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1 BRUSHLESS DC MOTOR ARRANGEMENT

5 The present invention relates to a brushless dc motor arrangement and more particularly to a permanent magnet dc motor which has field current applied thereto in pulses controlled by a semiconductor network in which the timing of the pulses, with respect to rotation of
10 the motor, is controlled by a rotor position sensor, for example a galvanomagnetic sensor, and typically a Hall generator.

 Various types of known brushless dc motors are usually supplied from a dc network which may be derived
15 from a battery of a vehicle, for example, at 12 or 24 V, the battery of a telephone central station at 48 or 60V, or a low-voltage supply from a control panel. Usually, only a two pole or two-terminal dc network is available, that is, a network which has one earth, chassis, or
20 reference terminal and an active terminal usually

1 the positive terminal. Two-terminal dc networks limit
the selection of circuits which can be used to drive dc
motors. In this regard, reference should be made to an
article by Rolf Müller, the inventor hereof, entitled
5 "Zweipulsige Kollektorlose Gleichstrommotoren" in the
"asr-digest", and especially Figs. 1 to 6 thereof.

If a three-terminal dc network is available,
for example, a 24 V network having a +12 V terminal,
earth or chassis, and a -12 V terminal, then simple
10 circuits can be used as shown, for example, in Figs.
2 and 5 of the aforementioned article. Few problems
arise with induced voltages which occur when the
windings of the motor are de-energized. It is, of course,
possible to form a three-pole network artificially by
15 connecting two capacitors in series across the network
supply to provide an artificial zero or centre terminal.
The capacitors required, however, must be of substantial
size. For a 25 V motor of 4 W power, two capacitors,
each of 220 μ F, 35 V, are needed. There is a danger of
20 short circuit if, as may occur, both output transistors
connecting the respective armature windings of the motor
are energized simultaneously. Special protective circuit-
ry is necessary to prevent switching overlaps of the
output transistors.

25 A full-wave bridge circuit can be used with a
two-terminal or pole dc network. This is comparatively
complex and requires many components, see Fig. 5 of the
referenced article. It is also possible to connect the
motor in a star winding or a two-filament, two-pulse
30 motor, with a centre tapped winding, see Fig. 3 of the
referenced article. Fig. 6 of this article illustrates
a circuit for a four-pulse motor having four armature
winding filaments which are star-connected.

A full-wave bridge circuit is efficient with
35 respect to utilization of the wire or copper in the

1 windings and also is capable of good recuperation of
inductive energy which arises upon commutation of the
windings. It requires, however, a considerable number
of components in the electronics and, also, components
5 which are relatively expensive, for example, four output
transistors, circuitry for four control signals for the
respective output transistors, of which two operate in
push-pull relationship. Circuitry is additionally needed
to ensure that the control signals are clearly temporally
10 separated. If two transistors connected in series across
the dc network are controlled to conduct, even if only
for a few microseconds, simultaneously, the resulting
short-circuit current would destroy the transistors.
Thus, reliability of motor operation requires substantial
15 protective circuitry.

A centre tapped winding, see Fig. 3 of the refer-
enced article, is frequently used in actual structures.
Only two output transistors are needed, and the motor
operates well with a two-terminal voltage source. There
20 is no danger of short-circuit current even if both
output transistors should have overlapping conduction
times during short periods. Only the efficiency of
operation is affected. It is difficult, however, to
recuperate the energy released upon commutation and high
25 voltage peaks may occur in the winding filaments which
are disconnected. Such voltage peaks can be suppressed
only with Zener diodes or with R/C networks, in which
the R/C networks are less effective than the Zener
diodes, although cheaper. Alternatively, it is possible
30 to avoid such voltage peaks by soft or gradual disconnec-
tion or interruption of current flow through the armature
windings; this, however, requires additional circuitry
and expense as, for example, shown in US Patent 4,099,104.

An improvement can be obtained, see US Patent
35 3,840,761, and particularly Fig. 20 thereof, by forming

1 the filaments of the armature windings as dual or
parallel filaments, see also Fig. 3 of the referenced
article. Making the windings as dual filaments, in
5 essentially in parallel, results in tight coupling of
the two filaments of the windings. The voltage peaks
are then avoided. It has been found, however, that such
a motor has a disadvantage which is not immediately
apparent. A square-wave voltage is applied over the
10 entire length of both winding filaments with the full
amplitude of the operating voltage, that is, in the
case of an operating voltage of the motor of 24 V, the
square-wave voltage between the filaments will be about
48 V. By definition, a square-wave voltage has steep
15 flanks. The relatively high voltages between the individ-
ual strands or filaments of the windings, and particu-
larly the steep flanks of the voltage pulse, substanti-
ally stress the insulation of the winding and cause
deterioration of the insulation as time progresses.
20 Thus, this type of winding is restricted to operation
with low operating voltages, that is, in the order of
between 12 to 24 V, since operation with higher voltage
places excessive stress on the insulation and impairs
reliability. If the motor is to operate under conditions
25 where reliability of operation is important, or with
higher operating voltages, double-insulated wire is needed.

It is an object to provide a brushless dc motor
arrangement which is suitable for operation from a two-
terminal dc network; which permits effective and complete
30 recuperation of inductively stored energy which arises in
the armature windings upon termination of the operating
pulses; which does not cause voltage peaks at the respec-
tively disconnected winding filaments and which does not
impair the integrity of the insulation of the winding
35 filaments; and which is simple in construction and permits

1 use of semiconductor control elements which, in turn,
can be easily controlled so that the electronic portion
of the motor arrangement can be constructed in both a
simple and inexpensive manner.

5 Accordingly, the invention provides a brushless dc
motor which has a stator, a permanent magnet rotor, sensor
means arranged on the stator for sensing the angular position
of the rotor, and armature winding means comprising at least
one pair of winding strands arranged on the stator, wherein:

- 10 (a) one winding strand of the or each pair
has one end connectable to one pole of a dc
network by first semiconductor means under the
control of said sensor means;
- 15 (b) the other winding strand of the or each
pair has one end connectable to the other pole
of the dc network by second semiconductor
means under the control of said sensor means;
- 20 (c) the other end of said one winding strand
is connectable to the other pole, and the other
end of said other winding strand is connectable
to said one pole, of the dc network;
- 25 (d) said first and second semiconductor means
are of opposite conductivity and are rendered
alternately conductive, in use, under the
control of said sensor means;
- (e) at least the ends of the winding strands,
connected to respective ones of said first and
second semiconductor means, are closely ac
coupled; and
- 30 (f) means are provided for taking up energy
stored in the respective winding strand upon
changeover from one strand to the other or
vice-versa.

The winding strands of the or each pair are preferably
35 closely inductively coupled, in which case the strands can be

1 formed as a bifilar winding arrangement, to provide a very
close inductive coupling therebetween. A coupling condenser,
for producing the close ac coupling between the winding
strands, may be arranged between the two ends thereof. In
5 such an arrangement, the energy storage capacity of the
coupling condenser can correspond, in respect of order of
magnitude, to the energy to be recovered from the
respective winding strand during commutation from one of
said semiconductor means of opposite conductivity to
10 the other. The inductive or transformer coupling provided
by the windings and/or the coupling capacitor can transfer
energy stored in a respective winding, which has current
flowing therethrough and in which current flow is then
interrupted upon disconnection of the respective one of
15 said semiconductor means via the other winding to
respective means for taking-up said energy.

The output signal of said sensor means, which is
dependent upon the angular position of the rotor, is
arranged to be supplied to said semiconductor means via
20 a network of passive structural elements, which network
may be a resistance network. Another coupling capacitor
may be provided in the connection between the network
and a control input of each of said semiconductor means.
Preferably, these capacitors have a capacity in the order
25 of several μF .

The sensor means preferably comprises a Hall integrated
circuit generator directly connectable to one terminal
of a dc network, the resistance network including a first
resistor connecting the output of said sensor means to
30 the control input of one of said semiconductor means,
whilst a second resistor can connect the output of said
sensor means to the control terminal of the other of said
semiconductor means, with a coupling resistor connecting
the output of said sensor means to the other terminal of
35 the dc network.

1 Advantageously, a constant voltage, voltage-limiting
element is connected between the output of said sensor
means and the second and third resistors, respectively,
to protect the output of said sensor means against any
5 high operating voltage applied across an associated dc
network. Preferably, another coupling capacitor with which
a discharge circuit is associated, is provided in the
connection between the resistance network and a control
input of each of said first and second semiconductor means.

10 Complementary semiconductor means may be provided
in the form of complementary transistors, preferably
a matched pair of Darlington transistors.

The angular position sensor means may be arranged to
provide, in operation only, an output signal of the binary
15 type at respective different voltage levels in accordance
with the selected orientations of the rotor, and the
network consisting of passive structural elements can
connect the alternately-occurring binary voltage levels
to both of said complementary semiconductor means, to
20 render said means alternately conducting.

Also, the invention includes a ventilator or fan
incorporating an axial air gap, brushless dc motor as
defined above.

Said sensor means, for example, the Hall sensor,
25 or any other suitable rotor position sensor, may be
arranged to provide a binary output signal which is either
"high" or "low", that is, it is of the binary output
type. The "high" or "low" signal can be referred to as a
1-signal or as a 0-signal, respectively. Conduction of
30 respective output transistors, which have their other
terminals connected to the respectively opposite terminal
of the supply to which the associated winding is connected,
is determined by the rotor position sensor signal, that is,
whether the signal is a 1-signal or a 0-signal. Thus,
35 alternately, the rotor position sensor controls conduction

1 of the one or the other one of the output semiconductors.
The transistors may have reversely-poled, free-wheeling
diodes connected thereacross for feeding energy back to the
dc network.

5 No voltage differences will occur between the two
windings which are substantially greater than the operating
voltage. Switching voltages which impair the effectiveness
of the insulation between the windings are likewise avoided,
since the two windings have, for all practical purposes,
10 a dc voltage thereacross which, even if the windings are
positioned in parallel, is no greater than the operating
voltage. Thus, even in parallel-wound operation, which has
substantial advantages in manufacture, use and operating
efficiency, the winding insulation is stressed only to the
15 extent of the voltage of the supply, thus insuring high life
and reliability of the motor arrangement and associated
circuitry.

Tight ac-coupling of the two windings can provide
essentially complete feedback or recuperation of inductively
20 stored energy in one of the windings, and suppression
of voltage peaks. The energy which arises in the winding
which has its supply voltage disconnected, is not
fed back directly to the supply, to a storage capacitor
or any other means for taking-up energy, but rather
25 indirectly. A free-wheeling diode may be connected in
reverse polarity with respect to, and across the control
semiconductor and then provides for current flow through
the winding which is then just being connected. The
invention may thus provide for an energy bridge between
30 the winding which is just being disconnected, and the
winding which is then just being energized, which energy
bridge transfers the inductively stored energy in one
of the windings to the other winding, with essentially
little loss and time delay, The energy being transferred
35 to the other winding may then be fed over a free wheeling

1 diode to the supply or to a storage capacitor, so that
voltage peaks are voided while the overall efficiency
of operation will be higher. Transfer of energy thus
occurs without danger to the insulation of the windings
5 by high voltage peaks, and this preferred inventive
arrangement is thus a substantial advance over the prior
art arrangements.

An additional, important and unexpected advantage
is obtained by the circuit. Semiconductor control elements
10 of opposite conductivity type can be controlled by a
single signal source providing alternate 1-signals and
0-signals, so that the control of commutation or selection
of application of pulses to the respective windings is
simple, resulting in an overall inexpensive circuit.

15 In order that the invention may be more fully
understood, various embodiments will now be described by
way of example and with reference to the accompanying
drawings in which:

Fig 1a is a highly schematic end view of a two-
20 winding, two-pulse energized external rotor motor in
accordance with the prior art;

Fig 1b is a schematic diagram of the two windings
of the prior art motor of Fig 1a.

Fig 2 is a schematic circuit diagram of a commutating
25 circuit for the motor of Fig 1a, in accordance with the
prior art;

Fig 3 illustrates a circuit diagram of a motor and
control system in accordance with a first embodiment of
the invention;

30 Fig 4, collectively, illustrates a highly schematic
representation of a parallel winding arrangement in which
Fig 4a is a representation of the winding arrangement,
and

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1 Fig 4b is the equivalent circuit representation utilizing the conventional dot notation;

Fig 5, collectively, illustrates a series of graphs of currents and voltages arising in the motor of Fig 3, in which Fig 5A is a time-current graph, Fig 5B a time-voltage diagram, and 5C a time-pulse current diagram;

Fig 6 illustrates a circuit diagram in accord-

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1 ance with a second embodiment of the invention; and
 Fig. 7 illustrates a circuit diagram of the
 preferred form of circuit of the present invention
 using Darlington transistors.

5 A basic, prior art motor, and its structure and
 general considerations, is illustrated in Fig. 1a, where-
 in an external rotor motor 10 has a two-pole rotor 11
 formed as a continuous magnetic ring. Magnetization is
 approximately trapezoidal, so that the magnetic flux
10 within the region of a pole is effectively constant, the
 gaps 12, 13 between the poles being narrow.

 The positions of effectively constant magnetic
 flux for the North pole are indicated by cross-hatching
 and for the South pole by stippling, in order to facili-
15 tate understanding of the principle of the present
 invention.

 The rotor 11 is radially magnetized, that is to
 say, it is a radially-magnetized, permanent magnet ele-
 ment made, for example, of barium ferrite, or it may be a
20 rubber magnet, the two pole gaps 12, 13 being shown in
 broken lines. The rotor 11 is illustrated in Fig. 1a in one
 of its two stable quiescent positions which the motor
 may take when it is de-energized. This stable position
 is determined by the shape of the air gap and the magnet-
25 ization of the rotor 11. The direction of rotation, in
 operation, is in accordance with the arrow 14.

 The stator 15 of the motor 10 is of a double
 T-shape and has an upper pole 16 and a lower pole 17
 which are both essentially umbrella or mushroom shaped in
30 cross-section. That is, each covers almost an entire
 pole arc. Slots 18, 19 are positioned between adjacent
 ends of the poles 16, 17 in which winding strands or
 filaments 20, 21 of a dual winding are positioned. The
 terminals of the winding 20 are shown at a1 and e1, and
35 the terminals of winding 21 are shown at a2 and e2, as

1 shown also in Fig. 1b. The windings 20, 21 have the
same number of turns and are wound in the same direction,
that is, if dc current flows from a1 to e1, then the
same magnetization of the stator 15 will occur, as when
5 the same dc current flows from a2 to e2. The conventional
dot notation is shown in Fig. 1b, that is, winding 20
has its dot at terminal a1, winding 21 at terminal a2.
A similar dot notation will be used in connection with
the other figures.

10 A rotor position sensor 25 is located on the
stator or in fixed relation thereto. As shown, the
rotor position sensor 25 is a Hall device, for example,
a Hall integrated circuit, positioned at a predetermined
angular position with respect to the stator 15, which
15 corresponds approximately to the slot 18. However, the
sensor 25 is slightly offset with respect to the slot 18
counter the direction of rotation 14, that is, in the
anti-clockwise direction, by a few degrees. The Hall
sensor 25 is controlled by the magnetic field of the per-
20 manent magnet 11 and provides a signal which depends on
the position of the rotor. This signal is either "high"
or "low" and, upon rotation of the rotor 11 and for all
practical purposes, provides a square-wave output, the
"high" and "low" portions of which are each approximately
25 180° - e1.

The air gap 26 over the extent of the stator pole
16 and the air gap 27 over the extent of the stator pole 17,
each has a very specific shape. Starting from the slot
18, and proceeding in the direction of rotation 14, the
30 air gap 26 increases approximately monotonically for an
angle of about 10° to 15° to a maximum 30 at a first
position. The air gap 26 then monotonically decreases
over about 170° up to approximately adjacent the opening
of the slot 19, where it reaches a minimum value d1.
35 The air gap 27, as shown, is identical. The shape of

1 these air gaps, in combination with the particular
type of magnetization of the rotor 11 and in operation,
causes the generation of a reluctance torque of a prede-
termined temporal course, as the rotor rotates, and as
5 known from German Patent Specification No 2,346,380.
Different types of motors may be used, of course,
rather than the motor described in Fig. 1. For example,
a coreless, axial air gap motor as described, for example,
in US Patent Specification No 3,840,761 (see particularly
10 Fig. 20) can be used. Alternatively, a four-pulse,
four-filament motor as described in the aforementioned
"asr-digest" literature reference (Fig. 6) could be used.
The particular type of motor does not form a part of
the present invention, although a motor with a non-uniform
15 air gap is preferred, since the output torque will be
more uniform throughout the rotation of the motor than
with a uniform air gap motor.

A suitably known circuit for the motor of Fig.
1a is shown in Fig. 2. A positive supply line 33 is
20 connected to a positive operating voltage U_b , for example,
a battery 34. The negative line 35 of the circuit is
connected to the negative terminal of the battery 34
which may be, say, 12, 24 or 48 V. Terminals e1 and a2
of the respective windings 20, 21 are connected to the
25 positive supply line 33, whilst terminals a1 and e2 are
connected to the collectors of two npn transistors 36, 37
whose emitters are connected to the negative line 35.
Each one of the transistors 36, 37 has a free-wheeling
diode 38, 39, respectively, connected thereacross. The
30 rotor position sensor 25 controls a switching circuit 42
having two outputs connected respectively to the bases
of the transistors 36, 37. When the transistor 37
receives a positive signal 43, it is conductive and
current will flow through the winding —————
35 21. At the same time, the transistor 36 must receive a

1 negative signal 44 to cause it to be non-conductive.
Conversely, when the transistor 36 conducts, the transis-
tor 37 must not conduct. Thus, oppositely poled signals
43, 44 are necessary and this renders the construction of
5 the circuit 42 quite complex, particularly if the
currents in the respective windings 20, 21 are to be dis-
connected gradually, to prevent the occurrence of switch-
off voltage peaks. If gradual or smooth disconnection of
the current is not possible, the diodes 38, 39 must be
10 formed as Zener diodes, resulting in comparatively
high radio noise interference which, in many instances,
is undesirable and, for some applications, is not permiss-
ible. A storage capacitor 45 can be used to at least
partially suppress stray interference.

15 In the first embodiment in accordance with the
present invention illustrated in Fig. 3, the windings
20, 21 are coupled, either capacitively or inductively
and reversely polarized diodes are provided in parallel
with the ability to couple energy released upon the non-
20 conductance of a respective transistor into the other
winding and to permit current flow then through the
diode connected to the other winding.

The circuit diagram of Fig. 3 is illustrative of
two embodiments of the invention which, from a consider-
25 ation of the diagram alone, are not separately apparent.
One of the embodiments, as illustrated in Fig. 3 utilizes
two windings 20, 21 (20', 21') which are wound in paral-
lel, as illustrated in Fig. 4a. Coupling between the
windings is inductive. If the windings 20', 21' are not
30 inductively coupled, or are only slightly so, for
example, if the motor has a coreless stator winding as
described in the applicants' US Patent Specification No
3,840,761 (Fig. 1), a coupling capacitor 47 is needed.
The size of the coupling capacitor 47, which may be
35 entirely absent, may have an effective capacity of zero

1 or close thereto, will depend upon the coupling of the
windings 20', 21' (20, 21). The capacitor 47, thus, may
be absent, be of a very small capacity, or be of a
sufficiently large capacity to effect coupling of the
5 inductive energy which is stored in the winding carrying
current into the other winding to be connected. The
coupling capacitor 47 can function also as an energy
storage element, so that the capacity of the capacitor
45 then need only be in the order of nF and will be used
10 only to suppress radio noise interference on the supply
lines 33, 35.

In the description to follow, components once
described and functioning similarly to other embodiments,
or in accordance with the prior art, have been given the
15 same numerals and will be described only once herein.

The embodiment of Fig. 3 has capacitive coupling,
using the capacitor 47. The Hall sensor 25 has one ter-
minal connected to the chassis or earth line 35 and the
other across a resistor 48 to the positive line 33. A
20 Zener diode 49 is connected in parallel to the Hall
sensor 25 to control its operating voltage to a suitable
value, for example to 5 V. The output 50 of the Hall
sensor 25 is connected to a resistance network 53 includ-
ing three resistors 54, 55, 56 which are serially connec-
25 ted. The output 50 of the Hall sensor 25 is connected to
the junction between resistors 54, 56. The other ter-
minal of the resistor 56 is connected to the base of an
npn transistor 58, whilst the resistor 55 is connected
at one side to the positive line 33 and its other side to
30 resistor 54. This junction is connected to the base of a
pnp transistor 57 which is complementary to the transis-
tor 58. The emitters of the transistors 57, 58 are
connected to the respective lines 33, 35, whilst their
collectors are connected to the dot terminals of the
35 windings 20, 21, that is, to terminals a1, a2. A free-

1 wheeling diode 59 is connected between the terminal a1,
that is, the collector of the transistor 57, and the
line 33. A free-wheeling diode is connected between
the winding terminal a2, that is, the collector of the
5 transistor 58, and line 35. The polarity of current
flow through the diode 60 is opposite that through the
transistors 57, 58, when the transistors are conducting.
Connection of the diodes 59, 60 with respect to the
transistors, in view of the polarity of conduction, is
10 also termed an anti-parallel connection.

The windings 20, 21 are coupled by a coupling
capacity 47 which is so dimensioned that it can receive
at least a portion of the inductive energy stored in
the windings 20, 21 without substantially increasing its
15 charge voltage u_c , that is, it does not essentially
exceed the line voltage between the supply lines 33, 35.

The terminals a1, e1; a2, e2 are similar to and
have been given the same notation as in Fig. 1. Voltage levels
at terminals a1, a2 are indicated as p_1 , p_2 , whilst currents
20 and other voltages shown in Fig. 3 are similarly
identified in Figs. 5A and 5C.

Operation, with reference to Figs. 5A to 5C is
as follows. Let it be assumed that the transistor 57 is
controlled to conduction. A current i_{20} will flow from
25 the line 33 through the current-carrying conduction path
of the transistor 57 and the winding 20 from the terminal
a1 to terminal e1. The stator pole 16 becomes a South
pole, and the stator pole 17 a North pole. If the trans-
istor 58 is rendered conductive, a current i_{21} will flow
30 from terminal e2 to terminal a2, the stator 16 becoming a
North pole and the stator 17 a South pole. In the
annular position of the rotor illustrated in Fig. 1, in
which the Hall sensor 25 is opposite a North pole of the
rotor 11, the transistor 57 is conductive and hence, the
35 winding 20 will have current flowing therethrough. When

1 sensor 25 is opposite a South pole, the winding 21 is rendered conducting, thus resulting in the direction of rotation indicated by the arrow 14. Thus, when the Hall sensor 25 is opposite a North pole, its output 50 will
5 be at a low value or, in binary notation, a zero level. This terminal, then, will have approximately the voltage of the negative, chassis or earth line 35, the transistor 58 will be non-conducting, and the transistor 57 will become conductive. Conversely, when a South pole is
10 opposite the Hall sensor 25, the output 50 will be high, that is, a 1-signal or positive, with the transistor 58 conductive and the transistor 57 non-conductive. Thus, one single output signal at the output 50 from the Hall sensor 25 permits control of the two transistors 57, 58
15 in push-pull, alternate conduction, or counter phase relationship by control over the resistance network 53. The control switching circuit 42 of Fig. 2, thus, in accordance with a feature of the invention, merely becomes a three-resistor resistance network.

20 Considering now commutation, let it be assumed that the transistor 58 is conductive and should be disconnected, such that the next current pulse then flows through the winding 20 upon conduction of transistor 57. When the transistor 58 is conductive, the capacitor 47
25 will have a voltage u_c thereacross, with the polarity as shown in Fig. 3, which is approximately equal to the average amplitude of the voltage which is induced by rotation of the permanent magnet rotor 11 in the windings 20, 21. This voltage is shown in Fig. 5B. The voltage
30 across terminals e_1 , e_2 differs continuously by the value of the supply voltage U_B , since the terminals e_1 , e_2 are connected to the lines 33, 35.

During commutation, that is, upon turn-OFF of the transistor 58, the current i_{21} in winding 21 begins to
35 reduce. The voltage p_2 at the terminal a_2 (Figs. 3 and

1 5B) will begin to rise until it is more positive, by
 about the value u_c , than the voltage U_B of the positive
 line 33 (Fig. 5B). At this instant, the voltage p_1 at
 the terminal a_1 has risen approximately to the value of
 5 the supply voltage U_B , due to the coupling of the termin-
 als a_1 and a_2 by the capacitor 47. As soon as the volt-
 age across capacitor 47 slightly exceeds the voltage U_B ,
 for example, by more than 0.6 V, the free-wheeling diode
 59 will become conductive and a current i_{59} will flow to
 10 the storage capacitor 45 or will be returned to the power
 supply network (Fig. 5C), so that the inductive energy
 from the winding 21 is recuperated over the energy bridge
 formed by the coupling of the winding 21 with the free-
 wheeling diode 59, in this instance, via the capacitor 47.
 15 Conduction of diode 59 prevents a further rise of the
 voltage p_1 and hence, due to the tight ac coupling
 between the terminals a_1 and a_2 by the capacitor 47, a
 further increase of the voltage p_2 , above a value which
 substantially exceeds $U_B + u_c$ (Fig. 5B). The currents
 20 through the respective winding 20, 21 are shown in Fig.
 5A, and the voltage relationships at the respective
 terminals at Fig. 5B.

In accordance with the present invention, there-
 fore, energy is transferred from the winding to be discon-
 25 nected or turned OFF, in the example, the winding 21, via
 the coupling capacity 47 and diode 59 to the source of
 the supply, for example, the battery 34 (Fig. 1) or the
 storage capacitor 45. The capacitor 47 clamps the volt-
 ages of the terminals a_1 and a_2 and, when the voltage p_1
 30 rises, the voltage p_2 likewise rises, and between the
 terminals a_1 , a_2 , that is, the voltages p_1 , p_2 , will be
 thereacross only an essentially uniform, unvarying
 voltage, namely, that voltage across the capacity 47. The
 terminals e_2 and e_1 will have only the uniform and essen-
 35 tially unvarying operating voltage U_B . Thus, the insu-

1 lation of the wires of the windings 20, 21 is stressed
only with the dc voltage of the network, which is moder-
ate, and is thus not overloaded with excessively high
voltages.

5 If the windings 20, 21 are coupled by a ferro-
magnetic core, analogous to a transformer, then a portion
of the energy stored in the winding which is de-energized
is transferred to the other winding, and the other winding
can then transfer this energy to the free-wheeling diode
10 59. In the foregoing example, that is, when the winding
21 is to be disconnected, with the transistor 58, after
conduction, being turned OFF, energy is transferred to
the winding 20, which then causes current to flow through
the diode 59, as before. Two energy bridges are then
15 provided, one over the coupling capacitor 47 and the
other over the transformer or inductive coupling between
the windings 20, 21. The capacitive value of the coupling
capacitor 47 thus should be matched to that of the trans-
former coupling between the windings 20, 21. If the
20 coupling between the windings is very small, for example
if the motor is a flat or "pancake" motor as illustrated
in the aforementioned US Patent Specification No 3,840,761
(Fig. 1 or 20), then the coupling capacitor 47 must have
a substantial capacity. If the motor is as shown in
25 accordance with Fig. 1 of the present application, then
a much smaller capacitor 47 can be used. If the coupling
between the two windings 20, 21 by the parallel winding
of the two windings 20', 21' (Fig. 4b) is tight, then it
is possible to eliminate entirely the coupling capacitor
30 47, since this tight coupling can be a sufficient and
simple energy bridge. Of course, some capacity between
the windings will also be present and additionally
contribute to the coupling. This capacity may be repre-
sented, also, by an equivalent small capacitor 47.

35 The windings 20', 21' are wound as bifilar, that

1 is, two-wire parallel windings. It is not sufficient to
merely wind two separate windings in common slots, in
order to obtain sufficient transformer coupling of the
windings and thus avoid the necessity of the capacitor 47.

5 The distance between the windings in an arrangement in
which the windings are merely placed in common slots
renders coupling between the individual windings incom-
plete. When the windings are wound on the armature, as
shown, for example, in Fig. 1a, incomplete inductive
10 coupling between the windings will result. Consequently,
and when using the circuit of Fig. 2 with the winding
arrangement of Fig. 1a, the energy transfer, particularly
upon rapid switching, is insufficient and voltage peaks
will occur in the winding which is turned OFF. If, how-
15 ever, in accordance with a feature of the invention, the
windings are wound commonly as a bifilar winding, so that
the windings are intimately mixed together, leakage flux
is practically entirely suppressed. The spatial
difference between windings in the arrangement of Fig. 1a
20 results in a somewhat loose inductive coupling. In con-
trast, and when using the winding arrangement shown in
Fig. 4a, in which the bifilar windings are intimately
mixed, the inductive coupling is tight and effective,
thus practically entirely suppressing leakage flux.

25 It has been found, surprisingly, that using a
bifilar winding in combination with the circuit of Fig. 3
results in a difference voltage which is essentially a
direct voltage between the two windings 20', 21', the
value of which at the windings terminals e1, e2, connec-
30 ted to the lines 35, 33, is equal to the operating volt-
age U_B , and the value of which at the winding terminals
a1, a2 corresponds roughly to the amplitude of the volt-
age which is induced by the rotating permanent magnet
motor in the respective windings in operation of the
35 motor. This voltage has a small alternating voltage

1 modulated or superposed thereon, its amplitude being
 approximately 50% to 70% of that of the operating voltage.
 The small alternating voltage can be suppressed by use
 of the coupling capacitor 47 connected between the collec-
 5 tors of the transistors 57, 58 or, at least with respect
 to the steepness of the flanks, sufficiently smoothed
 out, so that there is little danger of damage to the
 insulation due to voltage degradation. The insulation is
 not stressed by a square-wave voltage of substantial
 10 amplitude with steep switching flanks. Due to the
 symmetry of the circuit, induced energy is transferred
 from the winding 20 or 20' to the diode 60 in an
 exactly analogue manner (compare Fig. 5B). Energy
 stored in the winding 20 or 20', upon de-energization of
 15 the transistor 57, is transferred through the coupling
 capacitor 47 and/or transformer, inductive coupling of
 the windings to flow as current through the diode 60 to
 the power supply source, e.g. a battery 34 (Fig. 1) or
 to the storage capacitor 45.

20 In one operating example arranged for 24 V, and
 for a motor with a 4 W power input operating at 3000 rpm,
 the circuit of Fig. 3 with a motorwound in accordance
 with Fig. 1 that is two separately arranged windings 20,
 21, has the following values:

25	Zener diode 49:	5.1 V
	Hall IC 25:	TL 170
	resistor 54:	2.2 k Ω
	resistor 55:	100 Ω
	resistor 56:	5.1 k Ω
30	resistor 48:	3.3 k Ω
	capacitors 45 and 47:	22 μ F
	transistor 57:	BD 136
	transistor 58:	BD 135
	diodes 59, 60:	1N4148.

35 As can be seen from the foregoing example, only

1 few components are used which can be readily accommodated
on a printed circuit (PC) board. This is particularly
important when the circuit is to be combined with fans or
ventilators for electronic equipment of compact axial
5 dimensions, which is particularly important in fans or
ventilator motors in combination with electrical and
electronic equipment, since very little space is avail-
able for the motor itself.

The circuit has the advantage that the transis-
10 tors 57, 58 can be controlled with essentially square-
wave signals having the same phase position with respect
to each other but differing in dc voltage level. The
control signals for the transistors 57, 58 can thus be
generated by a single output from a Hall integrated
15 circuit (IC) generator without requiring an additional
phase inversion stage. As illustrated in Fig. 3, a
single output signal from the Hall IC sensor 25, and a
suitably dimensioned resistor network 54, 55, 56,
provides control of the two transistors in alternating
20 conducting cycles. The control network for the transis-
tors is thus simple and inexpensive.

As can be seen, the arrangement of Fig. 3 prov-
ides for galvanic connection of the bases of the transis-
tors 57, 58 via the resistors 54, 56. In accordance
25 with another feature of the invention, additional advan-
tages can be obtained by de-coupling the bases of the
transistors 57, 58 galvanically.

Separating the dc voltages on the bases of the
output transistors is illustrated in the circuits of
30 Figs. 6 and 7. Similarly, operating components previous-
ly described have been given the same reference numerals
and will not be described again. The Hall generator or
Hall IC sensor 25 is connected as illustrated in, and
described in connection with, Fig. 3.

35 Referring to the embodiment of Fig. 6, a coupling

1 network 65 is connected to the output 50 of the Hall
sensor 25 and has three resistors 66, 67, 73. The resis-
tor 66 has one terminal connected to the positive line
65, its other terminal being connected to the output of
5 the Hall sensor 25 and to one terminal of a resistor 67,
which has its other terminal connected to one terminal of
a capacitor 68 whose other terminal, in turn, is connected
to the base of a pnp transistor 69. A base-emitter
resistor 70 connects the base 69 to the $+U_B$ line 33 to
10 which also the emitter of the transistor 69 is connected.
The output of the Hall IC sensor 50 is further connected
to the resistor 73, the other terminal of which is
connected to a capacitor 74 which is connected to the
base of an npn transistor 75, having a base-emitter resis-
15 tor 76 connected to negative, chassis or earth line 35,
to which also the emitter of a transistor 75 is connec-
ted. The collector of the transistor 69 is connected
with the terminal a1 of the winding 20 (Fig. 1) or 20'
(Fig. 4). The collector of the transistor 75 is connec-
20 ted with the terminal a2 of the winding 21 or 21', respec-
tively. Free-wheeling diodes 59, 60 are connected, as in
Fig. 3, in anti-parallel relationship to the respectively
associated transistors 69, 75. A coupling capacitor 47
is connected between the terminals a1, a2 of the windings
25 20, 20', 21, 21'.

In operation, let it be assumed that a North pole
is opposite the Hall IC sensor 25, as shown in Fig. 1.
Its output voltage is a 0-signal and this is approxi-
mately at the voltage of line 35. Charge current will
30 flow over the emitter-base path of the transistor 69 to
the capacitor 68 and will charge this capacitor in
accordance with the polarity, as shown in Fig. 6,
causing the transistor 69 to become conductive, so that
current will flow in the respective winding 20, 20'.
35 Upon turn-OFF of the transistor 69, and current flow

1 through the winding 20 or 20', energy is transferred
from the respective winding 20, 20' via the transformer
coupling and the coupling capacitor, to result in current
flow through the diode 60 for recuperation or energy
5 retrieval. Subsequently, the transistor 75 will be
controlled to conduction. At this time, the capacitor
68 will discharge at least partially through resistors
66, 67, 70. The operation with respect to the transis-
tor 75 and capacitor 74 will be analogous. Resistors
10 70, 76 also draw off leakage currents which might arise
in the capacitors 68, 74. Thus, both capacitors continu-
ously receive a charge which varies due to the above-
described charge discharge cycles, resulting, however,
in an essentially uniform voltage of, say, a few volts
15 on the capacitors. The capacitors, thus, in operation
function almost similarly to small batteries which ensure
that the transistors 69, 75 safely non-conduct. As seen,
the capacitor 74 is charged with opposite polarity to
that of the capacitor 68.

20 In accordance with yet another feature of the
invention, the circuit prevents excessive current being
drawn, in case of a motor malfunction or interference
with rotation of the motor. If the rotor 11 blocks,
then the transistor which conducts will receive current
25 for only such a period of time until the associated
capacitor 68 or 74 is fully charged. Thereafter, the
transistor and with it the motor 10, will lose current.
This is an additional advantage of the inventive circuit
arrangement. Diode 77 in the positive supply line 65
30 is provided as a reverse-polarity protection diode to
prevent damage to the circuit components upon inadvertent,
erroneous polarity connection of the circuit to a battery
or other power source.

In an operating example, the following circuit
35 values are suitable for use with a 24 V operating voltage

1 and a motor of 4 W input power operating at 3000 rpm:

	Resistor 48:	3.3 k Ω
	resistor 66:	1.2 k Ω
	resistors 67, 73:	5.1 k Ω
5	resistors 70, 76:	22 K Ω
	capacitors 68, 74, 45:	15 μ F
	capacitor 47:	10 μ F.

10 Zener diode 49, Hall generator 25, the transistors and diodes were identical to those used in the circuit of Fig. 3.

The capacitors 68, 74, in the above example of 15 μ F, are of a substantial size which may be undesirable for certain applications.

15 Fig. 7 illustrates an arrangement in which substantially smaller equivalent capacitors can be used. The motor is designed to be wound in bifilar windings, as described in connection with Fig. 4, that is, parallel-positioned wires wound together. No coupling capacitor 47, or a coupling capacitor of only very small value, 20 is required for connection between the terminals a1 and a2 of the respective windings 20', 21'.

Complementary Darlington transistors 80, 81 are used, rather than ordinary transistors 57, 58; 69, 75 (Figs. 3, 6). The type of preferred Darlington transistor is that which already includes the emitter resistor 25 80' and an anti-parallel connected diode 80'' in the same transistor housing and connected as shown in Fig. 7.

Similar complementary components are used in the Darlington transistor unit 81, that is, as base resistor 30 81 and a free-wheeling diode 81''. The Darlington transistors have substantially higher current amplification than the simple transistors 57, 58; 69, 75 and, thus, they can be controlled by R/C circuits of high impedance.

35 The resistance network 82 forming the control switching circuit connected to the Hall IC sensor 25, is

1 similarly constructed in general principle as the
network 65, 56. The output 50 from the Hall IC sensor
25 forms a junction connected to resistors 88 and a
junction 83 of resistors 85, 86. A Zener diode 84 may
5 be connected between junctions 50 and 83 and is used
if the operating voltage U_B is, for example, more than
30 V. If the operating voltage U_B is, for example,
60 V, a Zener diode 84 having a Zener voltage of
30 V is used, in order to protect the Hall IC sensor at
10 its output 50 against excessive voltage levels. If the
operating voltage U_B is less than about 30 V, for example
24 V, then the Zener diode 84 is not needed. If the
operating voltages of the circuit of Fig. 3 or 6 exceed
30 V, and are, for example 48 or 60 V, then a Zener
15 diode similar to that of the diode 84 should be used
in the connection between the output 50 of the Hall IC
sensor 25 and a coupling resistor which, directly or
indirectly, is connected to the positive supply line 33.

Junction 83 (Fig. 7) is connected by a resistor
20 85 to the positive line 33 and further by resistor 86
with a series capacitor 87 which, in turn, is connected
to the base of the Darlington transistor unit 80. The
output 50 is further connected, through a coupling
resistor 88, to the capacitor 89 and then to the base
25 terminal of the Darlington transistor unit 81. As can
be seen, the Darlington transistor units 80, 81 are com-
plementary. A small capacitor 91, 92 is connected
across the base-collector terminal of the respective
Darlington transistor unit 80, 81 in a Miller circuit,
30 to suppress high-frequency interference. The emitter
of the pnp Darlington transistor unit 80 is connected
to the positive line 33 and its collector to the terminal
a1 of the winding 20'. The emitter of the npn Darlington
transistor unit 81 is connected to the earth, chassis or
35 negative line 35 and its collector to the terminal a2 of

1 the winding 21'.

Basically, the operation is identical to that of Fig. 6. Capacitors 87, 89 are charged to the polarity shown in Fig. 6 and function as small batteries which ensure reliable non-conduction of the transistors 80, 81 and, further, ensure rapid current disconnection, if the rotor 11 of the motor should be blocked.

Suitable values of circuit elements for a 24 V, 3000 rpm, 4 W motor in the circuit of Fig. 7 are:

10	Zener diode 84:	not necessary
	resistor 85:	3.3 k Ω
	resistors 86, 88:	10 k Ω
	capacitors 87, 89:	4.7 μ F
	capacitors 91, 92:	100...220 pF
15	transistor 80:	BD 678
	transistor 81:	BD 677.

All other circuit components are similar to those of Fig. 6, and the example has been selected with the same operating voltage to illustrate the comparison of circuit values. The Zener diode 84 is not needed since the operating voltage is below 30 V.

Comparison of circuit values of the circuits of Figs. 6 and 7 shows that when using the bifilar winding, which is the preferred embodiment, only a few and small electronic and electrical circuit components are used. The circuit of Fig. 7, thus, is the preferred and optimal embodiment.

The amplitude of the square-wave voltage between the windings, when using the prior art circuit of the aforementioned referenced US Patent Specification 3,840,761, particularly Fig. 20, is between about 36 and 44 V, with a 24 V operating voltage.

The amplitude of the square-wave voltage, when using the circuit of the present invention, between the respective windings, with otherwise equal operating

1 conditions, is between 12 to 24 V, with a small ac com-
2 ponent of 2 to 5 V superposed or modulated thereon. Such
3 a difference in voltage can be easily accepted by insu-
4 lation normally applied to the winding wire. High-
5 frequency, ac components are completely eliminated.
6 Thus, damage or degradation of insulation over long
7 operating periods of time need not be feared and a motor
8 arrangement is provided which has extreme reliability and
9 long operating life with a simple associated control
10 circuit using only few and readily available circuit
11 components.

12 Motors with four or six windings can be used,
13 in which case, the control circuit is then either doubled
14 or tripled, and appropriate sensing elements, that is,
15 rotor position sensors, such as, Hall generators, are
16 suitably positioned to be affected by the magnetic field
17 of the rotor, for example at the circumference of the
18 stator. In a four-pulse motor, Hall generators must
19 be offset by 90° -el., as is well known in the field.

20 The dot convention of the designation of the
21 windings utilized is that, upon rotation of a motor with
22 a permanent magnet rotor, voltages are induced in the
23 windings which are of equal phase. For example, let it
24 be assumed that the two windings with terminals a1-e1 and
25 a2-e2, respectively, have a voltage induced which, at
26 the same instant, is positive at the terminals a1 and a2,
27 so that a negative voltage will appear at terminals e1
28 and e2. Under those conditions, the terminals a1 and a2
29 each have a dot applied. The dot, thus, indicates that
30 the respective end of the winding within the motor is
31 subject to the same effect or has the same voltage
32 polarity.

33 The embodiment of Fig. 7 permits operation with-
34 out a coupling capacitor 47, as shown, or with a coupling
35 capacitor 47 of only very small value. This has the

1 additional further advantage that short-time simultane-
ous overlap of current through the transistors 80, 81
will not cause damage thereto. Any overlap, in time,
of current flow or conduction of both transistors 69, 75
5 in the circuit of Fig. 6 would, effectively, connect the
charged capacitors 45, 47 in series, resulting in des-
truction of the transistors 69, 75. Immunity against
spurious malfunction in the operation of the controlled
elements 69, 75, 80, 81, or the respective control cir-
10 cuits therefor, is another advantage of the circuit of
Fig. 7.

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1 CLAIMS

5 1. A brushless dc motor which has a stator, a permanent magnet rotor, sensor means arranged on the stator for sensing the angular position of the rotor, and armature winding means comprising at least one pair of winding strands arranged on the stator, wherein:

10 (a) one winding strand of the or each pair has one end connectable to one pole of a dc network by first semiconductor means under the control of said sensor means;

15 (b) the other winding strand of the or each pair has one end connectable to the other pole of the dc network by second semiconductor means under the control of said sensor means;

 (c) the other end of said one winding strand is connectable to the other pole, and the other end of said other winding strand is connectable to said one pole, of the dc network;

20 (d) said first and second semiconductor means are of opposite conductivity and are rendered alternately conductive, in use, under the control of said sensor means;

25 (e) at least the ends of the winding strands, connected to respective ones of said first and second semiconductor means, are closely ac coupled; and

30 (f) means are provided for taking up energy stored in the respective winding strand upon changeover from one strand to the other or vice-versa.

 2. A motor according to claim 1, wherein the winding strands of the or each pair are closely inductively coupled.

35 3. A motor according to claim 2, wherein the or each pair of winding strands is formed as a bifilar winding



1 arrangement, to provide a very close inductive coupling
therebetween.

2 4. A motor according to claim 1,2 or 3 including
a coupling capacitor, for producing the close ac coupling
5 between the winding strands of the or each pair, arranged
between the two ends thereof.

6 5. A motor according to claim 4, wherein the energy
storage capacity of the coupling capacitor corresponds, in
respect of order of magnitude, to energy to be recovered
10 from the respective winding strand during commutation from
one of said semiconductor means of opposite conductivity
to the other.

7 6. A motor according to any preceding claim, wherein
the output signal of said sensor means, which is dependent
15 upon the angular position of the rotor, is arranged to
be supplied to said first and second semiconductor means
via a network consisting of passive structural elements.

8 7. A motor according to claim 6, wherein the network
is a resistance network.

9 8. A motor according to claim 7, wherein another
coupling capacitor, with which a discharge circuit is
associated, is provided in the connection between the
20 resistance network and a control input of each of said
first and second semiconductor means.

25 9. A motor according to claim 8, wherein each coupling
capacitor has a capacity of the order of magnitude of
microfarads.

30 10. A motor according to any of claims 7 to 9,
wherein said sensor means comprises a Hall-IC which is
connectable directly to one pole of a dc network, and wherein
the resistance network has a first resistor, which is
connected between the output of the Hall-IC and the control
input of the respective semiconductor means connectable to
said one pole, a second resistor connected between the
35 Hall-IC output and said other pole, and a third resistor



1 connected between the Hall-IC output and the control input
of the respective semiconductor means connected to said
other pole.

5 11. A motor according to claim 10, wherein, between
the Hall-IC output and the second and third resistors, a
constant voltage component is provided, to protect the
Hall-IC output against excessively high operating voltages.

12. A motor according to claim 11, wherein the
constant voltage component is a Zener diode.

10 13. A motor according to claim 10, 11 or 12, when
dependent upon claim 8 or 9, wherein the first and third
resistors are each connected in series with a respective
coupling capacitor.

15 14. A motor according to claim 13, wherein the
respective coupling capacitors are in series with the
control input of the respective semi-conductor means and
the first and third resistors, respectively.

20 15. A motor according to any preceding claim, wherein
said first and second semiconductor means are alternately
controllable to be conducting by signals of the same phase
position provided by said sensor means.

25 16. A motor according to any preceding claim,
wherein said means in item (f) comprises unidirectional
conducting means connected in anti-parallel with said
semiconductor means, for recovering energy stored in the
respective winding strand upon changeover during controlled
pulsed current flow therein.

17. A motor according to any preceding claim which
is a double pulse, brushless dc motor.

30 18. A double-pulse brushless motor substantially
as hereinbefore described with reference to the accompanying
drawings.

19. The use of a motor according to any preceding
claim for driving a fan.

35 20. The use of a motor according to claim 19, wherein
the fan is of the axially short type.