NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1404

Brushless Direct Current Motors

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Preface

The work described in this report was performed by the Telecommunications Division of the Jet Propulsion Laboratory.

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Abstract

Brushless dc motors are gradually becoming competitive with the conventional dc motor. They are still somewhat more expensive, but this cost is well compensated by superior performance. Brushless dc motors could be built for power levels up to 50 kW with efficiencies superior to any other motor of the same size. Other advantages are the absence of commutator wear and arcing with associated problems, a high ratio of shaft torque to motor weight, and a convenient means of speed regulation, that also allow the motor to maintain high efficiency over a wide torque range. The prime applications at this time are in the area of aerospace and battery operated equipment, where high efficiency and high reliability are essential. Recent improvements, however, may soon permit widespread use of this motor in industry. The brushless dc motor may also prove to be an excellent drive for electric transportation vehicles, due to its simple and efficient speed control capability.

The brushless dc motor uses an electronic commutator. The semiconductor devices that switch the motor currents are controlled by a shaft position sensor. This commutator is not subject to the restrictions that govern commutator design in the conventional dc motors. An important feature of the electronic commutator is the capability to switch inductive loads. This allows switching of currents in motor coils while they are outside the neutral zone of the magnetic field. Another advantage is that each coil of the motor winding can be commutated individually without being connected to other coils in the conventional way. This permits the use of a multitude of switching sequences and simple switching circuits. The motor coils need not conduct current at all times, as is the case for conventional motors, but only during the passage of the strong magnetic field. The result is higher efficiency and lower operating temperature. This report shows how the use of unconventional motor windings and switching sequences will accomplish the advantages stated above, and how medium-size motors can be built without excessive electronic circuitry.

Brushless Direct Current Motors

I. Introduction

The direct current (dc) motor has long been considered the ideal motor for applications where high efficiency is important. It also has a higher ratio of torque output to motor weight than alternating current (ac) motors. It can be operated over a wide speed range and is well suited for speed regulation. However, this motor is not used as widely as one would expect from the foregoing remarks. This is because the dc motor is too expensive for many commercial applications, and not reliable enough for applications where the higher price could be justified. Premature failures of conventional dc motors are frequently traceable to the mechanical commutator. This is also the component that limits the normal operating life of this motor.

Several types of brushless dc motors that use electronic commutators instead of a mechanical commutator have been developed since 1960. The electronic commutator consists of a shaft position sensor and a number of semiconductor power switches, controlled by the sensor. Some motors use control circuits between the sensor and the power switches to accomplish start/stop, or reversal of the motor, or to regulate speed. Various types of shaft position sensors used photoelectric, capacitive, electromagnetic, or Hall-effect sensing. All motors had permanent magnet rotors and stationary conventional dc motor windings. This inside-out configuration is essential to a brushless design. Permanent magnets are used on the rotor to obviate the need for slip rings which would be needed to excite electromagnets. Early brushless dc motors were not always reversible. Some designs used two commutators—one for each direction of rotation. Most of the early motors employed quite complicated electronic circuits and were, therefore, relatively expensive. Gradually, the electromagnetic sensor emerged as the most desirable type, principally because the output can be made powerful enough to drive subsequent circuits without the need for amplifiers. This simplified the commutator so much that it could be used commercially for the first time. Grundig Corporation has used such a motor for a portable voice tape recorder.

The brushless dc motor became again simpler and less expensive after it was realized that it should not simply simulate the conventional motor. Many restrictions of the mechanical commutator do not apply to the more versatile electronic commutator. By going back to the principle of dc motor operation, it was discovered that certain unconventional motor windings and switching sequences resulted in simpler and less expensive electronic circuits, while at the same time, motor performance was improved over the already good performance of the conventional motor. It became apparent that the brushless motor has its own optimum designs, which are different from the conventional design.

The electronic commutator is superior to the mechanical commutator for two reasons:

(1) It is not dependent upon a geometric structure and can, therefore, perform more sophisticated switching sequences without being very complex.

(2) It is a stationary switch and, therefore, can be designed to interrupt heavy, inductive currents.

As a consequence, the electronic commutator does not require connection of the motor coils to form a ring winding, but can commutate the motor coils individually or the coils can be connected to form a star winding. Furthermore, the electronic commutator does not need to restrict switching to motor coils that are in the neutral zone of the field. It can execute a switching sequence that allows current flow only in those coils that are in the strong rotor field. This eliminates useless currents that produce losses but little torque.

Separately commutated motor coils or star windings allow construction of powerful brushless dc motors. Star windings allow the use of simple and inexpensive switching circuits. The elimination of useless currents increases the efficiency. A very efficient speed control is obtained by attenuating the *on* time of the coil currents. This allows reduction of torque by low-power devices to virtually zero without changing the voltage applied to the motor. Since many coil arrangements and switching sequences are possible with the electronic commutator, the motor designer has a wide latitude for obtaining excellent motors for specialized requirements.

The brushless dc motor is considered the most efficient small motor known at this time. It is also reliable, its operating life depending primarily on the bearings. Another advantage is that the electronic circuits can be separated from the motor. A portion of the total power loss occurs in the switching circuits. Removal of these circuits from the motor simplifies the cooling problem. Conversely, the circuits may operate in a cool environment, even if the motor operates in a hot environment.

The main disadvantage relative to the conventional motor is the higher cost of the electronic commutator. However, the brushless dc motor is no longer too expensive for the commercial market and the cost difference is shrinking with the advances in semiconductor technology. It is estimated that brushless dc motors could be built for output power of up to 50 kW at costs not much above the costs of conventional dc motors. This is particularly true if the advantages of the brushless motor are fully utilized. For example, the brushless motor can be turned on and off or reversed by switching of low-power sensor signals. The function of expensive high-power automatic switches needed for large conventional motors can be performed by the electronic commutator.

II. Motor Design

The brushless dc motor deviates from the conventional dc motor in its design, but not in its functional performance. The brushless motor does not have current flowing in the rotor. The field is generated by permanent magnets, mounted on the rotor, while the winding is in the stator. This does not affect their interaction and consequently the motor characteristics are the same.

A. Stator Design

Since the stator of the brushless motor is the equivalent to the rotor of the conventional motor, its geometric design cannot be very similar. The stator structure of the brushless motor resembles that of the induction motor or synchronous motor. In fact, the stator of such a motor can be identical except for the winding.

Usually the winding is embedded in slots, which can be open or closed and may have various shapes. Individual coils are inserted into a pair of slots that are spaced equal to or slightly less than one pole step. Each coil side will fill only half of the slot and one side of another coil will fill the balance of the slot space, as indicated in Fig. 1. This procedure avoids bulky end connections. With two coil sides sharing a common slot, the number of coils is equal to the number of slots.

The number of slots is dependent upon many factors such as motor size, number of poles, type of winding and commutator, desired operating characteristics, etc. Very small motors will have only two poles, while larger motors will use more poles to reduce the length of the end connections and the thickness of the yoke. For practically all brushless dc motors, the number of slots is made a multiple of the number of poles to assure equal treatment of all poles.

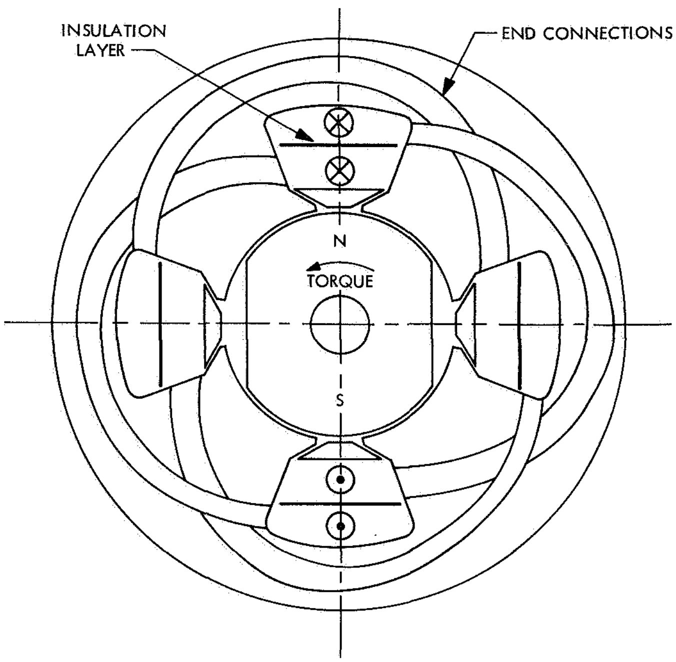

Fig. 1. Winding with two coil sides per slot

The highest torque is developed by a coil when it is aligned with a pair of poles. Current needs to flow only as long as the coil is in the dense magnetic field. If current would flow through the two slots that are at 90 deg to the pole pair in Fig. 1, the coil would only produce current losses but no torque. In determining the number of slots, the designer must consider the commutating sequence, the complexity of the commutator, the shaft position sensor resolution, the switching sequence, and the desired performance characteristics of the motor. The two-pole, four-slot motor of Fig. 1 would not be very efficient, nor would it develop a smooth torque, but the winding and the commutator would be very simple and the motor would be inexpensive.

B. Rotor Design

The rotor carries the field magnets and is constructed similar to the rotor of the synchronous generator, except that it uses permanent magnets to avoid slip rings. High field densities in the air gap can be achieved with the modern highly grain oriented permanent magnetic materials like Alnico IX or Allegheny Ludlum Alnico V-7. The field magnet must store enough magnetic energy not only to magnetize the magnetic circuit in the motor, but also to withstand the demagnetization effect of the highest possible motor current.

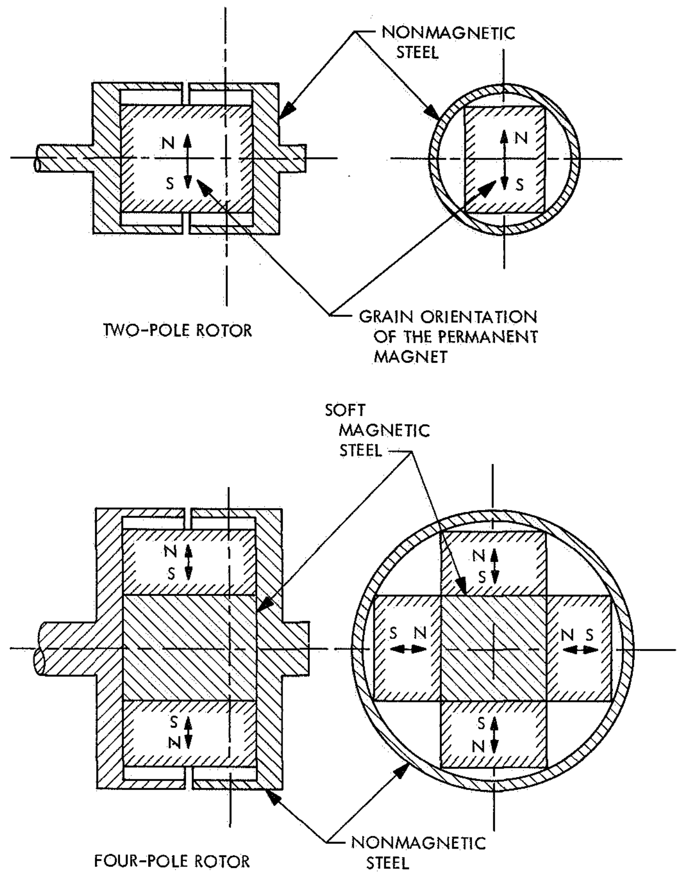

Fig. 2. Rotor constructions

The permanent magnetic materials are very hard and brittle and cannot be worked except by grinding. The magnet therefore needs to have simple shapes. Figure 2 shows possible rotor constructions for two-pole and four-pole motors that allow the use of permanent magnets in their raw material form. The magnet assembly is cemented into two nonmagnetic cups. These structures cause relatively long magnetic air gaps, that sometimes require the use of high energy materials like Alnico IX. But the long air gaps also have an advantage, because they reduce the demagnetization effect of the current on the magnets.

The rotor magnets are often magnetized after completion of the motor assembly. The whole motor is placed between poles of a powerful electromagnet and the rotor is allowed to align itself with the field. This procedure is very simple for two-pole motors, but difficult or impossible for higher numbers of poles. The pattern of the slots may impress itself into the rotor, especially if grain-oriented materials are used. This can be avoided by magnetizing the rotor outside of the motor and preventing it from demagnetization by a keeper designed to allow rotor installation into the motor without opening the magnetic circuit.

III. The Electronic Commutator

The purpose of the electronic commutator is to connect and disconnect each motor coil with the dc power supply at the right time and with the correct polarity. It consists of the shaft position sensor and the power switches. If special requirements are placed on the motor, there will sometimes be switches or a digital logic circuit between the sensor and the power switches. Reversibility is such a requirement. The brushless motor is not automatically reversible like the conventional dc motor because the electronic commutator is not bilateral.

A. Shaft Position Sensor

The shaft position sensor generates a set of signals that describes the position of the shaft at any time. Since the sensor has to work over the full speed range of the motor, the signal must be independent of motor speed. For most motors, the resolution and precision of the position sensing can be quite modest, as they affect motor performance very little. The shaft position sensors used in the past have several output terminals. The presence of an electrical signal on one of them indicates a certain angular position of the shaft. The resolution of the sensor is therefore proportional to the number of output terminals. Other types of sensors having only one output terminal could be constructed. These sensors would deliver the shaft position information in coded form. The currently used shaft position sensor consists of an element that generates a signal that is sensed by receivers at certain angular positions of the shaft and transformed into electrical signals. Each receiver relays this signal to its output terminal.

Several types of shaft position sensors have been successfully developed. The photoelectric sensor uses a central light source and several photocells or phototransistors around the light as receivers (Fig. 3). A shaft-mounted masking device allows illumination of a receiver only at a fixed angular increment. While illuminated, the receiver generates a small current that is amplified to yield a usable output voltage and current. This type of sensor is relatively precise and allows a high degree of resolution due to the small size of the photocells or phototransistors. However, amplifiers are required proportionally increasing cost and complexity.

Another type of sensor uses Hall elements. One implementation comprises an L-shaped, thin permanent magnet on the rear end of the rotor as the generator (Fig. 4). One pole points axially and the other pole points radially. The radial pole is shaped as a segment. The flux from this

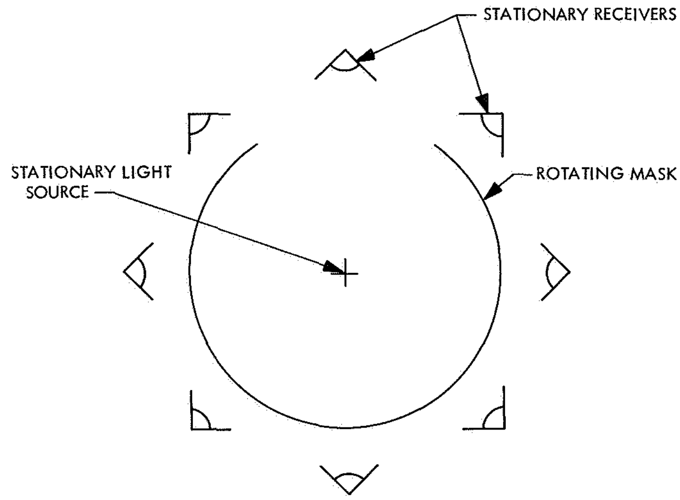

Fig. 3. Principle of operation of the photoelectric shaft position sensor

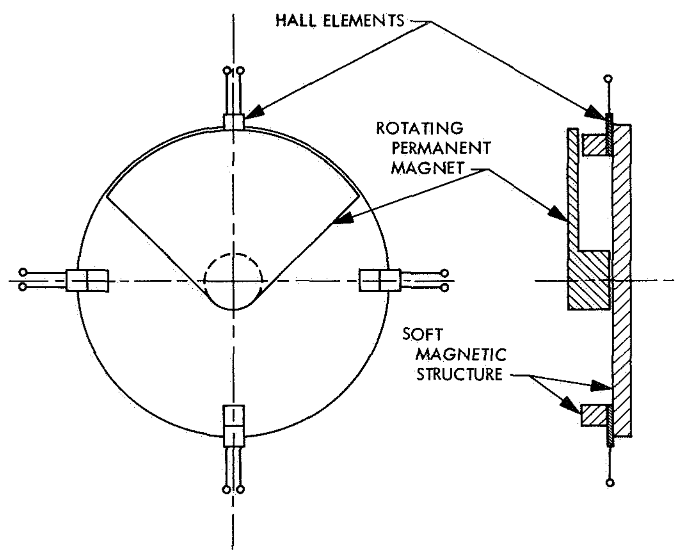

Fig. 4. Hall element shaft position sensor

magnet is received by a number of stationary soft magnetic structures. Each closes the magnetic circuit through a Hall element. Whenever the rotating magnet points toward a certain receiving structure, the respective Hall element generates a small voltage. The amplified outputs of the Hall elements are the shaft position signals. This sensor is comparable in performance to the photoelectric sensor.

Two other types of sensors transmit carrier signals to the various receivers. Both capacitive and inductive couplings are used. An oscillator generates either an electric field or a magnetic field of high frequency. In the case of the electric field, a number of plate capacitors are mounted in the stator of the motor in similar positions as photocells or Hall elements of other sensors. The rotor carries a thin dielectric segment, which passes through the plate capacitors one after the other, as the shaft rotates. Each plate capacitor is connected to the oscillator with a series resistor, as shown in Fig. 5. When the rotating segment passes between a pair of plates, its capacitance is increased by a large factor, resulting in a considerable increase of the current flowing through it. The current produces a high-frequency voltage across the resistor, which is amplitude-modulated with the shaft position information. This voltage is subsequently amplified and demodulated to yield a sensor output signal. Mechanically, this sensor is very simple and inexpensive; but for small motors, the plate capacitances are very small and

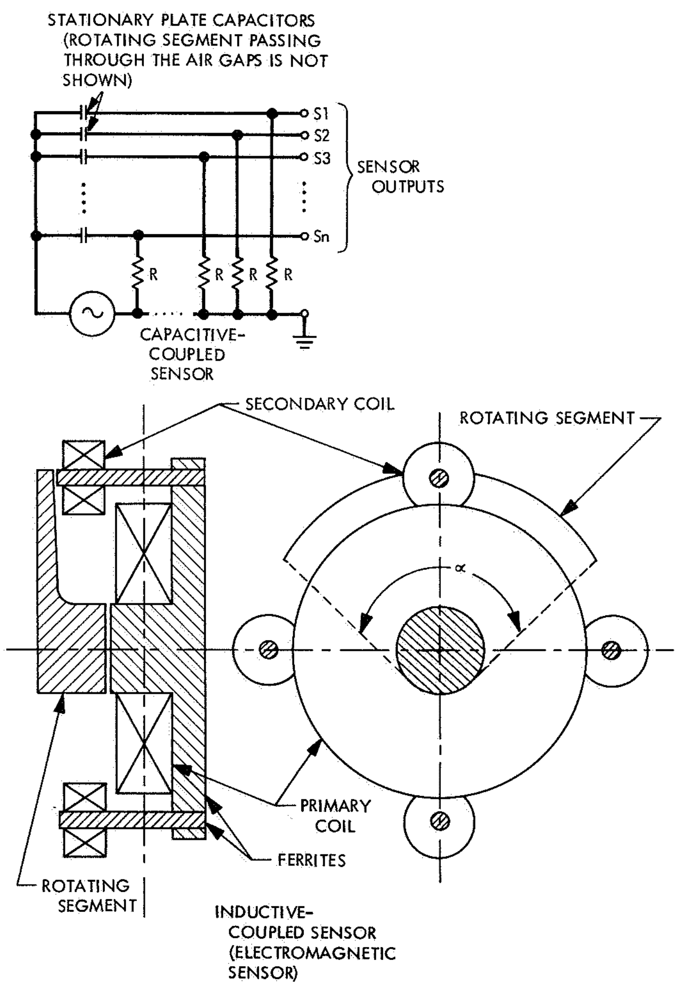

Fig. 5. Principle of operation of modulated carrier shaft position sensors

the stray capacitances are significant, resulting in a poor signal-to-noise ratio. For larger motors, however, this type of sensor might be more attractive.

If the oscillator is used to produce a magnetic field, the sensor resembles a transformer with the oscillator energizing the primary coil. The high-frequency magnetic field generated by this coil is carried to the rotor and back to the coil by a suitable magnetic structure and two narrow air gaps. This is shown schematically in Fig. 5.

The rotor carries a soft magnetic segment that directs the flux to different magnetic receiving structures, each of which has a small secondary coil. When the rotating segment is opposite a certain secondary coil, a high-frequency voltage is produced by this coil. When the magnetic segment is not opposite the secondary coil, only a small stray field will penetrate this coil, resulting in a low voltage. The secondary coils, therefore, produce high-frequency voltages, which are amplitude modulated by the shaft position information. This is similar to the capacitive sensor, except that the secondary coil output can be made powerful enough to drive the power switches without amplification. This results in a very inexpensive electronic circuit and a high efficiency for the commutator. Both modulated carrier shaft position sensors operate between ten and several hundred kHz. The electromagnetic type requires a true ac excitation with as small a dc component as possible to avoid such difficulties as saturation of the magnetic structure and signal components that are a function of motor speed. If a dc component is present in the primary coil current, there would be a positive voltage induced into the secondary coils as the rotating segment approaches their poles and a negative voltage as it leaves their poles. This voltage would be proportional to motor speed and could be troublesome at high speeds. Figure 6 shows an oscillator for this requirement. The demodulator circuit is shown in Fig. 7.

Waveforms of this type of shaft position sensor are shown in Fig. 8. The upper trace represents the voltage output of a receiver coil. The 200-kHz carrier frequency cannot be seen, except for the envelope and certain distortions from the sinusoidal form. The lower trace shows the demodulated sensor signal. It can be used directly to actuate the power switches. However, the slopes of this signal are not very steep and will actuate the power switches gradually, causing increased switching losses. These slopes can be controlled by contouring the tip of the sensor commutating arm only to a modest degree. If

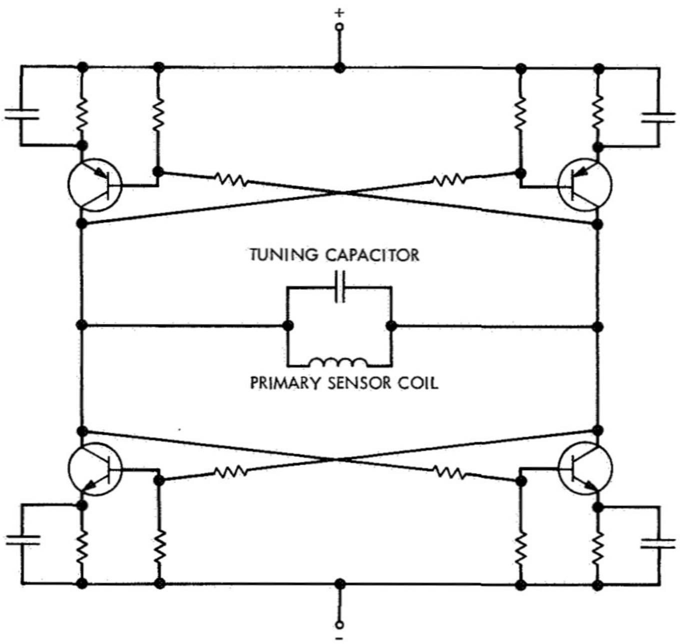

Fig. 6. Oscillator for electromagnetic shaft position sensor

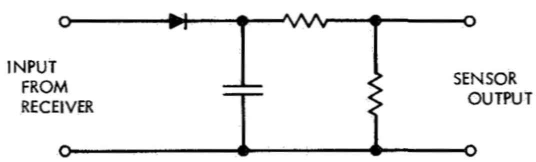

Fig. 7. Demodulator circuit

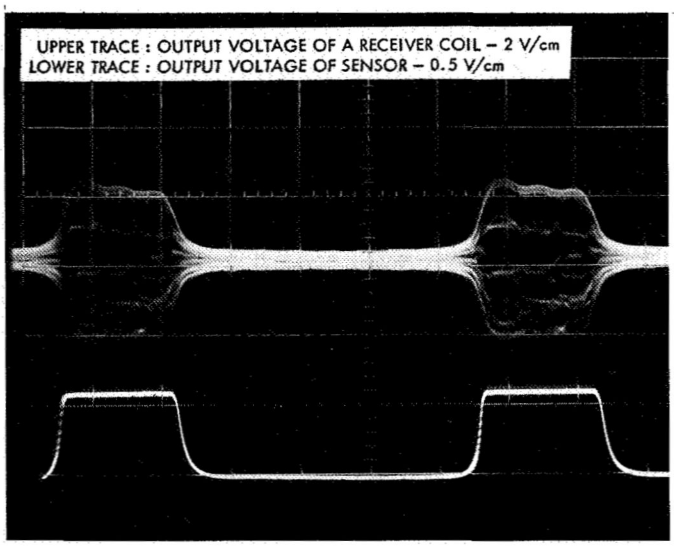

Fig. 8. Signal waveforms of the electromagnetic shaft position sensor

this slow switching is to be avoided, a Schmitt trigger circuit can be used to generate a rectangular sensor signal.

B. Power Switches

Circuits that connect and disconnect the motor coils with the dc motor supply shall be called power switches. They are controlled by the shaft position sensor. There are several identical power switches. In general, they connect the motor coils alternately in both polarities to the power supply, so the current can flow through each coil in both directions. The principle of the brushless motor shall be explained on an extremely simple example. Figure 1 shows a two-pole motor with four slots. A possible winding schematic including conventional commutator for this motor is shown in Fig. 9. The conventional motor has all coils connected to each other in the form of a ring and each node is also connected to a commutator bar. The arrows indicate the current flow in relation to the polarity of the brushes. The winding of Fig. 9 can be drawn in a different way, as shown in Fig. 10. Here the spacial distribution of the winding in the four slots is neglected to show the electrical connections better.

In Fig. 9 the brushes connect commutator bar 1 with the positive terminal of the power supply and bar 3 with the negative terminal. As the motor rotates, the winding and commutator bars move past the stationary brushes and magnetic poles. After one-half shaft revolution, the negative brush is riding on bar 1 and the positive brush on bar 3; then the current will flow through the motor winding in the opposite direction. The circuit shown in Fig. 11 will perform the same function if properly controlled. When control transistor T1 is conducting, current will flow from the positive terminal of the power supply through the bases of power transistors PT 1 and PT 4, turning them on. This connects node 1 of the winding to the positive terminal of the power supply and node 3 to the negative terminal. Current will flow through the motor winding in the same way as shown in Figs. 9 and 10 for the conventional motor. One-half shaft revolution later, control transistor T3 is conducting and current is driven through the winding in the reverse direction. Transistors T1 and T3 are never on at the same time. Note that the term power switch is used for an entire circuit, rather than for an individual component.

Each power transistor of Fig. 11 uses a relatively large resistor across base and emitter to assure complete and fast current cutoff. Each power transistor also has a reverse polarity diode across collector and emitter. The

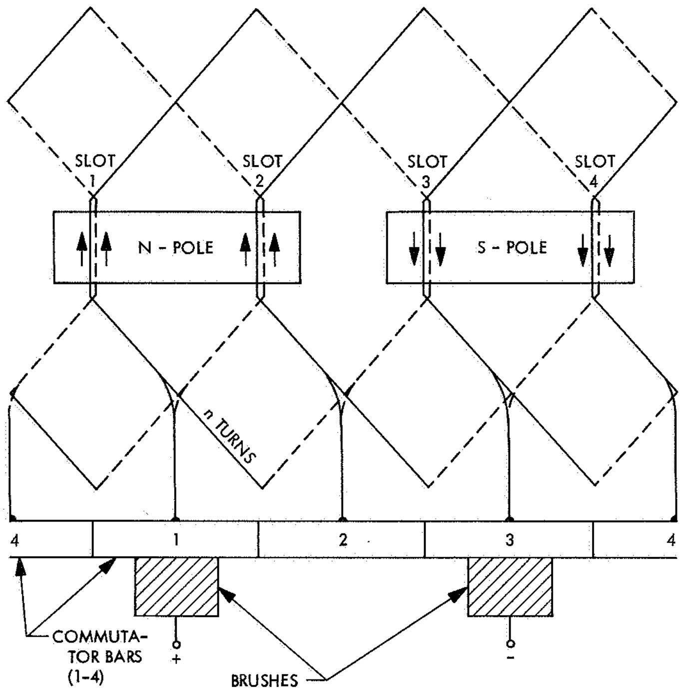

Fig 9. Winding and commutator of conventional two-pole, four-slot motor

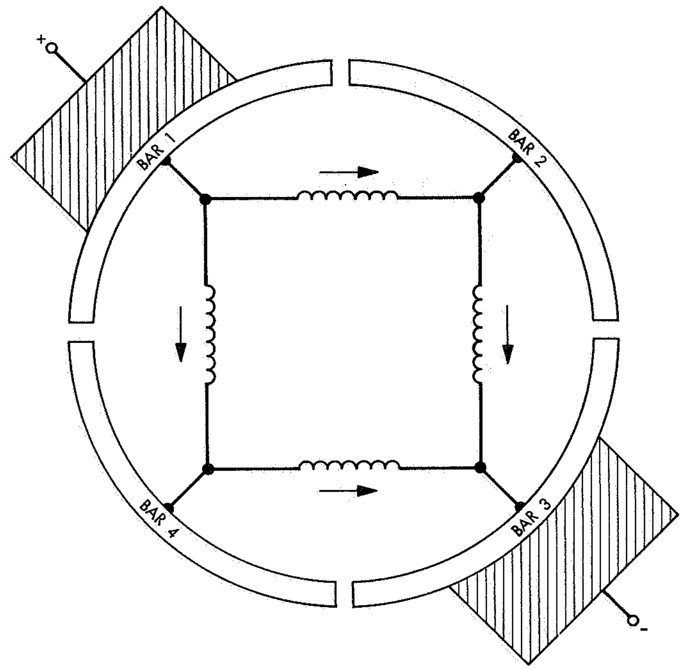

Fig. 10. Electrical connections of conventional two-pole, four-slot motor

power transistors switch inductive currents which resist quick changes by producing high voltages. When a transistor pair is turned off, a diode pair permits the current to flow back into the power supply until its energy is exhausted. In most cases, the current will flow into other power switches that are *on* at the time. These diodes serve the same purpose as wide brushes riding on narrow commutator bars of the conventional motor. But they are much more effective and allow switching of coils, while they are outside the neutral zone. This capability of the electronic commutator is very important. It not only eliminates the need for commutating poles, thereby making the motor more efficient, and less expensive, but it also permits the use of unconventional motor windings and switching sequences, as will be shown in Section IV.

C. Simulation of the Mechanical Commutator

Referring again to the example of a two-pole, four-slot motor (Figs. 9 and 10), two identical power switches are required to supply current to the four nodes of the winding. The second power switch performs the same switching sequence as the first power switch, but 1/4 of a shaft revolution later.

The four control transistors (T1–T4) of the two power switches are controlled by the shaft position sensor. A

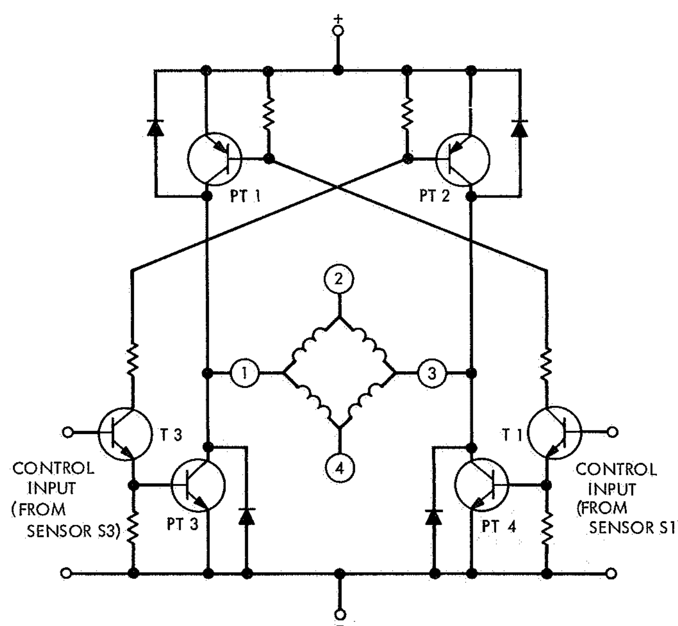

Fig. 11. Power switch

switching sequence consists, therefore, of four turn-on and four turn-off operations and repeats itself after every shaft revolution. In order to simulate the conventional commutator the four control transistors need to be turned on, one after the other. After every 90 deg of shaft rotation, the next transistor is turned on. Each transistor shall be on during the same length of time as a brush would be in contact with a particular commutator bar. For the motor shown in Figs. 9 and 10, this is the time required for the shaft to rotate 90 deg plus one brush width.

The shaft position sensors described in Subsection A all generate one pulse per shaft revolution on each of its output lines. (It will be shown later that this need not be true for motors having more than two poles.) If these signals are supplied to the bases of the control transistors T1–T4, they will turn them on during the full pulse duration.

The four turn-on operations of a switching sequence require four signals S1 through S4 from the shaft position sensor. Such a sensor has four receivers, equally spaced around the rotor, one receiver for every control transistor. The rotating part of the sensor must be mounted on the shaft in the correct position relative to the position of the coils. This is analogous to positioning the brushes.

The four turn-off operations of a switching sequence are obtained by properly adjusting the duration of the sensor pulses. This is a certain fraction of a shaft revolution and is determined by the shape of the rotating portion of the sensor (Subsection A). In the case of the electromagnetic sensor, the pulse duration is determined by the angle α of the rotating magnetic segment (see Fig. 5).

The four sensor signals for this motor are shown in Fig. 12. The pulse duration was arbitrarily fixed at 120 deg, which corresponds to a brush width of 30 deg. Figure 13 shows the resulting motor currents, neglecting distortions. This electronic commutator exactly duplicates the performance of the conventional commutator of Figs. 9 and 10, as long as the motor is not reversed. It will be shown in Section IV that brushless motors should not be designed by simulating the performance of the conventional commutator. Considerable advantages can be derived from unconventional designs.

D. Low-Power Start/Stop Control

The conventional motor is started or stopped by connecting or disconnecting the brushes to the power supply. For larger motors, this is usually done by automatic power switches. The brushless motor can be operated in the same manner. However, since it already uses controllable power switches, there is no need for additional power switches external to the motor. The brushless motor can

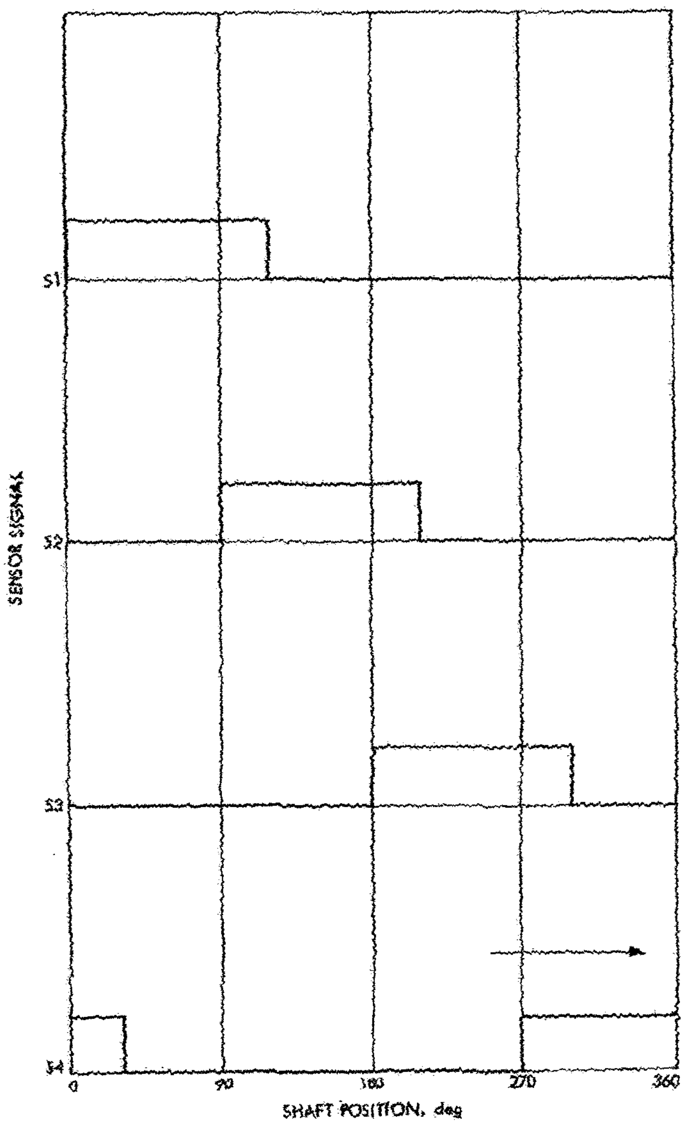

Fig. 12. Sensor signals for two-pole, four-slot motor

be started and stopped by switching of the low-power sensor signals, while the power supply remains connected to the power switches. The start/stop mechanization depends on the type of power switch used. All power switches described here are completely turned off by de-energizing all sensor outputs. For the electromagnetic shaft position sensor, this is done by switching off the oscillator.

E. Low-Power Reversing

The conventional dc motor is reversed by connecting the brushes with the opposite polarity to the power supply. This causes the current to flow in the opposite direction through all coils of the winding. For the brushless motor, this can be accomplished by reverse connection

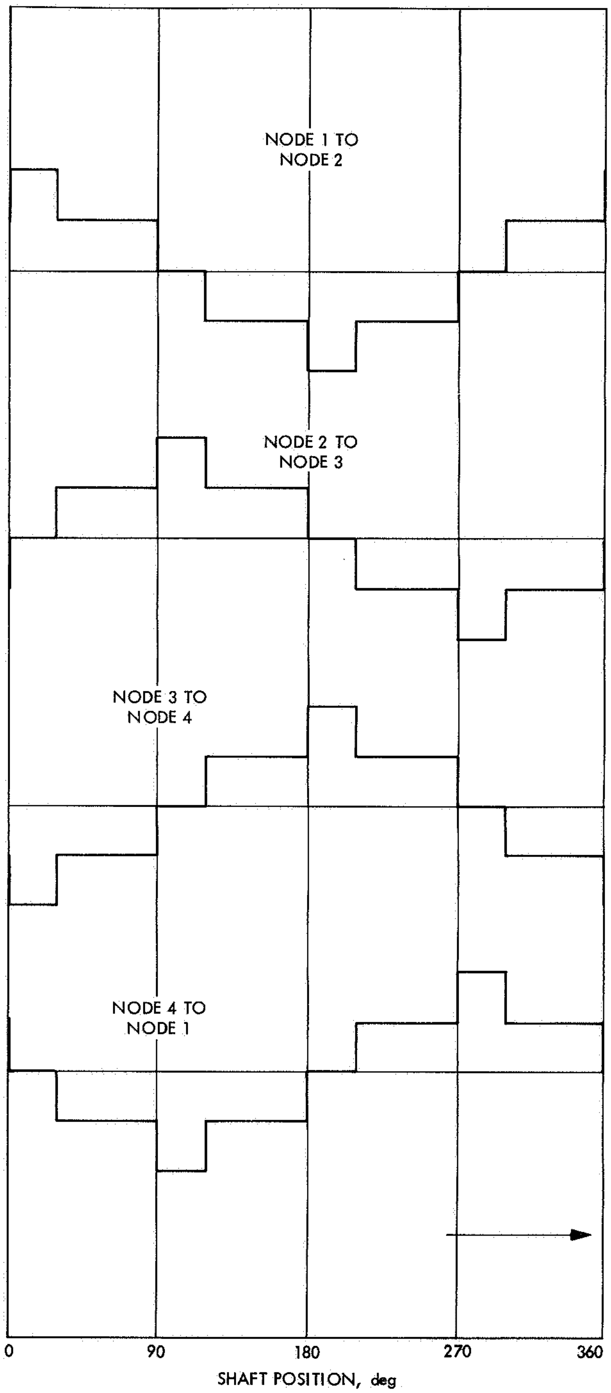

Fig. 13. Motor coil currents for two-pole, four-slot motor

of the nodes of the winding to the power switches. For a motor with many nodes, this is quite cumbersome. The same effect can be accomplished by actuating the power transistors in a different sequence.

Figure 11 shows that reversal is obtained by supplying sensor signal S1 to transistor T3 instead of T1 and S3 to

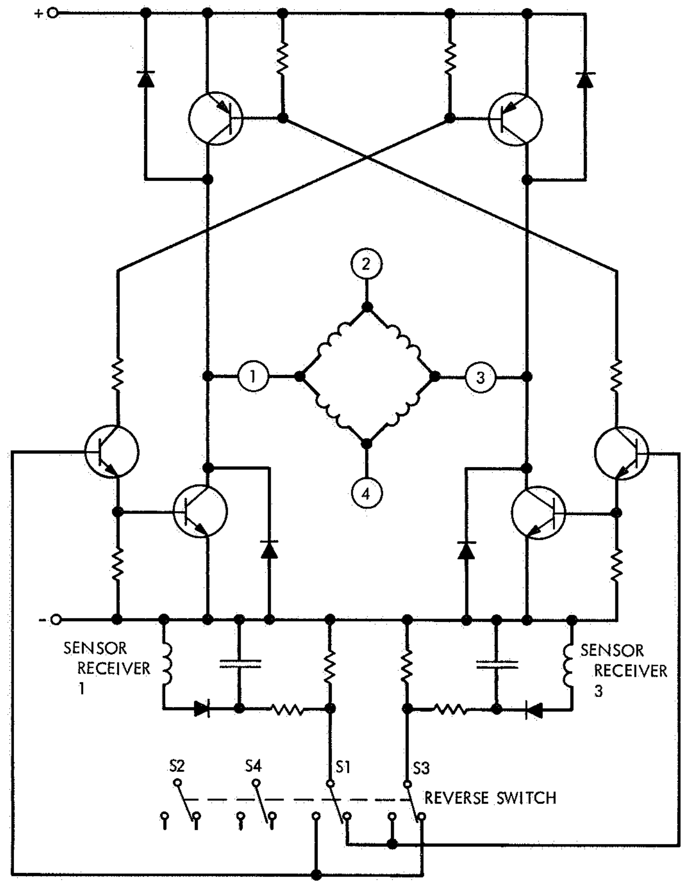

Fig. 14. Commutating circuit for reversible motor using a mechanical reverse switch

T1 instead of T3. This can be done by low power mechanical switches such as relays or by logic circuits. Figure 14 shows one commutating circuit (one pair of commutating points only) for the reversible motor using a mechanical switch.

Motors that employ the Hall-element shaft position sensor can be reversed by reversing the control current of the Hall elements because they are direction sensitive.

IV. Unconventional dc Motors

A. Comparison of the Brushless and Conventional Motors

The electronic commutator described in the previous section exactly simulates the mechanical commutator of a dc motor. If the motor has also a conventional winding, its performance will be identical. The losses of the two commutators are approximately equal. A power transistor in saturation has about the same voltage drop as that from a brush to a commutator bar. The power consumption of both the oscillator and the base currents of the power transistors are comparable to the losses caused by brush friction and arcing. The apparent similarity of the two motors, however, is not true in general. In the previous section, we have willfully simulated the conventional commutator. This limitation was imposed on the motor only for illustrative purposes. The mechanical commutator is restricted in its performance by the physical construction and certain mechanical shortcomings. The physical construction permits only very few alternate designs among which the designer can choose. A variety of switching sequences is impractical because of excessive complexity of the commutator. The mechanical shortcomings are "brush fire" and the sensitivity to voltage spikes between adjacent commutator bars, which can result in an arc all around the commutator. The conventional motor needs, therefore, a well established neutral zone in which all switching must be performed.

The electronic commutator has none of these limitations and, as a consequence, is much more versatile. Every commutating point is connected to a stationary switch, which can be activated at any time, and independent of other switches. Current can be simultaneously injected into the winding at more points without adding complexity to the system. The electronic commutator, therefore, permits a nearly unlimited number of different switching sequences.

Also, the improved switching characteristic of the electronic commutator allows switching outside the neutral zone. Voltage spikes can be avoided by providing the switched current with an alternate path through which it can dissipate its energy at leisure, and convert much of it into useful torque. The brushes short out adjacent bars of the commutator at certain times during the commutation sequence. The electronic commutator need not do that.

In order to utilize the more general nature of the electronic commutator to its full extent, the designer must free himself of the standard practice of dc motor design and go back to the fundamental laws upon which this motor is based. The most important law describes the force exerted on a conductor placed in a magnetic field, if current flows through it.

Thus,

$$d\mathbf{F} = (\mathbf{I} \times \mathbf{B})\, dL$$

where **F** is the force vector; **I** is the current vector; **B** is the magnetic field vector; $d\mathbf{F}$ is the differential of the force vector; and dL is the differential element of the conductor. The expression $(\mathbf{I} \times \mathbf{B})$ designates the vector cross product and is a vector normal to the plane formed by **I** and **B** (Fig. 15).

$$|(\mathbf{I} \times \mathbf{B})| = |\mathbf{I}| \times |\mathbf{B}| \times \sin \alpha$$

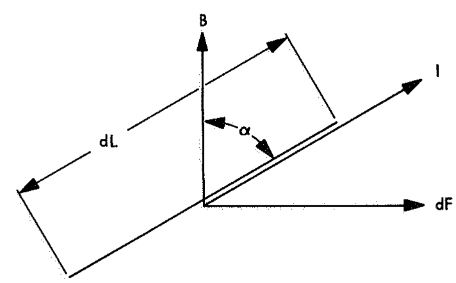

Fig. 15. Force exerted on a conductor placed in a magnetic field

Torque is generated by current flowing through those conductors that are in the field of the rotating permanent magnet. The commutator must assure current flow with the correct polarity through the conductors that are in the magnetic field. Conductors that are outside the magnetic field need not conduct current as they cannot produce torque. This is the basic requirement for the motor design. In the following paragraphs, the individual types of dc motors will be treated separately and the design aspects will be explained on simple examples.

B. Separated Motor Coils

The basic requirement of the dc motor, as previously described, does not say anything about the connection of individual motor coils. Therefore, current can be supplied to the coils independent of each other. The case of separately commutated motor coils shall be studied on the previously used example of a two-pole, four-slot motor (see Fig. 1). The rotor field in the air gap shall be assumed to cover a segment of approximately 120 deg for each pole, which means that each neutral zone covers 60 deg. The winding consists of four coils, wound with full pitch. Two coils are therefore embedded in the same slots and electrically equal. These coils can be connected either in series or in parallel and be commutated as one coil. As a result, this motor has actually two double coils. Figure 16 shows the desired currents in the double coils. Current shall flow through each coil during the 120 deg of a pole. No current shall flow during passage of the neutral zone of the field. The field transition on the edge of a pole does not need to be very abrupt. Neither must the current waveform of Fig. 16 be very accurate for good performance of the motor.

From Fig. 16, it can be seen that current is turned on for another double coil after every 90 deg of shaft rotation. Therefore, four sensor signals are required with a phase difference of 90 deg between each other. The on time of all four signals must be roughly 120 deg. These are the same sensor signals as used before, and they are shown in Fig. 12. Sensor signals S1 and S3 control one power switch and signals S2 and S4 control the other power switch.

Two power switches of the type shown in Fig. 11 are needed for the two double coils. The complete electronic circuit for this motor except for the oscillator is shown in Fig. 17. It is assumed that the electromagnetic shaft position sensor is used. This motor will have current flowing at all times at least in one double coil. Therefore, it will

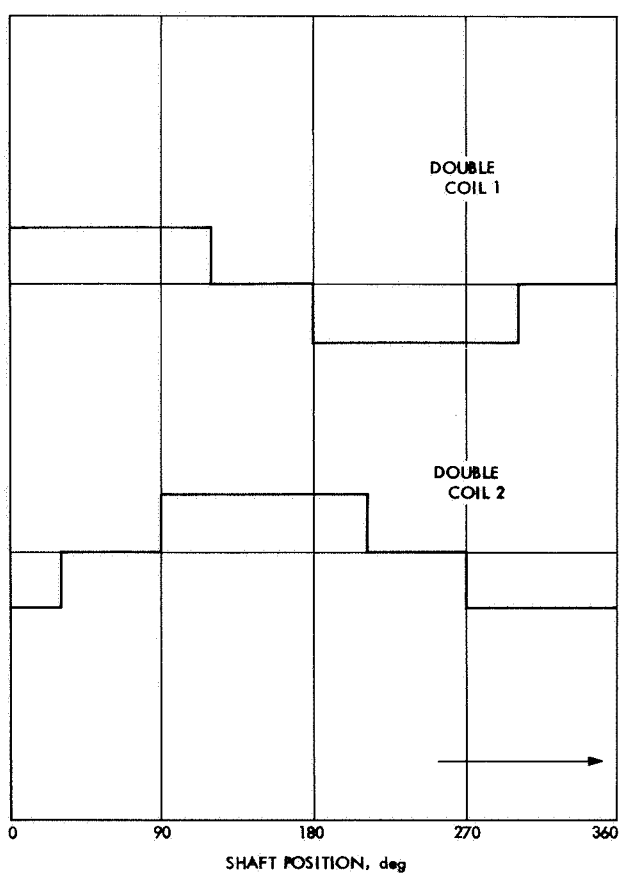

Fig. 16. Currents in two-pole, four-slot motor with separated motor coils

produce torque at any shaft position. This torque will vary with the shaft position and will not be very smooth because of the low number of commutating points. But the motor will have a higher efficiency than the conventional motor of the same design, having a four-bar commutator. This is due to the absence of two types of useless currents in the motor coils that produce losses but very little torque:

(1) Currents driven through the coils while they are temporarily in the neutral zone of the magnetic field.

(2) When the brushes pass from one commutator bar to the next, each will temporarily short out a motor coil, allowing any stray field in the neutral zone to generate current into a short circuit.

Type 1 currents of the conventional dc motor can be partly eliminated by using wide brushes. If this is done, however, type 2 currents increase unless the motor has a very pronounced and sufficiently wide neutral zone. Both types of useless currents cannot be completely suppressed. The same is true for the brushless motor if it is designed to simulate the mechanical commutator, as explained in Section III-C. With separated motor coils it is not only desirable but necessary to avoid current flow in the neutral zones because of the absence of any back electromotive force that otherwise limits the current.

Commutating separated motor coils has another advantage over simulation of the mechanical commutator. However, this is not obvious in the simple, four-coil example and will therefore be discussed later. This motor can be reversed by reverse connection of all motor double coils to the power switches. Reversing by low-power command is accomplished in the same manner as described in Subsection III-E.

C. Star-Connected Motor Coils

Separation of the motor coils allows the use of a simpler and sometimes more efficient power switch. This circuit, shown in Fig. 18, uses a symmetrical center-tapped dc power supply. For a battery-operated motor this type of power supply is usually no problem. In the previously used example of a two-pole, four-coil motor, the two power switches would use the same common lead. In the general case of n power switches, all would use the same common lead. This means that the motor coils are connected with each other to form a star. It is thought that this type of brushless dc motor will prove to be most

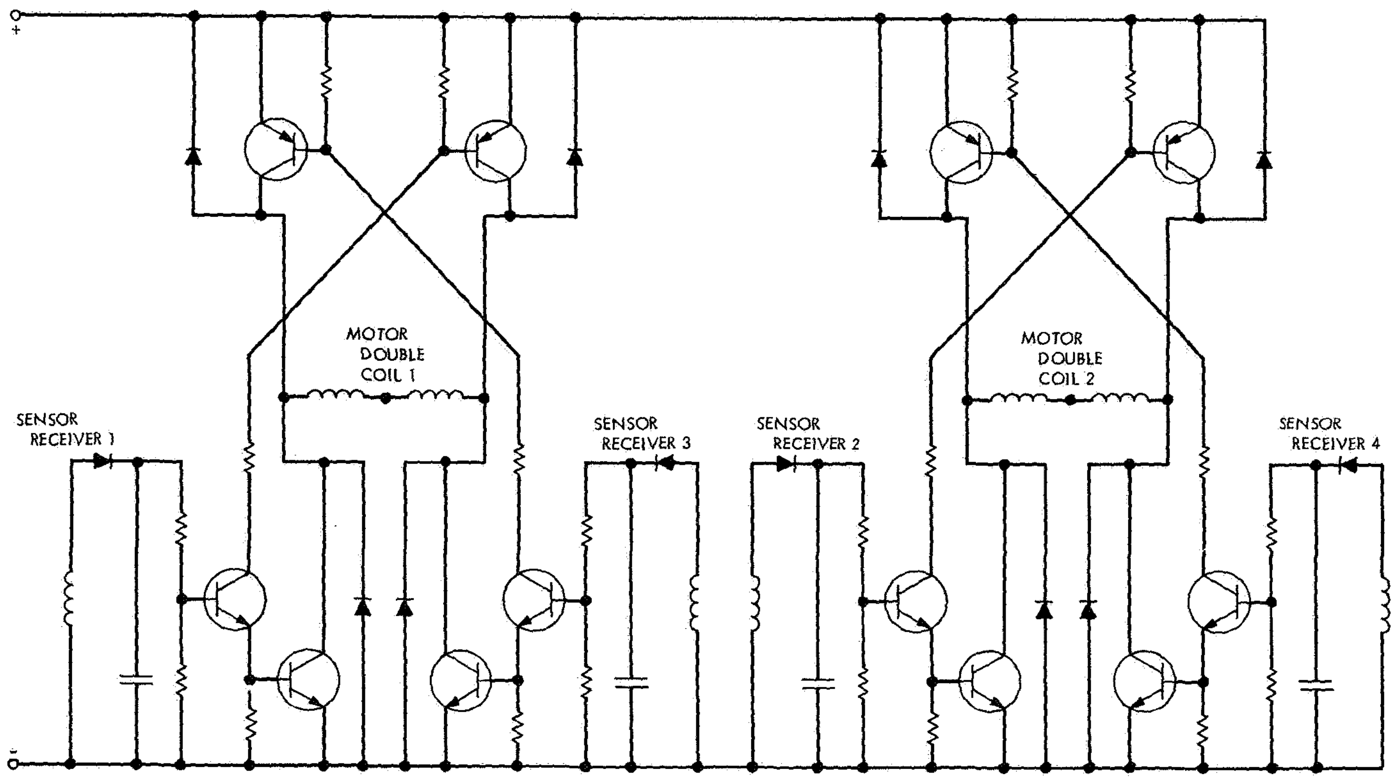

Fig. 17. Commutating circuit for two-pole, four-coil motor using separated motor coils

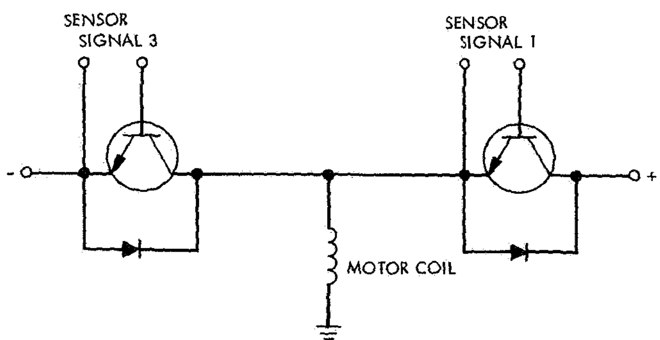

Fig. 18. Power switch for motor with star-connected motor coils

desirable for many applications because of its low cost and excellent performance. The complete commutating circuit for the two-pole, four-coil motor, except for the oscillator is shown in Fig. 19.

The upper trace of Fig. 20 shows the voltage (vertical sensitivity 5 V/cm) across a motor coil of a star-connected motor running at 5000 rev/min. The coil sees the positive potential of the power supply for a certain time. Then, it is switched off and the potential is undetermined for a certain length of time, after which it sees the negative potential of the power supply. The lower trace of Fig. 20 shows the current (vertical sensitivity 100 mA/cm) in the same coil. It is distorted from the rectangular shape by the influences of coil reactance, back electromotive force and transients, supplied by the switching of the other coils. In this example the current is off for approximately 45% of the time (horizontal sensitivity, upper and lower traces, 2 ms/cm). Reversing of this motor by low-power switching is somewhat more difficult, because each sensor signal controls alternately two different power transistors, which operate on a different potential. Additional transistors must be used to bring all sensor signals on the same potential. The complete circuit for the reversible motor is shown in Fig. 21. An alternate method would be to switch both sensor output lines. Then, the original power switch could be used, but the reverse switch would need twice the number of poles. Another alternative would be to use the power switch of Fig. 11.

D. Example of a High-Performance Motor

For good performance, a motor will use a larger number of coils and commutator switches. Some design aspects shall be explained in the example of a four-pole motor with 24 slots in the stator. The winding shall consist of 24 coils having a pitch of 5/6. Because of the two pole

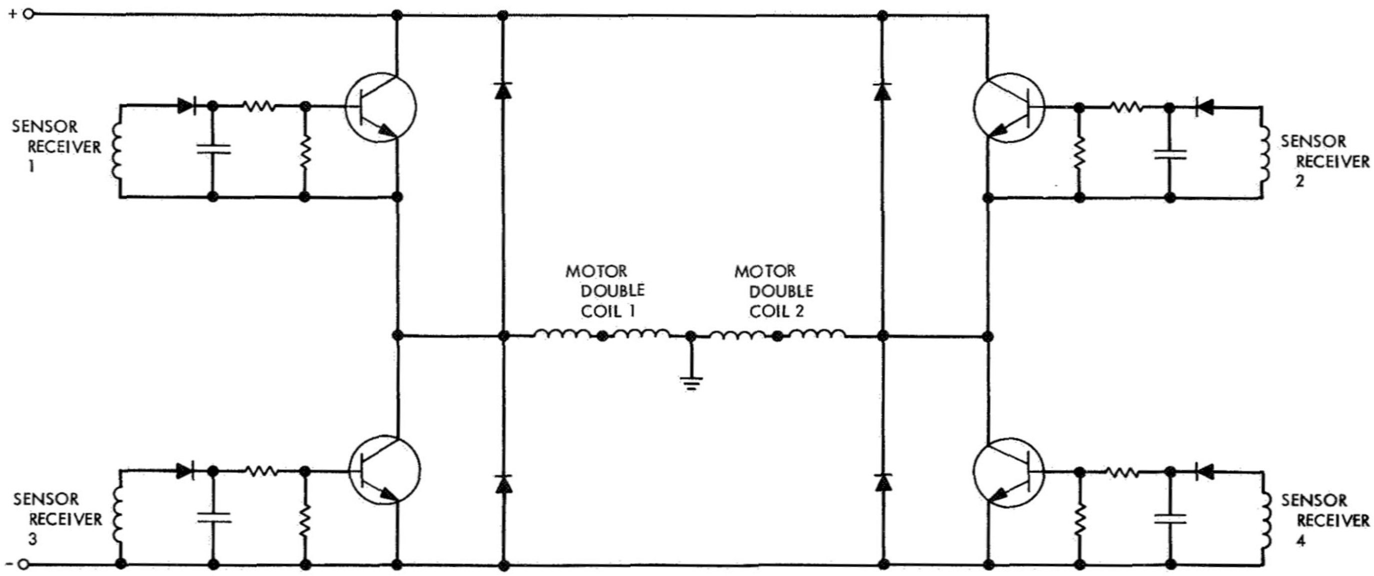

Fig. 19. Commutating circuit for two-pole, four-coil motor using star-connected motor coils

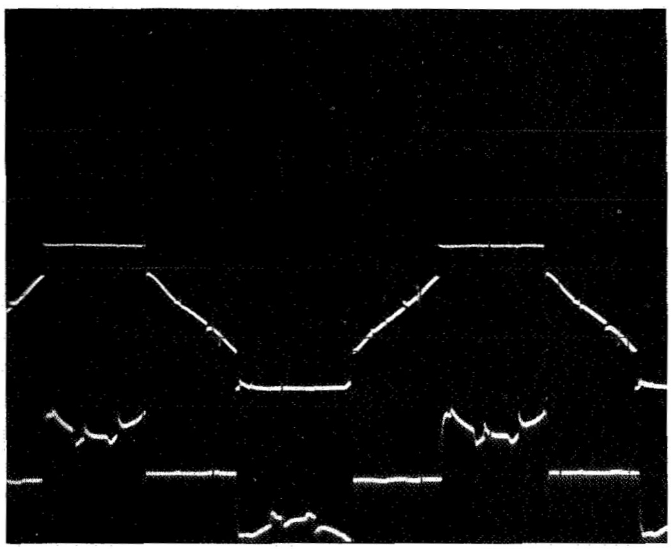

Fig. 20. Voltage and current waveforms of star-connected motor

pairs, the field in the air gap repeats itself after 180 deg. Therefore, opposite motor coils are exposed to the same field density at all times and are electrically equal. These coils can be connected in series or parallel to form double coils. Such a motor would use 12 power switches of either type shown in Fig. 11 or in Fig. 18. If the rotor construction is similar to the four-pole rotor of Fig. 2, a magnet pole would cover approximately 60 deg and the neutral zone would be 30 deg. The desired motor currents are shown in Fig. 22.

For any shaft position, there are four double coils having positive current and four other double coils having negative current. The remaining four double coils conduct no current. Whenever a positive or a negative current is turned on for one coil, another coil will have a current of the same polarity turned off. If the 12 double coils are star-connected, the current flowing into the star point will theoretically at all times be equal to the current flowing out of the star point. In reality, this is not quite true, because the current waveform is not exactly a square wave. However, such a winding would permit the use of the power switch shown in Fig. 18, even if no center-tapped power supply is available. In this case, the star point can be left floating.

From Fig. 22, it can be seen that current is turned on in the next coil after every 15 deg of shaft rotation. Because of the four-pole field, this is equal to 30 electrical deg. Twenty-four shaft position sensor signals are required to control the 12 power switches. However, for the four-pole motor, the electrical conditions repeat after every half shaft revolution. Therefore, 12 receiver coils placed in a half circle around the rotating assembly are sufficient.

In the case of the electromagnetic sensor, the rotating assembly consists of two soft magnetic 60-deg segments, which are opposite each other, as shown in Fig. 23. The $2n$-pole motor has n shaft positions which are electrically equal. Therefore, it uses n rotating segments and each

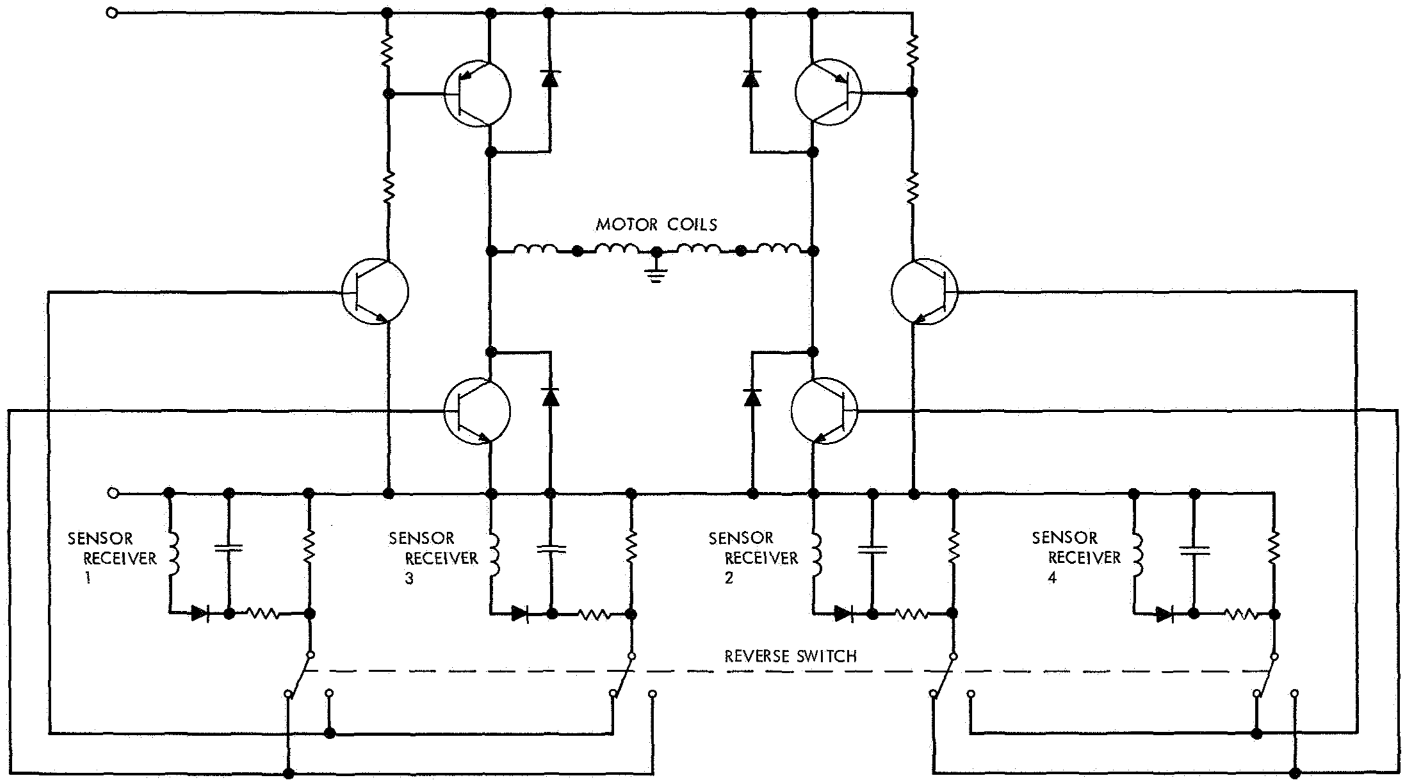

Fig. 21. Commutating circuit for reversible two-pole, four-coil motor using star-connected motor coils

receiver produces *n* pulses per shaft revolution. The sensor signals of the four-pole motor are shown in Fig. 24. Since there are only 12 sensor outputs for 24 power transistors, it is obvious that each sensor output must control 2 power transistors. By comparing Fig. 22 with Fig. 24, it can be seen that each sensor signal must produce a positive current in one double coil and a negative current in another double coil. If the power switch of Fig. 18 is used, this means each sensor signal must simultaneously actuate a power transistor tied to the positive supply line and another power transistor, in another power switch, tied to the negative supply line. This is the same problem that was discussed in the last paragraph for the reversible star-connected motor. It requires the addition of a transistor to every power switch, as shown in Fig. 21, or the power switch of Fig. 11. It can also be solved by using 24 sensor receivers.

By comparing Fig. 22 with Fig. 24, it can be seen that coil 7 has the same current as coil 1, except that it is in the opposite direction. The same is true for coils 2 and 8, etc. Coil 7 can, therefore, be connected with opposite polarity to coil 1, either in series or in parallel. The same can be done with coils 2 and 8. If this is done, the motor winding consists of six different sets of four coils each and only six power switches are required. Now, the 12 sensor signals control only 12 power transistors and the simple power switch of Fig. 18 can be used.

However, attention must be given to the fact that the star current is no longer zero at all times, but only in the average. A center-tapped power supply is required if the simple power switch shall be used. Figure 25 shows the electronic commutator of a four-pole motor using six power switches of the type shown in Fig. 18 and a possible connection of the 24 motor coils.

At all times, there are four sensor signals present (Fig. 24). This means that for the motor in Fig. 25, four power transistors are always turned on. On the average, two transistors allow current flow from the positive supply line into the common lead and two transistors allow current flow from the common lead to the negative supply line. The power transistors are, therefore, rated for one-half of the highest motor current, and for the full dc supply voltage. If the power switch uses 75-V 50-A transistors, the commutator can supply 7.5 kVA to the motor. If six power switches of the type shown in Fig. 11 are used, the commutator can supply 15 kVA to the motor. The first design, having 12 branches of the star, could

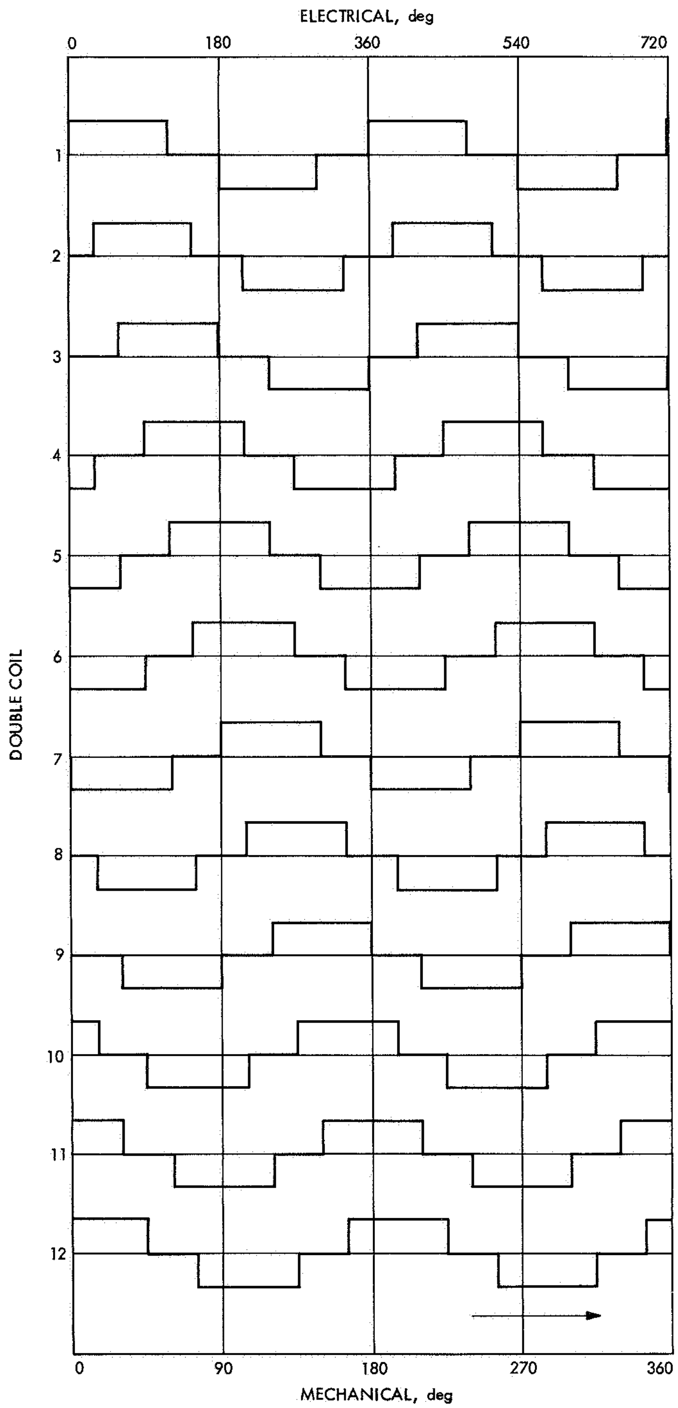

Fig. 22. Motor coil currents for four-pole motor

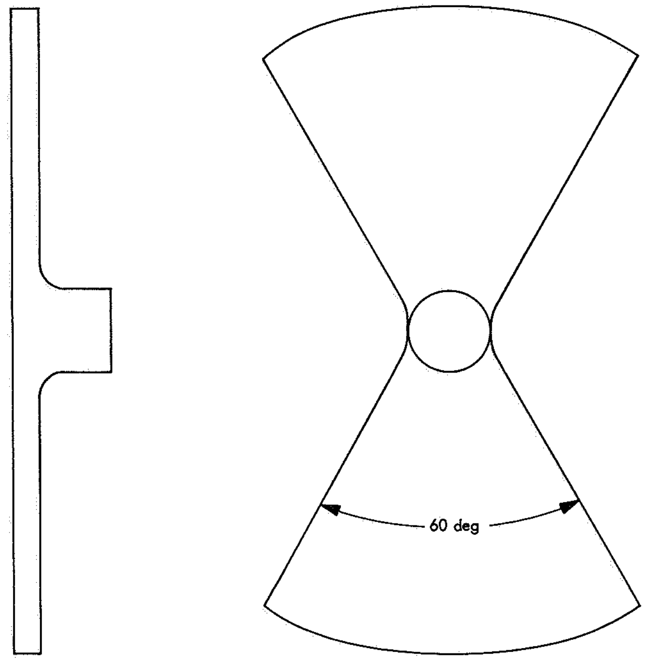

Fig. 23. Rotating segment of electromagnetic sensor for four-pole motor

supply up to 15 kVA to the motor with the simple power switch or 30 kVA with the one shown in Fig. 11. By using 24 power switches, one for each motor coil, the power of the commutator could again be doubled. This would still require only 12 sensor signals, but they must be more powerful.

If the motor uses separated or star-connected coils, more than 50% of the power switches are always in the *on* state. With the conventional ring winding, the number of power switches that conduct current is roughly equal to the number of pole pairs. Even for motors with many commutating points, only a few of the power switches are in the *on* state. Separated or star-connected windings utilize power switches better. They allow, therefore, construction of large brushless dc motors by simply using a sufficiently large number of motor coils and power switches.

The power of this commutator could be further increased by connecting two power transistors in parallel. In such a configuration, the two transistors will not carry exactly the same current, since no two transistors are identical, but with proper base resistors, their load can be made nearly equal.

E. Example of an Inexpensive Motor

A possible design for an inexpensive, medium-performance motor would have two poles, six slots and a six-coil winding. The coils could be wound either full pitch or better with two-thirds pitch. The rotor would consist of a cylindrical permanent magnet, charged across its diameter. It would be made of an isotropic material, such as Alnico II.

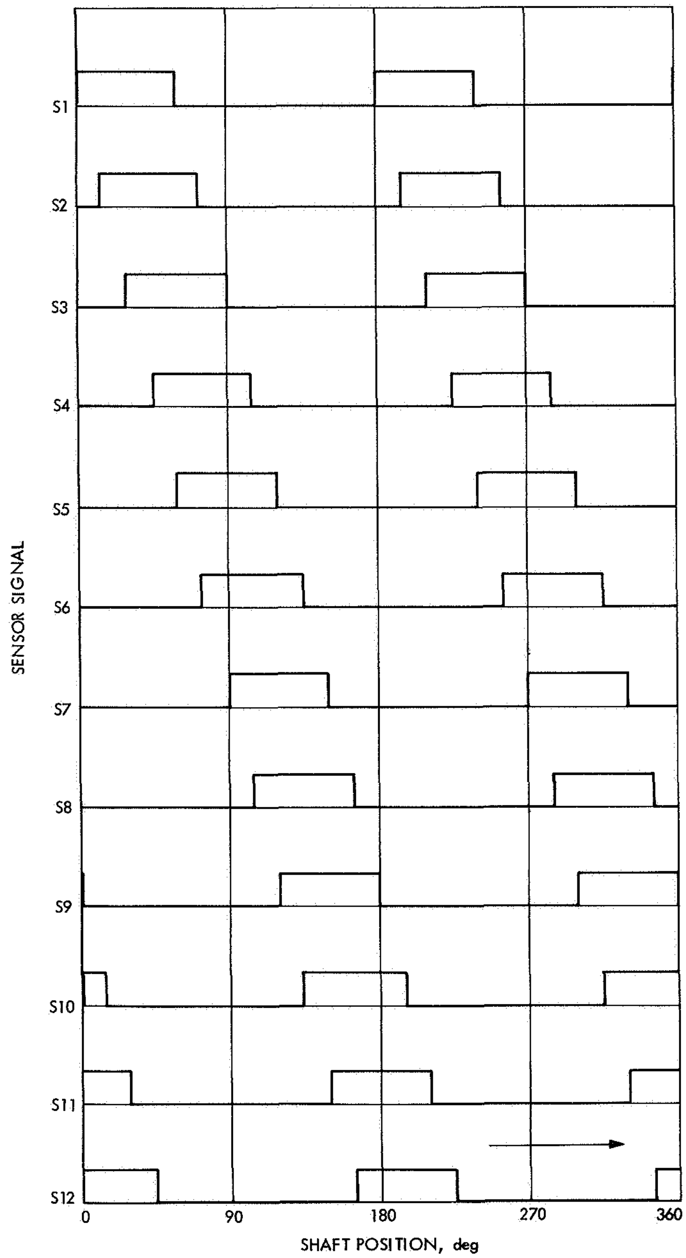

Fig. 24. Sensor signals for four-pole motor

The six coil currents have a phase shift of 60 deg. Coils 1 and 4 have the same current, but flowing in opposite directions.

As before, coil 4 can be connected to coil 1 with opposite polarity. The same can be done with coils 2 and 5, as well as coils 3 and 6. This leaves three coil pairs that require three power switches of either type. They are controlled by six sensor signals, having a phase angle of 60 deg to each other. The on time of the sensor signals would be roughly 120 deg.

If the designer is willing to sacrifice some of the performance of this motor, he can simplify the commutator by omitting the negative currents. Figure 26 shows a possible group of positive currents in the three double coils. The phase angle between these currents is now 120 deg and the on time is roughly 150 deg to assure overlapping currents. It is very important to assure current flow at least in one coil at any shaft position, and magnet poles covering a segment of more than 120 electrical deg.

The currents of Fig. 26 can be obtained by very simple power switches, shown in Fig. 27. Since only three power transistors are now used for the two-pole, six-coil motor, only three sensor signals are needed. They have exactly the same waveform as the coil currents, shown in Fig. 26. The complete electronic commutator for this motor is shown in Fig. 28, except for the oscillator.

The power switch of Fig. 27 does not permit the use of reverse diodes. But an inexpensive motor will not normally use high magnetic field densities, and voltage spikes caused by switching are not as severe as with high performance motors.

With presently available power transistors, this motor could be built for up to 0.5 kW of rated power. For mass production the circuit of Fig. 28 could be built as one integrated circuit with seven input terminals. The oscillator could also be built as an integrated circuit.

F. Speed Regulation of Brushless dc Motors

The brushless motor offers a number of methods for efficient regulation of the input power or torque. Perhaps the most convenient method is to attenuate the primary sensor current if the electromagnetic shaft position sensor is used. The induced voltage in the receiver coil increases gradually as the rotating segment approaches its core, and decreases gradually when the segment moves away from the core.

As shown in the oscillogram of Fig. 8, the sensor signal is not exactly a square wave, even though it gets clipped when the transistor which the signal is driving starts to conduct. High primary sensor current causes a high secondary voltage. The demodulated signal relatively rapidly reaches the voltage at which it turns the power transistor on. All motor coils receive the full current quickly and hold it during a relatively large portion of a shaft revolution. Therefore, the torque is high. If the primary current is reduced, the sensor pulses will have a slower rise and fall and turn the power transistors full on

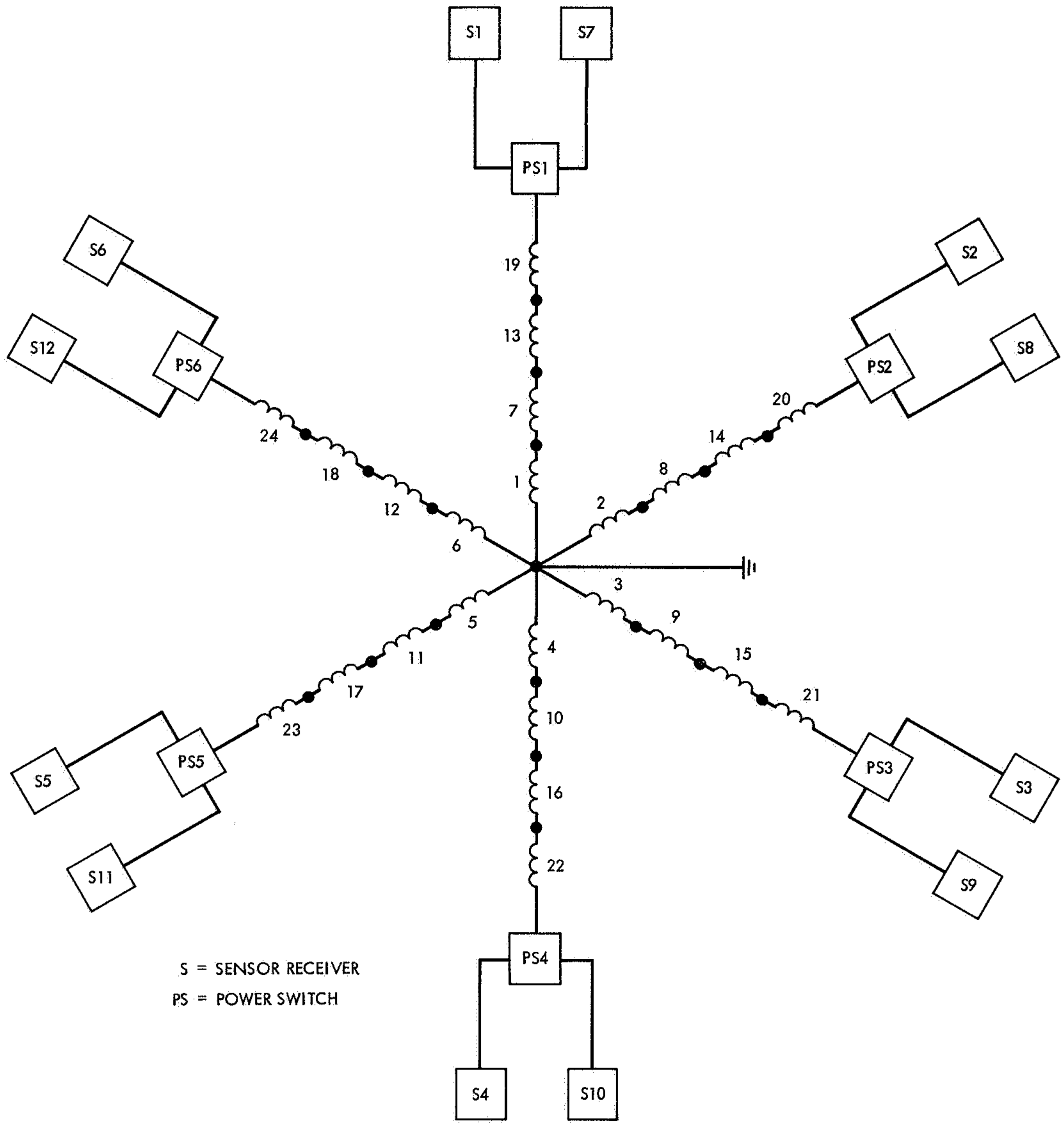

Fig. 25. Electronic commutator of four-pole motor

for a shorter period of time. This reduces the average motor current, even though it does not change the peak current amplitude in any coil. If the primary sensor current is further reduced, the secondary coil output will be insufficient to fully saturate the power transistors. This will reduce the amplitude of the coil current and further reduce the torque.

This type of speed regulation should not be employed over a very wide range of attenuated motor input power. If the power transistors are operated unsaturated, they may quickly overheat. If a wide range is desired, another method is recommended. If the leading edge of one or all of the sensor pulses is delayed by electronic circuits but not the trailing edge, the motor coil current will flow during a shorter fraction of a shaft revolution. This is a very efficient, inexpensive and safe method to reduce motor torque to virtually zero. By delaying the leading edge of the sensor signals, the motor efficiency is kept high, even at partial loads. The capability of high efficiency under partial and regulated loads makes this motor interesting for battery-operated vehicles.

The shaft position sensor of the brushless dc motor can be used to supply speed information. Each sensor receiver generates one or more voltage pulses per shaft revolution. It functions, therefore, as a low resolution tachometer. The resolution can be increased by summing all receiver signals. Possible applications include speed measurement and feedback speed control.

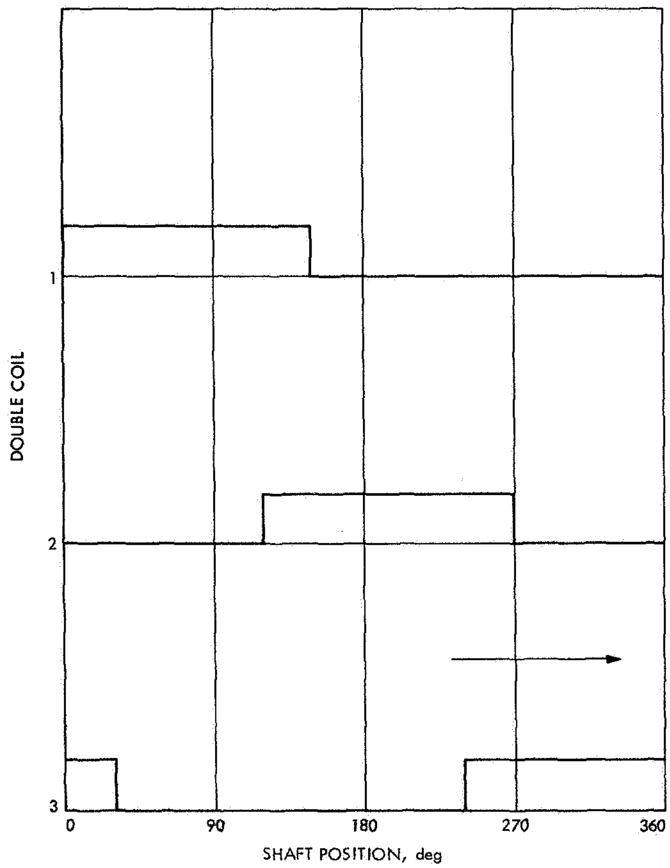

Fig. 26. Currents of simplified two-pole, six-coil motor

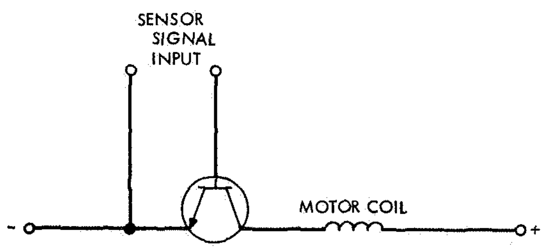

Fig. 27. Power switch for simplified motor

V. Motor Performance

An experimental brushless dc motor was constructed to evaluate different commutators. It was designed and constructed by H. C. Roters Associates under contract from the Jet Propulsion Laboratory. Some motor data are given in Table 1. This motor has each coil terminal brought out as a separate lead. This allows external coil connections to form conventional ring windings, or unconventional star windings and separated coils.

Table 1. Data for experimental motor

Characteristic	Data
Outside diameter[a]	0.75 in.
Length excluding shaft[a]	1.25 in.
Rotor diameter	0.3325 in.
Rotor magnet diameter	0.3125 in.
Rotor magnet length	0.372 in.
Magnet material	Alnico IX
Number of poles	2
Number of stator slots	12
Number of coils	12
Turns per coil	82
Coil resistance	12.2 Ω at 20°C
Number of sensor receivers	12
Type of sensor	Electromagnetic
Sensor carrier frequency	200 kHz

[a]No electronics included in motor package.

The motor coils were first connected to form a conventional dc motor winding. A shaft position sensor was constructed to simulate the conventional commutator, as explained in Section III. After the motor performance had been measured, the winding was reconnected to form a star and a new commutator was built, which was similar to the example of Subsection IV-D with six power switches and a symmetrical center tapped dc power supply. Figures 29–31 show the performance characteristics of this motor with the star winding at 20°C with a coil conduction angle of 100 deg. Figures 32 and 33 compare the efficiencies of this motor with star winding and with conventional ring winding. It can be seen that, besides the different voltage rating, the star-connected winding resulted in higher efficiency, except for very high torque output. The higher efficiency of the star-connected motor is due primarily to the absence of useless currents. Only at very high shaft torques is the conventional motor better because it can utilize the weak fields in the neutral zones to develop some additional torque.

The winding of the same motor was also connected to a simplified commutator, like the one shown in Fig. 28. The motor had six double coils, as before, and the *on* time for the current was 100 deg. Figures 34–36 show the motor performance with this simplified commutator. By comparing with Figs. 29–31 it can be seen that the torque capability has dropped considerably, but the peak efficiency is still high.

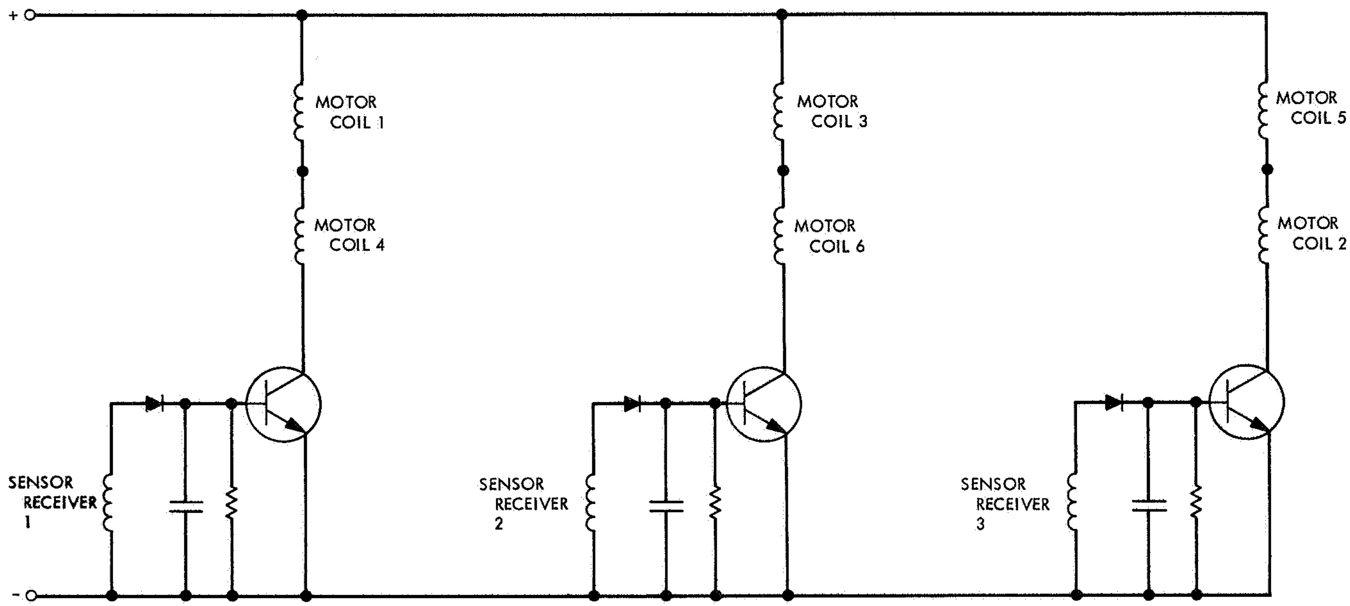

Fig. 28. Electronic commutator of simplified two-pole, six-coil motor

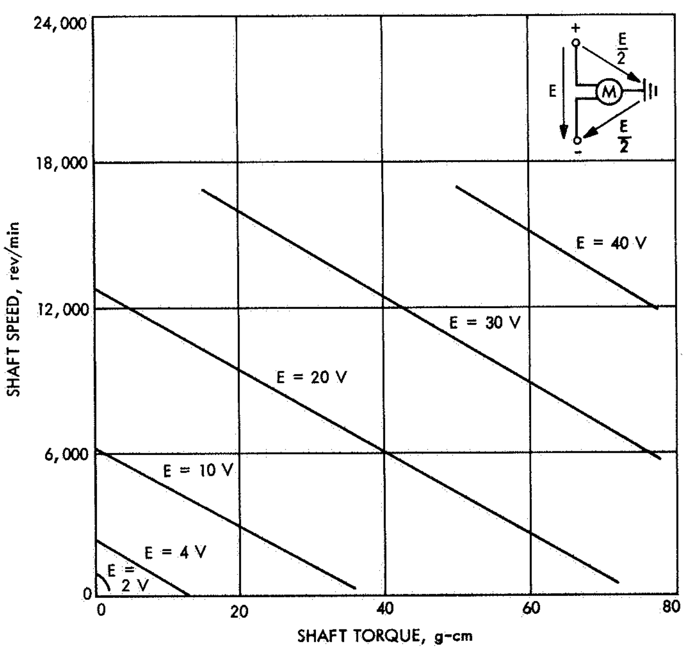

Fig. 29. Shaft speed and shaft torque of experimental dc motor

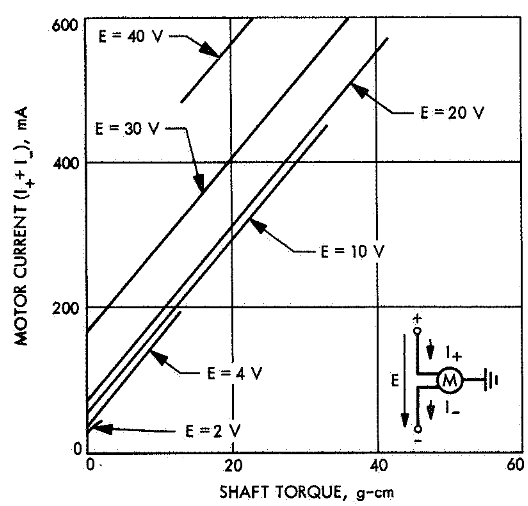

Fig. 30. Motor current and shaft torque of experimental dc motor

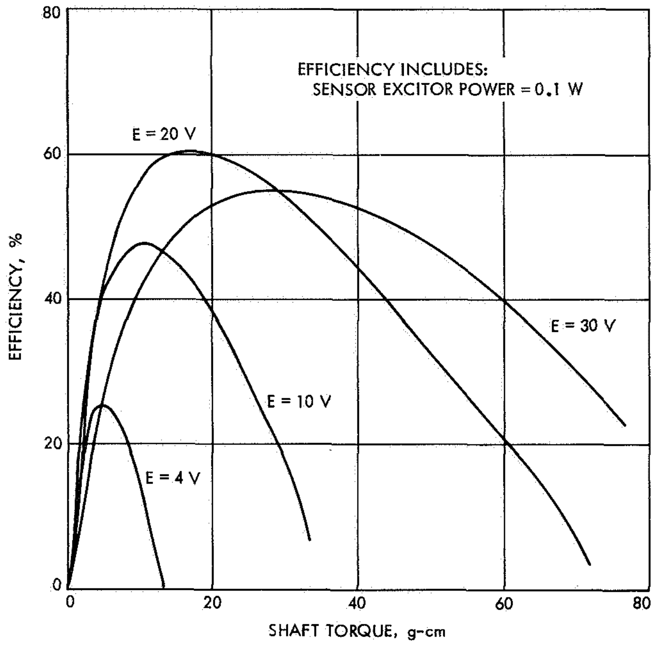

Fig. 31. Efficiency and shaft torque of experimental dc motor

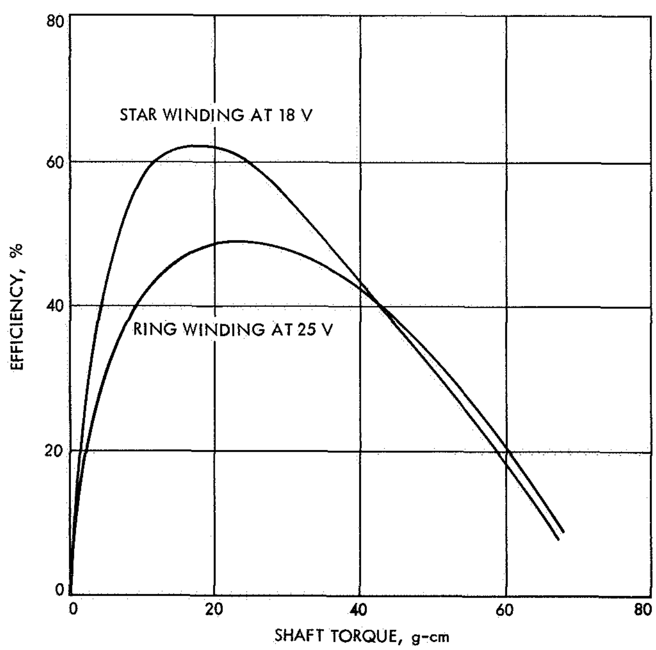

Fig. 32. Efficiency and shaft torque comparison for star winding and ring winding

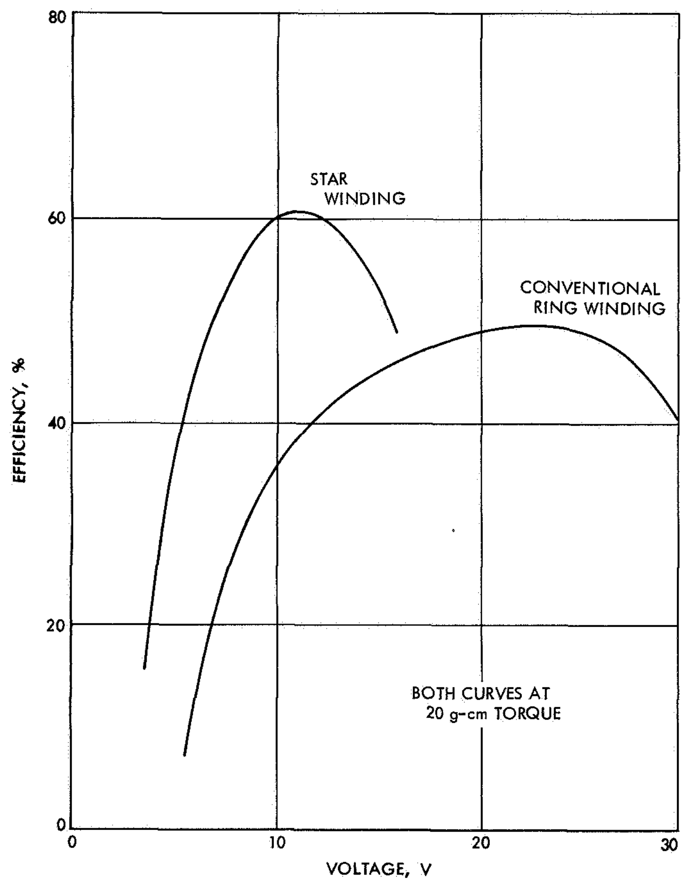

Fig. 33. Efficiency and voltage comparison for star winding and ring winding

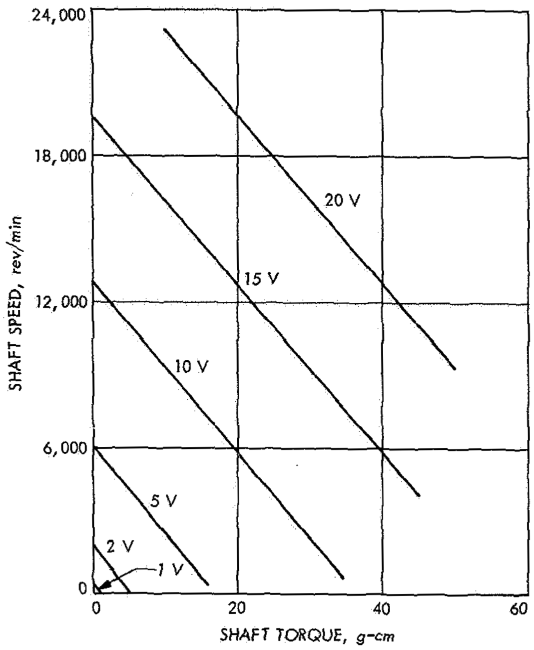

Fig. 34. Shaft speed and shaft torque of experimental dc motor with simplified commutator

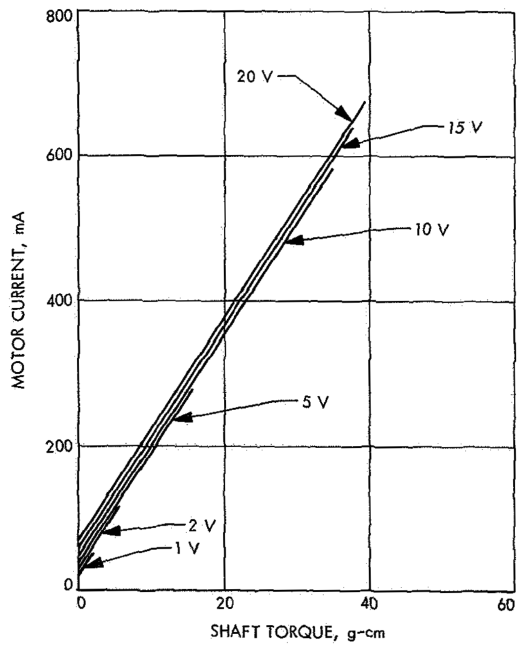

Fig. 35. Motor current and shaft torque of experimental dc motor with simplified commutator

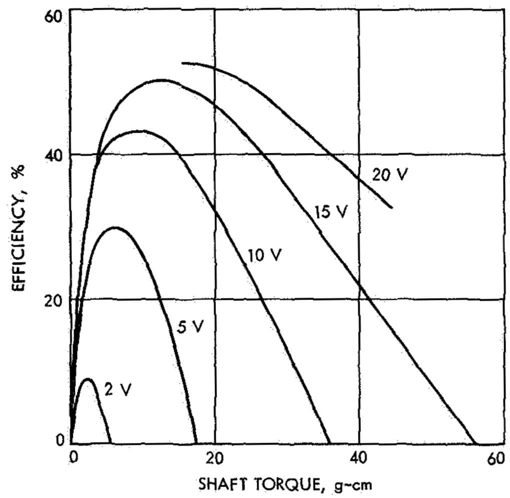

Fig. 36. Efficiency and shaft torque of experimental dc motor with simplified commutator