This invention relates to a variable-reluctance electric motor supplied by a direct current source, able to operate with a low speed and mainly comprising a rotor having teeth of uniform pitch, an annular stator in which magnetic studs or patches or the like have windings being selectively and temporarily energised by a d.c. supply, by means of switching devices of said stator windings under the control of a control device synchronized onto the instantaneous angular position of the rotor, the whole being such that the back-electromotive force and the delivered torque are constant for a given current.

The conventional construction for such machines is to embody the stator in the form of two rings of studs or patches or the like which are symmetrical of a centre-plane perpendicular to the machine shaft, each ring comprising four studs or the like per tooth. With this system, the maximum number of teeth possible is 10 or 12 and a large number of windings, as a rule, at least four windings per tooth, must be provided. If N denotes the mean motor speed in rpm and n denotes the number of rotor teeth, the usually electronic commutating facility provided must operate at a commutation frequency of 4Nn.

A slow-running motor is of use e.g. for driving a land vehicle by direct drive of the driving wheels without any step-down or for a surface or underwater vessel whose screws must be driven fairly slowly if performance is to be satisfactory. The only way of optimising the possibilities of the electronic switching facility in a slow-running motor of this kind is to increase the number of rotor teeth, in which event there is an appreciable increase in constructional complexity and in the copper weight of the windings.

It is an object of this invention to obviate these disadvantages by providing a novel machine construction in which the number of rotor teeth can be increased without any proportional increase in the number of windings, as a result of an appropriate regrouping of the studs or patches or the like in the windings.

Accordingly, this invention provides a machine of the kind hereinbefore specified wherein the stator has a number 4m of identical sectors which is a multiple of four and which is equal to or greater than eight, each sector comprising magnetic studs or patches or the like uniformly distributed at the same pitch as the rotor teeth and a single winding covering all the studs or the like of the sector, any two consecutive sectors being spaced apart from one another by an interval such that between any two consecutive sectors the rotor teeth are set back by a quarter pitch or a multiple (n) thereof with respect to the direction of the rotation of the rotor. Clearly, therefore, the number of rotor teeth is the same as the total number of sector studs plus n × 25% of the number of sectors, whereas the number of windings becomes the same as the number of sectors, so that the intended result is achieved. The reason for choosing at least eight sectors is to ensure that the rotor is in proper mechanical balance. The reason for the offset of 25% of the rotor pitch or a multiple thereof between consecutive sectors is of course, as will become more clearly apparent from the description, to ensure that the elementary back-electromotive forces and the mechanical forces are complementary.

Advantageously:

the peripheral length of each stud or patch or the like is less than the peripheral length of each rotor tooth, and the peripheral length of each between-studs projection is greater than the peripheral length of each such tooth. This feature ensures that sufficient dead times (times of zero induced voltage in the inside winding) are available for commutation;

each tooth is in known manner embodied by ferromagnetic lamellae embedded in a non-magnetic substance, and

the density of ferromagnetic substance over the peripheral length of each tooth is variable, being relatively high near the tooth axis and being lower in the two end parts around the relatively high-density axial part, for the magnetic flux in each stud then varies in time in accordance with a law enabling the elementary back-electromotive forces to be complementary.

The invention will be more clearly understood from the following description of an embodiment, reference being made to the accompanying drawings wherein:

Fig. 1 is a view in cross-section on the line I- I of Fig. 2 of a motor according to the invention;

Fig. 2 is a view in radial section of the same motor on the line II-II of Fig. 1;

Fig. 3 is a basic diagram of the electronic commutating or switching facility for the stator windings;

Fig. 4 is a diagrammatic diagram of the stator studs or patches or the like, of a rotor tooth at various times in a period, and of the programme of current flows through the stator windings;

Fig. 5 is a diagram showing variations of the elementary back-electromotive forces (emf's) in the various windings;

Fig. 6 is a diagram representing signals G_1 to G_4 applied to corresponding control electrodes of said switching devices of the stator windings;

Fig. 7 shows the geometric positions of energized stator windings at a determined time in the case of a eight stator windings motor; and

Fig. 8 shows a diagram analogous to that of Fig. 7 for a motor having sixteen stator windings.

As shown in Figs. 1 and 2, a variable-reluctance motor according to the invention has an axis I-I of symmetry of revolution and, perpendicular to such axis, a plane of symmetry III-III. The motor comprises a rotor 1 rigidly secured to a shaft 11 running in rolling bearings 12, 13 and a stator 2. Rotor 1 is embodied by a ring of laminations of non-saturable silicon iron having a high density of iron, said laminations having the same shape.

Teeth, as 101, which are in general shape oblong, extend from the cylindrical peripheral surface of the rotor ring into the stator-rotor air gap. In the example shown it is assumed that there are 50 teeth; they are disposed at a constant pitch of twice the peripheral length of one tooth; their density varies in that they have a short central portion with a relatively high iron density, e.g. 84%, symmetrically framed by two much lower density end parts, e.g. of 42%; it is a very simple matter to devise this 2: 1 ratio between the densities by means of overlapping in the central part of the sheets used for the two end portions; these laminations for instance may be identical and have the shape of a toothed wheel having a uniform pitch, the peripheral length of said laminations teeth being lower tha the peripheral length of stator studs, which is in turn lower than the peripheral length of rotor teeth. These laminations may be stacked with angular shifting with each other alternatively in a determined direction and in the opposite direction; said shifting for instance being equal to 2°. Of course, because of this lower density of the teeth the same become saturated when the magnetic field produced in the air gap is strong enough.

Stator 2 is also embodied by a ring of laminations of nonsaturable silicon iron having a high iron density.

Rectangular-based studs or patches or the like, as 201, extend from the cylindrical underside of the ring into the stator-rotor air gap. The members 201 are so distributed that the machine can operate on the known basis hereinbefore set forth. Accordingly, the stator of the example of Figs. 1 and 2 has eight identical sectors I - VIII each having six studs at the same pitch as the rotor teeth; however, any two consecutive sectors are separated from one another by a gap such that from one to the other the rotor teeth are set back by 25% of a pitch with respect to the direction of rotation of the rotor; consequently, in the example shown there are only

$$8 \times 6 = 48 \text{ studs } 201 \text{ for } 50 \text{ teeth;}$$

also, each sector comprises a single winding which covers all the six studs of the particular sector concerned. Of course, the cross-section of each winding is sufficient to achieve the required number of ampere-turns for producing an appropriate magnetic field between the stud undersides and the cylindrical part of the rotor.

The windings B_I to B_{VIII} are energized by a d.c. source S and switched or commutated, as will be seen hereinafter, e.g. by means of thyristors TH_1 to TH_4, in a circuit arrangement whose underlying idea is shown in Fig. 3. The control grids G_1 to G_4 of said thyristors are connected to a squared signals generator of known type supplied by source S and synchronized onto said rotor.

Current distribution between the windings is shown in Fig. 4. The top left-hand side of Fig. 4 shows how the studs of the various stator sectors I - VIII are offset from one another (by 25% of rotor pitch). The bottom left-hand part of Fig. 4 shows a rotor tooth considered during its advance of a pitch from the time t_o to time t_8, which are equidistant times in an interval corresponding to a movement of a pitch of the stator; the peripheral length of the tooth, as mentioned above, is between the peripheral length of a stator stud and the peripheral length of the normal gap or interval between two studs. The bottom right-hand part of Fig. 4 shows a graph on the same time scale and showing for the same period the conductive intervals (solid line), the non-conductive intervals (broken line) of the windings B_I to B_{VIII}, and the commutation or switching times, which are actually brief breaks and are denoted by crosses.

As will be clearly apparent, for instance, at the time t_3 the current flows through the windings B_I, B_{II}, B_V, B_{VI} at a time when the least dense portion of the teeth is entering the air gaps of the corresponding sectors and leaving the air gaps of the sectors III, IV, VII and VIII; also, at the time t_4 current continues to flow through the windings B_{II}, B_{VI} but is gradually being cut off in the windings B_I, B_V, at a time when the high density portion of the teeth is entering the air gaps of segments II, VI and leaving the air gaps of the sectors I, V.

What has just been stated with respect to the times t_3, t_4 can be repeated for the following times of the period considered, of course with a circular permutation of the indices.

The back-emf's produced in the various windings vary as shown in Fig. 5.

Fig. 6 shows signals G_1 to G_4 applied to the four control electrodes G_1 to G_4 of the thyristors which cause the flowing of currents in the eight stator windings of Fig. 4.

Fig. 7 shows a geometric diagram of energized windings energized at time t_3. These windings are referenced B_I, B_{II}, B_V and B_{VI}. At time t_5, after a rotation of the rotor of a quarter of a pitch, the energized windings are B_{II}, B_{III}, B_{VI} and B_{VII}

windings and it is clear that the energized windings have been shifted by a eighth of a circumference, which is equal to the length of a sector, in the direction of rotation of the rotor.

Fig. 8 shows a geometric diagram of energized windings at a determined time, in the case where it is provided 16 windings and 16 sectors, the shifting of stator studs from a sector to the following being also equal to a quarter of a pitch of the rotor teeth. Said energized windings are B_I, B_{II}, B_V, B_{VI}, B_{IX}, B_X, B_{XIII}, B_{XIV}, windings. After a movement of the rotor of a quarter of a pitch, the new energized windings are shifted of the length of a sector, that is to say 22°5, with respect to the previous energized windings. In said case, the studs pitch is further equal to the rotor teeth pitch, but the difference between the entire number of rotor teeth and the entire number of studs stator is equal to four. For instance, it may be provided 96 studs and 100 teeth, the number of studs associated to a winding being again equal to six.

In said motor with sixteen windings, the depth of magnetic circuit may be lower than the corresponding depth of a eight windings motor and the positionning of said windings in corresponding sectors is easier than in a eight windings motor.

To the extent that appropriate commutation establishes the current flow and maintains the same constant in the windings around the sectors whose air gaps the teeth are entering, the sum of the tangential forces of the magnetomechanical forces applied to the rotor, and the resulting torque, are constant. Torque is therefore substantially proportional to current at any rotor speed unless the stator studs and the cylindrical part of the rotor are saturated.

A machine of this kind is a variable-speed motor which has a very high torque-to-weight ratio and more particularly a very high torque in relation to the copper weight of the windings. For instance, a 14kg motor can provide a starting torque of 45 metres-newtons with a power dissipation not exeeding 700 watts.

Of course, a relatively powerful motor can, conveniently, have an exciting winding as well which is disposed in the stator coaxially of the shaft.