adjacent
the rotor teeth which is essentially the same as the average
flux density in the teeth, i.e. 23,000 gauss as predetermined,
will therefore not exceed the prescribed value, corresponding
30   to the minimum permeability value of 15. Hence, the machine as

constructed will operate to develop a torque close to its
maximum value owing to the low saturation in the rotor teeth,
while at the same time retaining a high efficiency ratio
since all remaining portions of the magnetic circuit including
especially the stator poles, are kept away from the saturated
condition in that their permeability value is substantially
higher than 15.

It will be understood that when, in operation, a
strong magnetic field H (e.g. about 10,000 oersteds) is
10   obtained between the stator poles and the reduced-radius
cylindrical part of the rotor, and as a rotor tooth enters
the area covered by a stator pole, then the electromagnetic
force F applied to the rotor is proportional both to the
transverse sectional area of the rotor tooth (on a radial
plane), and to the product of said field H by times the
average saturation flux density B of the tooth; since more-
over the teeth are saturated, this average flux density B
is the same as the average magnetization intensity in the
tooth.

20   Provided the field H is considerably higher than
that required to saturate the teeth, e.g. at least four times
and preferably at least ten or more times higher, a condition
that is eadily fulfilled by using a suitable magnetic material
for the rotor teeth such as the high-purity iron mentioned
above, then it is easily shown by simple calculation that the
sum of the magnetic field H plus average saturation flux
density B in the teeth is substantially equal to the average
flux density C selected for the stator poles and the cylindrical
portion of the rotor between the rotor teeth.

30   Thus, in the machine described, $H + B = C$, C being

a prescribed value. As to the magnetic force F applied to each rotor tooth this is proportional to the product H x B. It will be understood that it is most desirable in practice to make the force F as large as possible in a machine of given size and remaining structural characteristics, since both the developed torque and the power/mass ratio of the machine are proportional to the force F.

In order to make the quantity F = H x B a maximum, possible, remembering that the sum H + B of the factors in this product is equal to a constant C, it is well-known from elementary arithmetic that the two factors in the product should be made equal, i.e. H = B = 1/2 C. It is also known that as the two factors H and B depart gradually from their optimal value 1/2 C in opposite sides, the product of said factors, which product equals F times a proportionality factor k, varies parabolically, i.e. decreases first at a very slow rate, then increasingly fast. This is illustrated in the following tabulation:

V a l u e s o f :			% Reduction
H	B	kF = H x B	in F
0.5 C	0.5 C	0.25 C	0 %
0.4 C	0.6 C	0.24 C	4 %
0.3 C	0.7 C	0.21 C	16 %
0.25C	0.75C	0.19 C	24 %
0.20C	0.80C	0.16 C	36 %
0.15C	0.85C	0.13 C	48 %
0.10C	0.90C	0.09 C	64 %
0.05C	0.95C	0.05 C	80 %

According to the invention, the relative values of H and B should be selected as close as practical to the

common optimal value of 0.5 C. However, the above table shows

that considerable departures may be tolerated from this

theoretical optimum while still retaining the benefits of

the invention. Thus, in view of various practical considerations

in the manufacture of the machine, it may sometimes be desirable

to select one of the two values H and B as small as 0.15 C and

the other as large as 0.85 C, in which case the percentage

reduction in the resulting force F is less than one half from

its maximal value. Preferably however one of the two values of

10   H and F is selected not lower than 0.30 C and not higher than

0.70 C, in which case the magnetic force F is not less than

84% of its theoretical maximum as shown by the above table.

The same statement can be expressed in different

terms as follows: according to the invention, the machine is

so constructed that the average magnetization intensity in

the rotor teeth should lie within the range of from about

60 % to 333 % (or preferably from about 85 % to about 125 %,

the optimum value being about 100 %), of the magnetic field

present adjacent the stator poles. That the two statements are

20   equivalent can easily be shown as follows: consider for example

an average magnetic field strength of 10,000; the maximum flux

density is 20,000 gauss. Then, considering the broad above-

mentioned range of 15 % - 85 %, 15 % over 20,000 is 3,000 and

85 % over 20,000 is 17,000. Referring these average field

strength values present in the rotor teeth to the 10,000 gauss

magnetic field present adjacent the stator poles, it is seen

that the respective ratios are 10,000/3,000 = 333 %, and 10,000/

17,000 = 59 %, rounded off to 60 %.

While it has been indicated that maximum power/mass

30   ratio is obtained when the values of H and B are equal,

and each being equal to 0.5 C, it should be understood that

this statement is not always strictly true. In some cases,
e.g. if the magnetic field H does not remain uniform over
the total displacement of a tooth past a stator pole but
varies (e.g. sinusoidally) during such displacement, then the
optimum ratio may depart somewhat from that indicated.

In order to ensure that the magnetic field required
to saturate the teeth is low in comparison to the magnetic
field H created by the stator poles, the rotor teeth should
be made from a material having a relatively rectangular
10 magnetization curve, such as the high-purity mentioned earlier.
Thus, in the case of iron containing 99.98 % Fe, 95 % of the
saturation flux density are attained with a magnetic field
less than 200 oersteds, which of course is many times lower
than the usual maximum value of say 11,000 to 12,000 oersteds
for the field H.

The above considerations show how it is possible
in all cases to construct the stator and rotor of a variable
reluctance machine of given power rating so as to fulfil the
dual condition taught by the invention and achieve the
20 advantages accompanying the fulfilment of such condition.

Fig. 3 of the drawings illustrates a four-pole
alternator constructed in accordance with the invention. The
alternator comprises an annular stator 11 formed with the
four equispaced polar projections 13a, 13b, 13c and 13d, and
a rotor 18 secured on a rotatable shaft 19 and formed with
the pair of opposite magnetic projecting portions or teeth
20a, 20b. Both the stator and rotor are constructed in
accordance with the teachings of the invention, e.g. in the
manner explained in connection with Figs. 1 and 2, so as to
30 provide a high degree of saturation within the rotor portions

20a, 20b while providing a substantially unsaturated magnetic condition in the remaining magnetic circuit portions of the alternator including especially the stator poles.

Each of the four stator poles 13a through 13d carries a respective field winding 14a through 14d. The four windings have their adjacent ends B-C, D-E, F-G and H-A, connected together and to a common one of the four terminals I, J, K and L, which thus form the four apices of an impedance bridge. Across the bridge diagonal I-K, an excitation voltage

10   is applied from d-c excitation source 17 having its poles connected through lines 16a and 16b to terminals I and K respectively. From the other bridge diagonal K-L, the output alternatating voltage is derived through the lines 15a and 15b.

In accordance with a preferred arrangement in this form of the invention, the angle c subtented by each of the two rotor teeth 20a, 20b, is made equal to the sum of the angle a subtented by one stator pole such as 13c plus the angle b subtented by an interpolar space of the stator.

20   In operation, considering the rotor 18 to be revolving clockwise (arrow F1), it is evident that as the leading end M of either rotor tooth, say 20a, is moving past the leading end R of a stator pole, e.g. 13a, then the trailing end N of the same rotor tooth is moving past he leading end P of the stator pole 13d immediately preceding said first pole 13a. Hence, the magnetic flux traversing winding 14d of pole 13d is decreasing at the same rate as the flux through winding 14a of pole 13a is increasing. In other words the rates of flux variation in any pair of adjacent stator poles such as 13a and

30   13d are equal but reverse at any given instant of time. As a

result the induced e-m-f's in the two windings 14a and 14d at

any time are equal and opposite in sign (or phase condition),

and the opposed terminals I and K of the bridge circuit are

at all times at equal a-c potentials, so that there is no

circulation of alternating current through the d-c excitation

lines 16a and 16b. All of the input energy applied as mechanical

energy of rotation to rotor shaft 19 is collected (neglecting

inevitable minor losses in the magnetic and electric circuits)

as alternating voltage energy across the output terminals J

10   and L of the bridge circuit, so that the efficiency ratio is

at a maximum. It is essential to observe that this highly

desirable mode of operation is only made possible by the basic

teaching of the invention that the magnetic teeth of rotor 18

are substantially saturated while the remaining magnetic circuit

portions of the alternator are unsaturated. Otherwise, the

rates of flux variation in adjacent stator poles would not at

all times retain equal absolute values and opposite signs,

nor would the excitation terminals I and K be at all times at

equal a-c potentials as described above.

20   It will be understood that various modifications may

be made in the embodiments shown and described, as by varying

the number and configuration of stator poles and/or magnetic

portions of the rotor, and that the teachings of the invention

may be applied to variable-reluctance machines of other types

than those shown, including both motors and generators, wherein

the movable part of the machine may be a rotor, as shown, or

a reciprocating member.