

SPECIFICATION

Brushless d-c motor

- 5 The invention relates to a brushless d-c motor with a permanent magnetic rotor. Its poles exhibit a magnetization, which runs a course clearly deviating from a sine function on the pole surface when viewed in the direction of rotation. The course is in particular about rectangular or trapezoidal and possibly the poles of the rotor are separated from each other by symmetrical or asymmetrical pole gaps.
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- 15 It is known to obtain pulses from the main winding of a brushless d-c motor in operation. The frequency of the pulses is proportional to the momentary rotor speed and can therefore be used for measuring or controlling the motor speed. However, the frequency is relatively low, to wit $p \times \omega_{\text{mech}}$, wherein p is the number of pole pairs and ω_{mech} is the angular velocity of the rotor in 1/s. Furthermore, the pulses obtained ("decoupled") are easily influenced in their relative phase position with respect to each other and relative to the position of the rotor by the driving currents flowing in the main winding. A speed control employing these pulses for comparing nominal and actual values is thereby very negatively influenced and easily continuous oscillations of the rotor can be produced.
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- Therefore, it is an object of the invention to provide a brushless d-c motor, which generates with little equipment requirements pulses having a sufficiently high frequency proportional to the motor speed. The pulses are preferably uninfluenced by the driving currents flowing in the main winding of the motor.
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In accordance with the invention, this object is achieved by providing a brushless d-c motor comprising:

- (a) a permanent magnet rotor, the poles of which have a non-sinusoidal magnetisation and are separated by pole gaps;
 - (b) a stator;
 - (c) a main armature winding;
 - (d) means for pulse energising the main armature winding; and
 - (e) a sensor winding positioned on the stator adjacent the associated armature to provide output signals induced in the sensor winding, which signals are a harmonic or a multiple of the base frequency induced in stationary conductors on the stator during operation of the motor,
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- wherein the sensor winding and main armature winding are of different pitches and are relatively positioned to avoid transformer coupling therebetween.
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- The spacial harmonic fields formed in the nonsinusoidally magnetized rotor poles induce voltages in the sensor winding corresponding to the harmonic wave, for which the sensor
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winding is dimensioned.

The fundamental wave is suppressed substantially and in many embodiments completely.

- 70 The sensor winding is so disposed as to suppress transformer coupling between it and the main winding and to substantially avoid such coupling. This is achieved by a special selection of the spacial phase position between the main winding and the sensor winding and possibly by deletion of several winding steps and/or spacial phase shifting of part of the sensor winding with respect to the other part. A particularly simple arrangement of the sensor winding results when separate slots are provided therefor, having a position exactly defined relative to the main winding. For economic reasons, it is advantageous to place the sensor winding directly into the slots of the main winding, since then no additional slots are required for the sensor winding. Even under this limiting condition in accordance with the invention sensor windings are possible, which do not exhibit transformer coupling with the main winding. This can be achieved, for example, by having a sensor winding comprising two simple wave windings shifted relative to each other by a certain angle. In certain cases, individual winding steps have to be deleted as will be shown clearly in the following by way of example. Further details and advantageous developments of the invention are shown in the description which follows and in the drawings of embodiments, which are not to be construed as a limitation of the invention. In the drawings:
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Figure 1 a sectional view through a first embodiment of a motor of the invention,

- 105 Figure 2 a sectional view through the stator of a second motor according to the invention, which is similar to the first embodiment represents an external rotor motor,

- Figure 3A-3C pictures explaining Figs. 1 and 2,
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Figure 4 a circuit diagram explaining the invention,

- Figure 5 a variant to Fig. 3B showing main windings employed with the sheet metal stamping of Fig. 2, which windings can be advantageously employed even independently of the sensor winding,
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- Figure 6 a plan view of the stator winding of a four pole motor with planar air gap and a sensor winding suitable for decoupling of the second harmonic wave,
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- Figure 7 an alternative type to the sensor winding of Fig. 6, which is particularly suitable for flat motors having an axial stray field,
- 125
- Figure 8 a second alternative type to the sensor winding of Fig. 6, which is also particularly suitable for flat motors having an axial stray field,

- Figure 9 an enlarged representation of the unrolled magnetization represented in Fig. 3A
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of a rotor for a cylindrical air gap,

Figure 10A the course of the magnetization of the rotor shown unrolled in Fig. 9,

Figure 10B the course of the induced voltage in the conductor L according to Fig. 9 upon a complete revolution,

Figure 10C, D, E the fundamental, the second and fourth harmonic wave of the voltage shown in Fig. 10B,

Figure 11 a sensor winding for decoupling of the fourth harmonic of the motor shown in Fig. 6,

Figure 12 a variant to Fig. 11, also for decoupling of the fourth harmonic,

Figure 13 a sensor winding for decoupling of the 15th harmonic of the motor shown in Fig. 6 at a slightly reduced scale,

Figure 14A-14D a representation for illustrating the construction of a sensor winding for decoupling of the second harmonic (Fig. 14C) and of the fourth harmonic (Fig. 14D), respectively, of an external rotor motor employing the sheet metal stamping shown in Fig. 2 and the type of stator winding shown in Fig. 5,

Figure 15 the frequency spectrum resulting from analysis of the voltage u shown in Fig. 10B, wherein the amplitude of the fundamental and of the first harmonic is shown only numerically,

Figure 16A-16E a variant of a four pole, three strand, three pulse brushless d-c motor, which is formed as an external rotor motor and the stator of which having a sheet metal stamping with 24 equally distributed slots 1'-24', into which are wound the three stands of the stator winding and a sensor winding (Fig. 16D) for decoupling the third harmonic,

Figure 17A-17E a variant with a two pole, three strand, three pulse brushless d-c motor, which again is formed as an external rotor motor and the stator sheet metal package of which has 6 equally distributed salient T-poles as well as 6 auxiliary slots B, D, F, H, K and M for receiving a sensor winding (Fig. 17D) for decoupling of the third harmonic,

Figure 18A-18F a variant with a two pole, two strand, four pulse brushless d-c motor which again is formed as an external rotor motor and the stator sheet metal package of which has four equally distributed salient T-poles and four auxiliary slots B, D, F and H, wherein the sensor winding (Fig. 18F) is again constructed for decoupling of the third harmonic and in a very specific way laid out for avoiding transformer coupling with the two strands of the main winding,

Figure 19A-19E a variant with a four pole, two strand, four pulse brushless d-c motor, which here again is formed as an external rotor motor and the stator sheet metal package of which is identical to that of Fig. 16A and receives the two strands of the stator winding as well as the sensor winding (Fig.

19D) for decoupling of the third harmonic,

Figure 20A-20E a variant with a two pole, three strand, three pulse brushless d-c motor, here again an external rotor motor, the stator sheet metal package of which comprises three equally distributed salient poles as well as 15 auxiliary slots for receiving the sensor winding (Fig. 20E) for decoupling of the ninth harmonic,

Figure 21 a basic representation of a circuit for operating the motors according to Fig. 16, Fig. 17 and Fig. 20, and

Figure 22 a basic representation of a circuit for operating the motors according to Fig. 18 or Fig. 19.

Fig. 1 shows a stator sheet metal package 10 for an external rotor motor having the permanent magnetic external rotor designated as 11 and shown only schematically. The magnetization of the rotor 11 is shown in unrolled form in the Figs. 3A and 9. The angles are indicated in Fig. 9 for reference purposes. Two unlike monopole zones always meet directly, for example in Fig. 9 a north pole zone 13 and a south pole zone 14, each 120° electrical long. In the same circular path 15 (Fig. 9) wherein a galvanomagnetic sensor 16 (in general a Hall-generator) is attached at the stator the monopole zone 14 is extended toward the left by an extension 18 by 60° electrical, the monopole zone 13 is extended toward the right by an extension 19 by 60° electrical, whereas in the other circular path 17 next to the extension 18 a zone 22 (north pole) is located and next to the extension 19 a zone 23 (south pole) is located. The extension 18 and the zone 22 form together a dipole zone, similarly the extension 19 and the zone 23. The same is then repeated in the manner shown in Figs. 3A and 9 very explicitly. The circular paths 15 and 17 have about the same width.

Fig. 10A shows the course of the magnetization over the rotor 11 shown in Fig. 9. In one case the course is shown over circular path 15 as measured by the sensor 16 and this is designated as B_{15} ; in addition the course over circular path 17 is indicated in dashed lines and designated as B_{17} .

This course is in part identical to that of B_{15} , to wit over all four monopole zones of this four pole rotor 11.

When a conductor L (Fig. 9) is disposed across to the full width of the rotor 11 and when a uniform relative motion between the rotor 11 and the conductor L occurs, then an instrument 25, for example an oscilloscope, measures an induced voltage u at this conductor L as shown in Fig. 10B.

As can be recognized from Fig. 10B the monopole zone 14 for example induces a negative voltage 26 and the monopole zone 13 a positive voltage 27. The dipole zone formed by the extension 18 and the north pole 22 induces two identical oppositely di-

rected voltages, the sum of which is zero according to the section 28 in Fig. 10B. The same holds for the extension 19 and the south pole 23, which again together induce the voltage zero, which corresponds to section 29 in Fig. 10B. To the right of this section a section 26' follows, which respective to its form is identical to section 26.

Placing the zero point of the abscissa axis between the sections 26 and 27, then the voltage u is an uneven trigonometric function, that is $f(t) = -f(-t)$. This function can be decomposed with Fourier analysis into sinus curves of different frequencies and amplitudes, of which Fig. 10C shows the fundamental, Fig. 10D the second harmonic and Fig. 10E the fourth harmonic. The third and the sixth harmonic are approximately equal zero. The Figs. 10C to 10E show the decomposition of the voltage u according to Fig. 10B in its fundamental and its first harmonics. Of course, further harmonic waves are present, and Fig. 15 shows the full frequency spectrum, that is the absolute values of the amplitudes of the individual harmonic waves of the voltage shown in Fig. 10B.

It can be recognized that the harmonic waves having an ordinal number 1 divisible by three show very small amplitudes and that the harmonic waves with the ordinal numbers 2, 4, 5, 7, 8, 11 and 14 based on their relatively large amplitudes are offered for evaluation. It has to be considered that with high ordinal numbers only then useful amplitudes are provided when the slopes of the voltage shown in Fig. 10B are steep. When the slopes are less steep, then practically only the second, fourth, fifth and eighth harmonic can be evaluated.

The individual harmonic waves can be filtered in the usual way, for example by way of band pass filters, from the voltage which is obtained from the device 25 (Fig. 9). This method is cumbersome and has the disadvantage of providing only upon reaching of the desired speed of rotation a control signal and the starting has to be achieved in a different way.

In accordance with a preferred embodiment of the invention the harmonic waves are decoupled in such fashion as to be available with each speed. This development of the present invention starts with the concept of considering the rotor 11 to be composed of different magnets, which each have a magnetization according to Fig. 10C, 10D, 10E etc (the further harmonic waves can be numerically easily calculated in the usual way). The next starting point is the consideration that from these—fictitious—magnetizations of various kind a certain one has to be taken and evaluated for the generation of the harmonic wave corresponding to it. This is achieved by employing a sensor winding having a distance of the magnetically active winding sections

adapted to this—fictitious—magnetization and thereby acting as a harmonic analyzer decoupling mainly only this harmonic from the total of harmonic waves present.

70 An ironless stator can be employed for the invention and this variant is explained by way of Figs. 6 to 8. Initially, the technique is explained with a stator from slotted iron sheets and more particularly with the stator 75 sheet metal package 10 shown in Fig. 1 of an external rotor motor. The transfer to an internal rotor motor follows simply by reflection at the cylindrical air gap, which is designated as 34 in Fig. 1.

80 For the reception of four main windings the stator sheet metal package 10 has eight slots, that is 35, 36 for a main winding 37; 38, 39 for a main winding 40; 43, 44 for a main winding 45; 46, 47 for a main winding 48.

85 The two slots of a main winding in each case are separated by 120° electrical, and the individual main windings in each case have an angular distance of 180° electrical from each other, that is they are as shown equally distributed around the circumference of the stator sheet metal package 10.

Figs. 3A to 3C show unrolled the motor of Fig. 1. Ordinarily the figures would be drawn on top of each other, but then the drawing 95 would be unreadable for practical purposes. Therefore its three components are drawn one beneath the other in proper position wherein naturally in operation the position of the stator constantly changes relative to the rotor 11.

100 The main windings 37 and 45 are connected in series (of course, a parallel connection would be possible) and its connectors are designated as 49 and 50. Similarly the main windings 40 and 48 are connected in series 105 and its connectors are designated as 51 and 52.

Fig. 4 shows the position of the main windings in a corresponding circuit controlled by a Hall-generator 16 placed exactly in the 110 middle between the main windings 37 and 40 at the stator 10, compare Figs. 1 and 3B. The Hall-generator 16 controls two pnp-transistors 54, 55 of a differential amplifier. The transistors 54, 55 serve as driving elements 115 for npn final stage transistors 56, 57, of which transistor 56 controls the current in the main windings 40 and 48 and transistor 57 controls the current in the main windings 40 and 48. One of the current connectors of the 120 Hall-generator 16 is connected via an npn-transistor 58 serving as a variable resistor to the plus-line 59 and the other current connector via a resistor 60 to the minus-line 61. The emitters of 54 and 55 are connected to each 125 other and via a joint resistor 64 to 59. The collector of 54 is connected via a resistor 65 to 61 and directly to the base of 57. The windings 37, 45 are connected with their connector 50 to the collector of 56 and with 130 the connector 49 to the plus-line 59. Simi-



larly, the windings 40, 48 are connected with their connector 52 to the collector of 57 and with their connector 51 to the plus-line 59. A controlled gain amplifier 63 controls the transistor 58, which in the present case controls the speed via the control current flowing into the Hall-generator 16. For determining the actual speed serves a sensor winding 80 adapted to respond to the second harmonic.

10 Its construction is described in the following.

The operation of the circuit according to Fig. 4 is very detailed disclosed in the context of Fig. 2 of the German Offenlegungsschrift DE-OS 27 30 142 and it is referred to this.

15 For receiving the sensor winding 80 for the second harmonic the stator sheet metal 10 comprises eight auxiliary slots 71 to 80 equally distributed around the stator circumference and having an angular distance from each other of 90° electrical. The position of all slots relative to each other is shown in Figs. 3B and 3C by scale and designated with the same reference marks. For example, it can be recognized that the auxiliary slot 71 (Fig. 3C) is located exactly in the middle between the main slots 35 and 36, that the auxiliary slot 72 is located exactly in the middle between the main slots 36 and 38, etc.; that is the slot arrangement of Fig. 1 shows mirror symmetry. Reflecting one of the two stator halves along one of the symmetry axes, for example the axis 79, then corresponding slots coincide, for example 35 and 36, 78 and 72, etc.

The winding according to Fig. 3C is a wave winding 80, which is looped back into itself, that is the winding goes from connector 83 through the slot 77, to the slot 76, then to the slot 75 etc to the slot 71 and from there back to the slot 78 and the slot 77. There the direction of the winding is reversed and the same now runs in reverse direction again through slot 78, then slots 71 to 76 and is then run to the outside very close to the connector 83.—If the sensor winding 80 would end at the slot 77 (connector 84 in Fig. 3C shown with dashed lines), then the same harmonic of the induced voltage would be covered, but the amplitude would only be half as large and in particular such a winding would also cover pulsating stray fields, which run in parallel to the rotor shaft designated as 85 in Fig. 1.

Returning the sensor winding by the same angle of rotation of 720° electrical to the starting point is effected such that axial stray fields induce two exactly equal size, but oppositely directed voltages in the sensor winding 80, which cancel each other and do not influence the controlled gain amplifier 63 and the quality of the control.

Naturally, for increasing the starting voltage, the sensor winding can be wound several times around the stator 10, for example two full revolutions, and then returned by the same angle to the starting point in case such

axial fields are to be compensated.

The individual magnetically active sections of the sensor winding 80 (in the slots 71 to 80) each have from each other an angular distance of 180° electrical: $L + n \times 180^\circ$ electrical; wherein $n = 0, 1, 2, \dots$ and L = ordinal number of the harmonic to be covered. In the present case $L = 2$ and $n = 0$ and therefor this angle amounts here to 90° electrical. The sensor winding 80 comprises at least two magnetically active sections. It covers the second harmonic of the rotor magnetization shown in Fig. 10D and generates therefor a measuring voltage of relatively high frequency, which is twice the frequency, which can be withdrawn from the Hall-generator 16, and in addition the zero passages have substantially more uniform distances compared to the zero passages of the Hall-voltage. In such a motor for example the Hall-generator 16 provides four pulses pro revolution, the sensor winding 80 in contrast eight pulses pro revolution. In case the speed controller 63 (Fig. 4) is constructed for the evaluation of the frequency (and not of the amplitude) of the voltage applied to it, then a very accurate speed control with good long term stability and small temperature dependence can be achieved. Such a speed controller shows for example the German Offenlegungsschrift DOS 26 16 044.

For example a sheet metal package analog to Fig. 1 with a diameter of 80 mm and a height of 18 mm can be cited into which a one wire sensor winding 80 was wound according to Fig. 3C. The rotor magnet 11 had an induction of 1.2 kG. At a speed of 3600 rpm an a-c voltage with an effective value of 0.3 volts resulted between the connectors 83 and 86.

It is a particular advantage of the described mirror symmetrical arrangement of the sensor winding 80 that the induced voltages in it transformed from the main windings cancel each other and therefor do not interfere with the control process.

The arrangement according to Fig. 1 has the disadvantage that a special sheet metal stamping is required, which is only economical with larger numbers of motors. The invention however can also be realized with commercial sheet metal stampings and this is shown in Fig. 2 in connection with Figs. 3A to 3C. There the same reference marks are used for the same or equally acting parts as were used in the previous part of the description.

The sheet metal stamping 88 is also intended for a four pole motor with external rotor corresponding exactly to the rotor of Fig. 1 and reference is made to the description there. The sheet metal stamping 88 has 24 slots 89 of identical shape, which each have a distance from the other of 15° mechanical = 30° electrical. The individual windings

are positioned completely identical with those of Fig. 1 such that in total eight slots remain without windings. The first main winding is here again designated as 37 and the two slots around which it is wound have a distance from each other of 120° electrical.

The second main winding is designated as 40, the third main winding is designated as 45 and the fourth main winding is designated as 48. They are, as shown, equally distributed around the stator circumference and are formed like the main winding 37. The magnetically active sections of the sensor winding 80 are designated as 80' and have each a distance of 90° electrical from each other and each lies on the angle bisecting line between two neighboring slots of the main windings in order to avoid as described a transformer coupling between the main windings and the sensor winding. The arrangement of the sensor winding 80 is identical to that of the scheme according to Fig. 3C and it is referred to the corresponding description.

In case it is desired to wind more copper into the sheet metal stamping according to Fig. 2, then the loop winding 92 shown in Fig. 5 can be employed instead of the winding pattern according to Fig. 38 (3B7). In accordance with Fig. 5 two winding sections are placed in two neighboring slots 93 and 94, then two empty slots 95 and 96 follow and then again two slots 97 and 98 with windings follow. The larger angle step γ_1 amounts to 120° electrical and the smaller angle step γ_2 amounts to 90° electrical. The angles are explicitly shown in Fig. 5. This embodiment of the winding results in a better copper filling factor, wherein the induced voltage is somewhat rounded and a more favorable course of the momentum generated by the motor results. It is a disadvantage of this arrangement that the sensor winding cannot any longer positioned exactly mirror symmetrical relative to the main windings, since in Fig. 5 the sensor winding should be either in slot 95 or in slot 96. In case the slot number is doubled in a conventional sheet metal stamping, then of course the sensor winding can also with the winding pattern of Fig. 5 be arranged with mirror symmetry, since then between the slots 95 and 96 an additional slot is located into which the sensor winding of the corresponding section can be placed. The main winding is then advantageously distributed over six or eight slots, whereas it is distributed in Fig. 4 only over 4 slots.

This problem can also be resolved without an increase of the number of slots by a further step of the invention and it is referred to Figs. 14A to 14D for this purpose.

Fig. 14A shows the 24 slots 89 of the stator sheet metal package according to Fig. 2 in the usual unrolled way. Fig. 14B shows the arrangement of the stator winding 92 relative to the slots 89 of Fig. 14A. The stator wind-

ing is identical to that of Fig. 5 and therefore is here not described again. As explained, this arrangement results in a more favorable course of the momentum compared with the arrangement of Fig. 1, and the latter is not particularly favorable for electro motors and serves predominantly for explaining the basic principle of the invention.

In this arrangement of the stator winding 92 each time a tooth is positioned in the middle of a stator pole and these 'middle teeth' are in Fig. 14A the teeth 111, 112, 113 and 114.

The invention starts with the consideration to provide to this middle tooth a symmetry by having on each side of this tooth located a like magnetically active winding section. Like shall mean in this context that when the sensor winding is passed by a d-c current, then on both sides of the tooth the same current direction is present. Thus it is achieved that even in this case the sensor winding is not transformer coupled with the individual stator windings. The angle indications to the Figs. 14C and 14D refer as in the preceeding to the angles given for the main poles as they are shown in Figs. 9 and 10.

Fig. 14C shows a sensor winding 115 for decoupling of the second harmonic. As can be easily recognized, starting from a connector 116 the winding is first led to the right as a wave winding with a winding step of 180° electrical: $1 = 90^\circ$ electrical in such manner as to be positioned in each case to the right of the middle teeth 111 to 114. The winding direction is reversed at the end and the winding 115 is returned again to the right to a connector 117, but now it is positioned to the left of the middle teeth 111 to 114, that is shifted by one slot partition. Thus on both sides of the middle teeth are positioned like magnetically active coil sections, that is in the coil sections situated at both sides of one middle tooth during operation a voltage of the same direction is induced. Such an arrangement is again electrically symmetrically relative to the stator winding 92 that no transformer coupling occurs.

More difficult is the arrangement of a sensor winding for decoupling of a fourth harmonic in the winding construction of Fig. 14B. Such a sensor winding requires a coil step of 180° electrical: $4 = 45^\circ$ electrical, and since the slots 89 have a distance of 30° electrical, a magnetically active section of the sensor winding would have to be situated on a tooth head.

Fig. 14D shows the solution of this problem in accordance with the invention by providing a sensor winding 118 for the decoupling of the fourth harmonic. This winding starts at a connector 121 and runs from there towards the left, and in particular alternating with winding steps of 30° and 60° electrical such that in each case a magnetically active section



is situated to the left of the four middle teeth 111 to 114. After passing through all slots the winding direction is reversed and the wave winding runs again with alternating 30°- and 60°-steps through the slots toward the right to the connector 122, however as shown shifted by a slot partition such that now the magnetically active sections are situated to the right of the middle teeth 111 to 114. Like winding sections of both wave windings are situated for example jointly in the slots 94 and 97 and similarly like winding sections are situated on both sides of the middle teeth that is for example on both sides of the middle tooth 111 in the slots 95 and 96. With other words: all 24 slots are at least one time covered, but a third of them is covered twice. The angular distance of the doubly covered slots to the next two winding sections of opposite direction also amounts to 30° electrical and 60° electrical that is on the average 45° electrical as is shown in Fig. 14D for the slot 97. This average distance corresponds to the fourth harmonic to be decoupled. The angular distances of 60° and 30° electrical also present correspond to the third and sixth harmonic, which are according to Fig. 15 practically both equal to zero and therefor do not interfere.

A doubled number of stator slots allows to decouple the fourth and eighth harmonic in analogy to Figs. 14C and 14D, wherein then compared to the figures shown all angle steps would have to be halved. In other words, Fig. 14C and Fig. 14D would have to shrink to half width under consideration of the symmetry relative to the middle teeth in order to avoid transformer coupling. Naturally, in accordance with the same principle sensor windings can be constructed for other slot numbers and other harmonics.—The position of the galvanomagnetic sensor 16 between two main windings is also shown in the Figs. 5 and 14B.

The Figs. 6 and 8 and 11 to 13 show possible constructions of sensor windings for a four pole flat motor. Its rotor is shown in Fig. 8 of the German Offenlegungsschrift DE-OS 27 30 142 and its main winding corresponds to the winding shown in Fig. 9 of said Offenlegungsschrift. It comprises four about sector shaped flat coils 101 to 104, which are positioned around a shaft 100 with equal angular distances of each 180° electrical (= 90° mechanical). The Hall-generator 16 is disposed on the bisecting line of the angle between the coils 102 and 103. The connectors of the four coils are designated in analogy to Fig. 4 with 49, 50 and 51, 52, respectively. The circuit corresponds to the circuit of Fig. 4.

Figs. 6 to 8 show sensor windings for decoupling of the second harmonic. In Fig. 6, the magnetically active sections 105 of the sensor winding, which is herein designated as

106 (this number is therefor indicated in parenthesis in Fig. 4), in each case on the bisecting line of the angle between the main windings 101 to 104 and on their middle axes. A wave or meander shaped winding is thus obtained and its connectors are designated in Fig. 6 as 107 and 108. The meander can be passed several times for increasing the voltage. It is important that the magnetically active sections 112 extend over the full width of the rotor magnet, which is indicated in Fig. 6 by dot-dashed lines.—The magnetically active sections 105 have in each case a distance from each other of 90° electrical in order to pick up only the second harmonic.

The sensor winding 106 of Fig. 6 is suitable for flat motors having no stray field in the direction of shaft 100. By way of the kind of winding described the sensor winding 106 is not transformer coupled to the main windings 101 to 104.

In case a stray flux occurs in the direction of the shaft 100, the sensor windings 106' according to Fig. 7 and 106'' according to Fig. 8, respectively, can be employed. The basic form according to Fig. 6 is employed in both cases, but in Fig. 7 the winding is looped back on the same path resulting in a doubling of the starting voltage. This arrangement also corresponds to that according to Fig. 3C. In Fig. 8 the return path 110 runs around the shaft 100, but not any longer across to the rotor 109, that is the latter does not induce any voltages in the return path 110 upon rotation, however by the stray flux running in the direction of the shaft. In Fig. 7 as well as in Fig. 8 the voltages mutually cancel, which are induced in the corresponding sensor winding by the stray flux running in shaft direction. The return path 110 can also be disposed within the meander winding.

In Figs. 6 to 8 the sensor windings can be provided as a printed circuit on a thin foil and can be mounted in this form on the stator transformer-decoupled and in proper position

The Figs. 11 and 12 show for the same four pole motor according to Fig. 6 sensor windings for decoupling of the fourth harmonic, that is with an angular step of 45° electrical = 22.5° mechanical between the magnetically active sections as is shown in Figs. 11 and 12.

In Fig. 11 the sensor winding is designated as 124 and its connectors are marked as 125, 126. The construction corresponds completely to that of Fig. 7, that is the wave winding is looped back again on the same path to the exit.

In Fig. 12 the sensor winding is designated as 127 and its connectors are marked as 128 and 129. The construction corresponds completely to that of Fig. 8, that is a return path 130 is here looped back around the full shaft 100. For clarifying the orientation relative to

the main winding 101 to 104 according to Fig. 6, there and in Figs. 11 to 13, a dash-dotted reference line 133 is drawn running in all four figures through a magnetically active section of the corresponding sensor winding and representing the bisecting line of the angle between the stator windings 101 and 103.

Fig. 13 shows the sensor winding 135 printed on an insulating foil 134. The magnetically active sections of the sensor winding 135 have an angular distance of 180° electrical: $15 = 12^\circ$ electrical and are thus suitable for decoupling of the 15th harmonic or for a sixty pole tacho-magnet. A return 136 here again loops around the shaft—not shown—in order to substantially compensate axial stray fluxes. The connectors of the winding 135 are designated as 137 and 138. In accordance with Fig. 15 the decoupling of the 15th harmonic is less advantageous than for example the decoupling of the 11th or 14th harmonic, which both have considerably larger amplitudes. By an appropriate selection of the angle between the magnetically active sections such a decoupling can be provided for easily. For the 11th harmonic the angle between two magnetically active section would be for example 180° electrical: 11.

Fig. 15 shows as already indicated the frequency spectrum of the voltage shown in Fig. 10B. The Amplitude $\hat{u}$ of the voltage shown in Fig. 10 is set to be 100%. It can be recognized that the fundamental of this voltage has an amplitude of about 87.8% of $\hat{u}$, that the second harmonic is about half the size of $\hat{u}$, that the fifth harmonic is about $1/5$ and the eighth harmonic about $1/8$ of $\hat{u}$. Fig. 15 is valid for a voltage with steep slopes. When the slopes are less steep, then the harmonics beginning with the fifth harmonic have only very small amplitudes. Depending on the shape of the preferably trapezoidal magnetization of the rotor there is an upper limit of the ordinal number of the harmonics which still can be employed when a sensor winding is desired with a not too high number of turns.

The sensor windings according to Figs. 11, 12 or 13 (especially those of Fig. 11) based on their compensation of stray fields independent of their origin from either the motor or the apparatus are useful in connection with especially sensitive and fast control circuits (for example phase regulators, so called PLL-circuits, which generally use a quartz standard). Such sensor windings practically do not effect an enlargement of the motor and therefore result in very compact motors. The invention can also be employed in this manner in motors having a rotor magnet field deviating considerably from a sinusoidal shape and which can be analysed by analogy to Figs. 10C to 10E with respect to spacial harmonic wave fields of different frequencies and ampli-

tudes. This is illustrated in the following by way of additional examples of embodiments. For such other nonsinusoidal fields, other forms of magnetisation will result, as will be described below with reference to Fig. 18B or 20B.

For the same or equally active parts, the same reference numerals are used as in the previous figures. For purposes of unification of nomenclature, terminology is employed as is defined in the article of the inventor entitled "Two pulse brushless d-c motors" in the Journal "Asr-digest für angewandte Antriebstechnik" Volume 1-2, 1977. Figs. 21 and 22 of the present application correspond to Fig. 4 and Fig. 5 of that article and reference is made thereto for further illustration.

Definitions:

The *pole number* refers always to the pole number $2p$ of the rotor. For example, the motors according to Fig. 16 and Fig. 19 are four pole motors and those according to Figs. 17, 18 and 20 are two pole motors. The invention is, of course, also useful for higher pole numbers. However, with increasing number of poles, the distance between the magnetically active sections of the sensor winding decreases accordingly.

The *strand number* refers to the number of separate windings of the stator and could also be designated as phase number. For example, Figs. 16, 17, 20 and 21 show three strand motors, since the stator winding in each case comprises three separate strands, and Figs. 18, 19 and 22 show two strand motors.

The *pulse number* indicates how many current pulses for the stator or drive power winding are provided for a revolution of 360° electrical. For example, in Fig. 16 upon a rotation of 360° electrical, that is, a half revolution of the rotor, each of the three strands receives a current pulse when the circuit of Fig. 21 is employed, namely, three pulses are provided. Fig. 16 thus shows a three pulse, four pole, motor, whilst Fig. 17 and Fig. 20 also show three pulse motors. Upon a rotation of 360° electrical in Fig. 18, which is here a full rotor revolution by way of the electrical in Fig. 18, which is here a full rotor revolution by way of the circuit of Fig. 21 two current pulses are fed to each of both stator windings, that is four current pulses, that is the motor is four pulse; also the motor according to Fig. 19 is four pulse.

Both three and four pulse motors generate in all rotor positions an electromagnetic drive torque, that is such motors can start from any given rotational position. The higher the pulsicity, the lower are the variations of the torque provided by the motor.

The *magnetization of the rotor* exhibits in Figs. 16 to 19 always about the same form as is shown by way of example in Fig. 18B, that is about trapezoidal. In Fig. 20 the magnetization (Fig. 20B) of the rotor (Fig. 20C) is about



rectangular, that is it shows very steep slopes. The external rotor is in all cases constructed identically to that external rotor 11 of Fig. 1. The rotor magnet is shown in each case in unrolled representation in the Figs. 16B, 17B, 18C, 19B and 20C.

The representation of the windings in the Figs. 16 to 20 is done as usual and is therefore not each time described in detail. In each case the slots of the sheet metal stamping are numbered for example in Fig. 16A from 1' to 24' and these slots are then unrolled represented again, for example between Figs. 16C and 16D, showing the exact relation to the unrolled windings and it can be clearly recognized which windings are disposed in which slot and how these windings are connected. This representation displays the form and connections of the individual windings in such perfection as to allow any person skilled in the art to be guided. The representation of the windings in the sheet metal stamping provides the current direction in the usual fashion: a dot indicates that the current flows out of the plane of the figure and a cross that the current flows into the plane. This refers to the current arrows arbitrarily fixed in the unrolled representations. (Of course, in the sensor winding flows an a-c current during operation and not a d-c current!).

The Hall-generators and other sensors are shown in each case in their position in the sheet metal stamping and in the unrolled representation. Their designation agrees with the designation in Figs. 21 and 22, respectively.

The same sheet metal stamping 88 is employed in Fig. 16 as is in Fig. 2 that is 24 slots 89 are provided, which are designated sequentially from 1' to 24'. A short pitch three strand main winding 130 is provided and its three strands are designated as 131, 132 and 133. The three Hall-generators controlling these strands are disposed as follows: Hall-generator 34 between slot 6' and 7': controls strand 131

Hall-generator 135 between slot 10' and 11': controls strand 132

Hall-generator 136 between slot 14' and 15': controls strand 133.

The sensor winding 137 (Fig. 16D) serves for covering the third harmonic and has therefor between its magnetically active sections a distance alpha of 180° electrical: $1 = 60^\circ$ electrical, that is in Fig. 16D 30° mechanical, since the rotor is two pole. The sensor winding 137 comprises two wave windings that is one from the connector 138 towards the right running wave winding 139 and one to the other connector 140 towards the left backward running wave winding 141, which is shifted with respect to the wave winding 139 by an angle beta in space, wherein beta = 90° electrical: $1 = 90^\circ$ electrical:

cal: $3 = 30^\circ$ electrical (1 = ordinal number of the harmonic wave to be covered).

The phase position relative to the main winding 130 is selected such as to exclude transformer coupling with the main winding: The main winding 131 starts in the slot 1', the main winding 132 in the slot 3' and the main winding 133 in the slot 5'. The sensor winding 137 runs from connector 138 to the slot 2', then back through the slot 3', then through the slots 5', 7', 9', ... 23' to slot 1' and from there back to slot 24' and then to slot 22', 20', ... 6', 4' to the connector 140.

The shape of the voltage u_s induced in the sensor winding 137 follows from Fig. 16E. Obviously this voltage comprises harmonics, however the distance of the zero passages is very uniform and therefore this voltage is very suitable for control purposes. Therefore, Fig. 16 represents the most preferred mode of the invention.

If with the sheet metal stamping a full pitch, three strand main winding is employed, then the sensor winding cannot be positioned in the slots 89 without being transformer coupled with the main winding. A solution suitable for this case is shown in Fig. 17 wherein the sensor winding again is employed for (Fig. 17D) decoupling of the third harmonic.

The sheet metal stamping 145 according to Fig. 17A is provided with six symmetrically distributed, salient T-poles 146 with a concentrated full pitch, three strand main winding 147, the three strands of which are designated as 148, 149 and 150. The individual strands are angled in the diameter that is in the main slots A, C, E, G, J, and L.

For reception of the sensor winding 153 in the middle of each stator pole 146 a slot B, D, F, H, K and M is provided, wherein a wave winding according to Fig. 17D is inserted. This runs from the slot B with a winding step of 180° electrical: $1 = 60^\circ$ electrical toward the right until slot B (?) and from there in the same way backward to the slot D. The form of the voltage induced in the sensor winding 153 during operation can be recognized from Fig. 17E.

The three Hall-generators (or other equivalent sensors) are disposed as follows: Hall-generator 34 at the slot A: controls strand 148.

Hall-generator 135 at the slot E: controls strand 150.

Hall-generator 136 at the slot J: controls strand 149.

The corresponding circuit is shown in Fig. 21.

Also in the case of the two stranded winding with by 90° electrical against each other shifted winding strands the present invention allows to avoid the transformer coupling between the main winding and the sensor winding. This is shown in Figs. 18 and 19.

Fig. 18 shows a two pole, two strand motor

with a full pitch main winding 159 (Fig. 18E) inserted in a sheet metal stamping 160 with four symmetrical salient T-poles 161 that is in the four main slots A, C, E and G. The two
 5 strands of the main winding 159 are designated as 162 and 163 and wound in diameter as indicated in Fig. 18A. In addition two Hall-generators 164, 165 are provided in a relative to each other shifted position of 90°
 10 electrical and of which the one is situated at the slot C and controls the stand 163 whereas the other is situated at slot E and controls the strand 162.

Four auxiliary slots B, D, F and H are
 15 provided for receiving the sensor winding 166. Starting at slot A clockwise, then B is from A 60° and D from A 120° distant. Starting at slot A counterclockwise, then H is from A 60° and F is from A 120° distant, as
 20 is clearly shown in Fig. 18A.

Starting with a connector 167 the sensor winding 166 runs initially through slot A, then the slots B, D, F and H and returns to slot A. There the winding direction reverses
 25 back to slot H and further to the slots D and B and to the second connector 168. Thus the winding step is 180° electrical: 1, that is 60° electrical. However in the middle of the unrolled representation in each case two winding
 30 steps have been left out, that is two winding steps for each pair of poles p, in order to avoid transformer coupling between the main winding 159 and the sensor winding 166. Correspondingly, in a four pole motor two
 35 times two winding steps would have to be left out and then a rotation symmetrical winding would be obtained providing the advantages, since thereby partition errors of the rotor magnet are better compensated.

40 The corresponding circuit for four pulse operation is shown in Fig. 22. The shape of the tacho-voltage u_r at the sensor winding 166 is shown in Fig. 19E. This voltage varies corresponding to the fundamental of the magnetization of the rotor magnet, however the
 45 distances of the zero passages are relatively uniform and can therefor be used for control purposes.

If it is desired to employ a usual sheet
 50 metal stamping, for example the sheet metal stamping 88 according to Fig. 2 with 24 slots 89, also for a two stranded, four pulse motor, then according to the invention therefor a specific sensor winding can be provided for
 55 decoupling of the third harmonic, wherein by spacial phase shifting of part of the sensor winding by 30° electrical (with reference to the pole distribution of the rotor magnet) versus the other part and by additional deletion of certain winding steps the transformer
 60 coupling can be lifted relative to both strands of the main winding. Such a motor is shown in Fig. 19. The sheet metal stamping 88 has 24 slots 89 which are designated as 1' to 24'
 65 as in Fig. 16. The rotor is magnetized as four

poles, compare Fig. 19B, and the main winding has two strands 172, 173. The Hall-generator 164 is disposed between the slots 12' and 13' and controls the strand 172,
 70 whereas the Hall-generator 165 is disposed between the slots 15' and 16' and controls the strand 173. The distance between the two Hall-generators 164 and 165 thus is 90° electrical = 45° mechanical. The course of the
 75 main winding 171 is unambiguously shown in Figs. 19A and 19C. The main winding 171 is 5/6 short-pitched. Fig. 19D shows the course of the sensor winding 175. Starting with a connector 176 the same runs through
 80 the slots 4', 7', 9', 11', 16', 19', 21' to the slot 23' and from there back again through the slots 21', 18', 16', 14', 9', 6', 4' and 1' to the other connector 177. Like the sensor winding 166 the sensor winding 175 is also
 85 mirror symmetrical and also leaves out in each case two winding steps. Furthermore, the sensor winding 175 comprises four sections 178, 179, 180 and 181, which are shifted against each other. In each of the four sections the
 90 same angle step of 180° electrical: 1 = 60° electrical is employed, for example from slot 2' to slot 4', and from slot 4' to slot 6'. The sections 178 and 180 are in phase, as are the sections 179 and 181. The section 178 is
 95 shifted in phase compared to the sections 179 and 181 by an angle γ of 90° electrical: 1 = 30° electrical, and the same holds for the section 180. Through this move and the deletion of the middle winding steps it is—
 100 surprisingly—possible to avoid also in this case a transformer coupling with both strands of the main winding 171.

Fig. 19E shows the shape of the voltage u_r at the sensor winding 175. Also in this case
 105 the voltage comprises a small part of the fundamental wave of the rotor magnet.

For covering the ninth harmonic with a rotor magnet (Fig. 20C) having an about rectangular magnetization as shown in Fig.
 110 20B (this figure shows the course of the induction in the direction of rotation and measured over the circumference of the rotor) an arrangement according to Fig. 20 is employed. In this case the sensor winding 185
 115 has to have a sensor step width corresponding to a ninth of the step width of the main winding 186, that is amounting to only about 20° electrical. In a small or tiny motor in general the slot number of $9 \times 2p$ required for
 120 this cannot advantageously be used for the main winding. Thus according to the invention a stator arrangement with salient poles 187 and a concentrated main winding 186 is more suitable. The winding 186 is herein
 125 short-pitched and is disposed in three main slots A, G and N. The three strands of the main winding 186 are designated as 188, 189 and 190.

In addition 15 auxiliary slots B-F, J-M and
 130 O-S are provided having in each case a

distance from each other of 20° electrical = 20° mechanical and from the main slots A, G and N, compare Fig. 20A.

The Hall-generators 134 to 136 are arranged as follows:

The Hall-generator 134 is disposed between the slots H and J and controls the strand 188.

The Hall-generator 135 is disposed between the slots O and P and controls the strand 189.

The Hall-generator 136 is disposed between the slots B and C and controls the strand 190. This is shown in Fig. 20 symbolically.

The sensor winding 185 is constructed as a wave winding. It starts at the connector 193, runs to the slot A and from there further through all slots B, C, etc until back to slot A and turns there and runs back via all slots S, R, Q, etc to slot B and to the other connector 194. By comparing Fig. 20D with Fig. 20E it can be easily recognized that in this case no coupling between the sensor winding 185 and the main winding 186 occurs, that is at the connectors 193 and 194 a frequency is obtained being nine times larger than the frequency available at the Hall-generators 134 to 136 and therefore allowing a good speed control.

Fig. 21 shows schematically the permanent magnetic rotor 195 of a three pulse motor having three winding strands connected as a star and designated as S 1 to S 3 and the star point 196 is connected to the positive voltage U_g . Three npn-transistors 197, 198, 199 are provided for feeding these three strands. In each case the transistors are connected with their collector to the corresponding strand and with their emitter to the negative line 200, that is ground. The Hall-generator 134 controls the transistor 197, the Hall-generator 135 the transistor 198 and the Hall-generator 136 the transistor 199. This control is only represented schematically: Normally the control is provided by driving transistors. In Fig. 16 for example the strands S 1 to S 3 would correspond to the strands 131 to 133, in Fig. 17 the strands 148 to 150 and in Fig. 20 the strands 188 to 190. During each revolution of the rotor 195 of 360° electrical successively each of the three strands S 1 to S 3 receives a current pulse, that is in total three pulses and the operation is three pulse and continuously a torque is generated since the three current pulses mutually overlap.

Fig. 22 shows schematically the rotor 203 of a four pulse motor having two strands designated as S 4 and S 5 and connected with their star point to ground (0 volt). The other connection of the strand S 4 is to the emitter of an npn-transistor 205 and the collector of an npn-transistor 207. In the same way the other connection of the strand S 5 is connected to the emitter of an npn-transistor 207 and to the collector of an npn-transistor

208. The collectors of the transistors 205 and 207 are connected to the positive voltage $+U_g$ and the emitters of the transistors 206 and 208 are connected to a negative voltage

$-U_g$. For example, when the transistor 206 is conducting, then a current flows in the other direction through S 4 and when the transistor 206 is conducting a current flows in the other direction through S 4. Because of the symmetry of the circuit the same holds for S 5 and the two transistors 207 and 208.

A control device 210 provides control of the transistors 205 to 208. Rotor position signals are fed to the control device 210 from the two Hall-generators 164 and 165. The transistors 205, 207, 206 and 208 are successively excited resulting in a rotating field driving the rotor 203.

In Fig. 18 the stands S 4 and S 5 correspond to the strands 162 and 163, in Fig. 19 the strands 172 and 173.

The present invention allows with very simple means to obtain a measuring voltage with a high frequency relative to the frequency of rotation of the motor and with a relatively uniform period of duration as is required especially for speed control employing a frequency as a measure of the frequency of rotation. The preferably employed sensor winding acts as a high pass filter and should preferably extend over 360° electrical or an integer multiple thereof in order to minimize partition errors, for example from an unequal distribution of the slots or a nonuniform magnetization of the rotor, and in order to obtain a very uniform period of duration. Provisions are preferred in flat motors to eliminate interference from axial stray fields.

105 CLAIMS

1. A brushless d-c motor comprising:
 - (a) a permanent magnet rotor, the poles of which have a non-sinusoidal magnetisation and are separated by pole gaps;
 - (b) a stator;
 - (c) a main armature winding;
 - (d) means for pulse energising the main armature winding; and
 - (e) a sensor winding positioned on the stator adjacent the associated armature to provide output signals induced in the sensor winding, which signals are a harmonic or a multiple of the base frequency induced in stationary conductors on the stator during operation of the motor, wherein the sensor winding and main armature winding are of sufficient pitches and are relatively positioned to avoid transformer coupling therebetween.
2. A brushless d-c motor according to claim 1, wherein the main armature winding is a two strand winding.
3. A brushless d-c motor according to claim 1 or 2, wherein the sensor winding is non-uniform with respect to adjacently posi-



distance from each other of 20° electrical = 20° mechanical and from the main slots A, G and N, compare Fig. 20A.

The Hall-generators 134 to 136 are arranged as follows:

The Hall-generator 134 is disposed between the slots H and J and controls the strand 188.

The Hall-generator 135 is disposed between the slots O and P and controls the strand 189.

The Hall-generator 136 is disposed between the slots B and C and controls the strand 190. This is shown in Fig. 20 symbolically.

The sensor winding 185 is constructed as a wave winding. It starts at the connector 193, runs to the slot A and from there further through all slots B, C, etc until back to slot A and turns there and runs back via all slots S, R, Q, etc to slot B and to the other connector 194. By comparing Fig. 20D with Fig. 20E it can be easily recognized that in this case no coupling between the sensor winding 185 and the main winding 186 occurs, that is at the connectors 193 and 194 a frequency is obtained being nine times larger than the frequency available at the Hall-generators 134 to 136 and therefore allowing a good speed control.

Fig. 21 shows schematically the permanent magnetic rotor 195 of a three pulse motor having three winding strands connected as a star and designated as S 1 to S 3 and the star point 196 is connected to the positive voltage U_B . Three npn-transistors 197, 198, 199 are provided for feeding these three strands. In each case the transistors are connected with their collector to the corresponding strand and with their emitter to the negative line 200, that is ground. The Hall-generator 134 controls the transistor 197, the Hall-generator 135 the transistor 198 and the Hall-generator 136 the transistor 199. This control is only represented schematically: Normally the control is provided by driving transistors. In Fig. 16 for example the strands S 1 to S 3 would correspond to the strands 131 to 133, in Fig. 17 the strands 148 to 150 and in Fig. 20 the strands 188 to 190. During each revolution of the rotor 195 of 360° electrical successively each of the three strands S 1 to S 3 receives a current pulse, that is in total three pulses and the operation is three pulse and continuously a torque is generated since the three current pulses mutually overlap.

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208. The collectors of the transistors 205 and 207 are connected to the positive voltage $+U_B$ and the emitters of the transistors 206 and 208 are connected to a negative voltage $-U_B$. For example, when the transistor 206

is conducting, then a current flows in the other direction through S 4 and when the transistor 206 is conducting a current flows in the other direction through S 4. Because of the symmetry of the circuit the same holds for S 5 and the two transistors 207 and 208.

A control device 210 provides control of the transistors 205 to 208. Rotor position signals are fed to the control device 210 from the two Hall-generators 164 and 165. The transistors 205, 207, 206 and 208 are successively excited resulting in a rotating field driving the rotor 203.

In Fig. 18 the stands S 4 and S 5 correspond to the strands 162 and 163, in Fig. 19 the strands 172 and 173.

The present invention allows with very simple means to obtain a measuring voltage with a high frequency relative to the frequency of rotation of the motor and with a relatively uniform period of duration as is required especially for speed control employing a frequency as a measure of the frequency of rotation. The preferably employed sensor winding acts as a high pass filter and should preferably extend over 360° electrical or an integer multiple thereof in order to minimize partition errors, for example from an unequal distribution of the slots or a nonuniform magnetization of the rotor, and in order to obtain a very uniform period of duration. Provisions are preferred in flat motors to eliminate interference from axial stray fields.

105 CLAIMS

1. A brushless d-c motor comprising:
(a) a permanent magnet rotor, the poles of which have a non-sinusoidal magnetisation and are separated by pole gaps;

(b) a stator;

(c) a main armature winding;

(d) means for pulse energising the main armature winding; and

(e) a sensor winding positioned on the stator adjacent the associated armature to provide output signals induced in the sensor winding, which signals are a harmonic or a multiple of the base frequency induced in stationary conductors on the stator during operation of the motor,

wherein the sensor winding and main armature winding are of sufficient pitches and are relatively positioned to avoid transformer coupling therebetween.

2. A brushless d-c motor according to claim 1, wherein the main armature winding is a two strand winding.

3. A brushless d-c motor according to claim 1 or 2, wherein the sensor winding is non-uniform with respect to adjacently posi-



tioned main armature winding portions throughout the circumference of the motor.

5. A brushless d-c motor according to claim 1, 2 or 3, wherein the poles of the permanent magnet rotor have at least approximately trapezoidal or rectangular magnetisation, the stator has a slotted core, with the slots circumferentially distributed therearound and with the main armature winding located in respective ones of the stator slots, and wherein the sensor winding is located in respective ones of the stator core slots with a predetermined number of sensor winding sections arranged successively in the same angular direction such that the average angular spacing between adjacent sections is $180^\circ - e1/L$.

L being the ordinal of the harmonic to be obtained from the sensor winding which, on return to its first section, is displaced by one stator slot with respect thereto.

5. A brushless d-c motor according to claim 1, 2 or 3, wherein the poles of the permanent magnet rotor have at least approximately trapezoidal or rectangular magnetisation, the stator has a slotted core, with the slots circumferentially distributed therearound and with the main armature winding located in the stator slots, and wherein the sensor winding is located in respective ones of the stator core slots, with a predetermined number of sensor winding sections arranged successively in the same angular direction such that the average angular spacing between adjacent turns is $180^\circ - e1/L$.

L being the ordinal of the harmonic to be obtained from the sensor winding which is a wave winding.

6. A brushless d-c motor according to claim 1, 2 or 3, wherein the sensor winding includes a first section having a first winding angle and a second section having the same winding angle as that of the first section but being wound in the reverse direction to that of the first section, thereby compensating for stray axial fields during operation of the motor.

7. A brushless d-c motor according to claim 6, wherein the motor is an axial air gap motor.

8. A brushless d-c motor according to claim 6, wherein the motor is a cylindrical air gap motor.

9. A brushless d-c motor comprising:
(a) a permanent magnet rotor having a non-sinusoidal magnetisation;

(b) a stator having a slotted core, with the slots circumferentially distributed therearound;

(c) a main armature winding on the stator;

- (d) means for pulse energising the main armature winding; and

- (e) a sensor winding positioned over the stator and having substantially uniformly distributed magnetically active sections arranged to sense a harmonic of the voltage induced by

the rotor during operation of the motor,

- wherein the main armature winding is a three strand winding located in respective slots of the stator core and the sensor winding includes magnetically active sections positioned in respective slots of the stator core which are located substantially intermediate two adjacent stator core slots in which respective strands of the main armature winding are located, thereby avoiding transformer coupling between the main armature winding and the sensor winding during operation of the motor.

10. A brushless d-c motor according to claim 9, wherein the main armature winding is an essentially full-pitch winding.

11. A brushless d-c motor according to claim 9 or 10, wherein the main armature winding is a concentrated winding.

12. A brushless d-c motor according to claim 9, 10 or 11, wherein the sensor winding includes three uniformly distributed magnetically active sections for each pole of the rotor, to sense the third harmonic.

13. A brushless d-c motor according to claim 9, 10 or 11, wherein the sensor winding includes nine uniformly-distributed, magnetically active sections for each pole of the rotor, to sense the ninth harmonic.

14. A brushless d-c motor according to claim 9 to 13, wherein the stator has salient poles with auxiliary slots formed therein and the sensor winding is located in the auxiliary slots.

15. A brushless d-c motor according to claim 14, wherein the number of salient stator poles is greater than the number of rotor poles.

16. A brushless d-c motor according to claim 9 to 15, wherein the magnetization of the rotor is essentially trapezoidal in shape and sequential rotor poles are magnetized over a distance of approximately $180^\circ - e1$ in a similar shape and manner of magnetization with respectively reverse directions of the magnetic field or polarity.

17. A brushless d-c motor according to claim 9 to 15, wherein the magnetization of the rotor is approximately rectangular and sequential rotor poles have a length of approximately $180^\circ - e1$ of essentially similar shape and manner of magnetization, but with respectively reverse polarity of direction of magnetization.

18. A brushless d-c motor according to claim 9 to 17, wherein the sensor winding is a single-phase winding.

19. A brushless d-c motor according to claim 9 to 18, wherein the sensor winding extends over $n \times 360^\circ - e1$, in which n is 0, 1, 2, ...

20. A brushless d-c motor substantially as hereinbefore described with reference to the accompanying drawings.



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