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ELECTRONICALLY-COMMUTATED DC MOTOR WITH HALL ELEMENTS

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I. INTRODUCTION

Since its advent, the motor as a means of converting electric energy into mechanical one has contributed much toward the development of the present-day technology. Also, the motor itself has been diversified in types and refined in every respect. Now we can see DC motors, induction motors, synchronous motors and other variations used in the various fields. In the early times, the motor manufacturers placed emphasis on the realization of more sturdy and more powerful motors. As the motor application technology has progressed in diversity, the requirements of the motor have become more and more exacting and sophisticated. Not only the quality of energy the motor can deliver, but the quality of energy has become increasingly talked about in all seriousness. For example, constant speed characteristics, variable speed and its control characteristics, dynamic response, vibration, electrical and mechanical noises, reliability and durability in special working conditions have become important criteria in judging specific motors.

The DC motor is well known for its excellent constant speed control characteristics, speed regulation and starting torque characteristics, but it leaves much to be desired as it inevitably uses brushes and commutators which in almost all cases are responsible for major troubles. In recent years, a rapid progress in the electronic equipment for civil and industrial purposes has opened up a new outlet for DC micro-motors. Naturally, their performance has greatly been improved, and their costs reduced sharply. At the same time, the brushes and governors have taken an indubitable shape of a problem that stands in the way of further development of DC motor and its application. Naturally, strong voices are heard of that urge the elimination of brushes from industrial drive system and from micro-motors.

On the other hand, a long stride made in the semiconductor technology has made it possible to apply semiconductors to power fields. In the micro-motor fields, also, the electronic governor is beginning to supersede the mechanical type to meet the users' needs. Now the development of the various types of novel, perfectly-brushless micro-motors is on the way.

Some time ago, Siemens succeeded in the development of inexpensive, utility Hall elements of excellent characteristics and a series of electronic brushless motors embodying them. Fully appreciating Siemens' developments, FUJI has developed a variety of unique electronic motors for use with civil electronic equipment and special industrial machinery. With the proven high reliability, FUJI electronic motors are galantly debouching into unlimited sphere of their applications.

II. KINDS OF BRUSHLESS MICRO-MOTORS AND FEATURES OF HALL SYSTEM

1. Various Kinds of Brushless Micro-Motors

In order to realize commutation without counting on commutator and brush, the rotor position must be detected in a contactless way, and the brushless motor meeting this requirement is classified by detecitve method as follows.

1) Optical method

In this method, light beam is chopped in synchronism with the running of the motor, but response, detective efficiency and transmitter and receiver system, costs are problems.

2) High-frequency induction method

A position detective revolving transformer on the rotor is excited at a high frequency, and the position signal is detected by a detective coil to work a switching circuit, which supplies torque current. Workable, but problematic when electrical noise suppression is considered.

3) High-frequency oscillator on/off method

The output of a resonance circuit is forced through a detective coil to interrupt the high-frequency oscillation in tune with rotor positions. This chopped signal is applied to a transistor to switch an electronic commutator circuit. This method is also problematic when electrical noise is required to be suppressed.

4) Mechanical contact method

Reed switches arranged to be acted upon by the rotating magnet are used to switch commutator circuit. Mechanically, the speed is limited, and noise is liable to develop because of mechanical switching.

5) Magneto-electronic transducing element system

Simple in construction, yet reliable in detective performance. High frequency is not used, and the performance is highly stabilized and free from electrical noise. This method is subclassified into Hall element method and magneto-resistance element method. In the magneto-resistance method in which an element whose resistance changes with change in the intensity of magnetic field is used, an additional magnet is required for the purpose of biasing because the resistance changes in proportion to the second power of the intensity of magnetic field and because the sensitivity of the element is very small as the intensity of the magnetic field in the air gap of practical motor is very small. Accordingly, it is more costly than the Hall element method.

In addition, there is a transistor micro-motorf or extremely small output purposes, in which a switching transistor is driven by the voltage induced in a datective coil. This motor requires special contrivance for its start-up. For example, the rotation direction is determined by the difference in time constant between two RC circuits, and power transistors are controlled just as with a ring counter circuit. Various other modes have also been developed and proposed, and the classification abovə is based on major operating principles.

2. Features of Hall Element Method

Backed by an abundance of excellent features and by the market needs, the electronic motor coming under the category of Hall element method is most promising among other brushless motors.

(1) Comparatively simple and sturdy in construction
(2) Extremely low in noise level
(3) Longeval because there is no wearing part other than bearing.
(4) Capable of doing constant speed control and speed regulation over a wide range.
(5) Excellent starting characteristics
(6) Low electrical noise, which in turn minimizes evil influence to other machines.
(7) Maintenance-free and highly reliable
(8) There is no factor that limits the output, but power transistor.

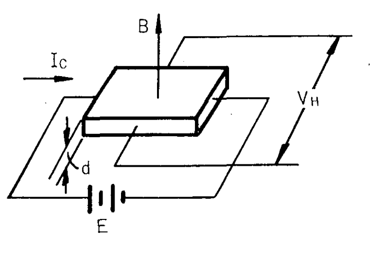


Fig. 1 (a) Principle of Hall element

In addition, various control modes are available if suitable auxiliary circuits are combined. The only demerit, if any, is the cost that is higher than the motor with brushes.

III. ELECTRONIC MOTOR AND ITS OPERATING PRINCIPLE

1. Hall Element

Some 100 years ago, the Hall element was found by an American, named E.H. Hall. It is an element that works on an electromagnetic effect, and its application in practical fields has been prompted since around 1960 in keeping with the progress of intermetallic semiconductor technology. *Fig. 1 (a)* shows a Hall element. When the Hall element is subjected to an electrostatic field and a magnetic field running normal thereto, it will generate Hall electromotive force in the direction normal to both fields.

The Hall electromotive force generated is given by the following formula.

Hall electromotive force, $$V_H = \frac{R_H}{d} I_C \cdot B$$

Where, R_H : Hall constant

The relationship between the Hall voltage and the intensity of magnetic field is represented by the curve, a, appearing in *Fig. 1 (b)*.

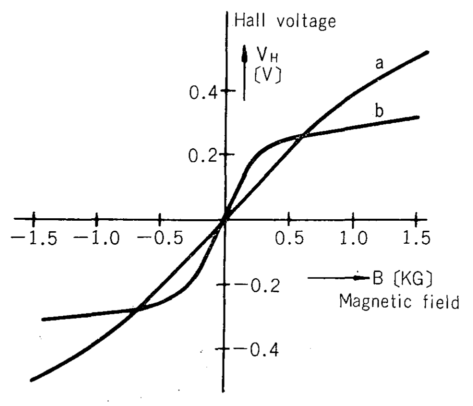
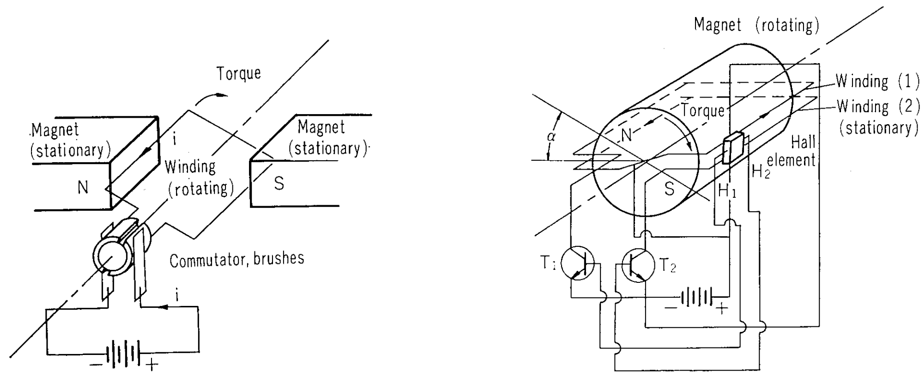


Fig. 1 (b) Characteristics of Hall element

The materials of which Hall element is made include Ge and Si in Group IV and alloyed semiconductors of elements in Groups III and V, like InSb and InAs. Si, with a large Hall constant, has been used for measurement purposes over a wide range of temperatures, while InSb and InAs, with a high electron mobility, can handle control power as a suitable resistance can be obtained even when a thin piece is used.

In order to increase the sensitivity of the electronic motor, a ferrite plate is used to focus magnetic flux. Its characteristic curve is represented by (b) shown in *Fig. 1 (b)*. Since a large Hall vcltage can be attained in the vicinity of room temperatures



(a) DC motor with commutator (b) Electronic motor

Fig. 2 Operational principle of DC motor and electronic motor

at a low cost, InSb is used for the electronic motor. Since however itis largely dependent on temperature, the control circuit is designed to be immune from its temperature characteristics.

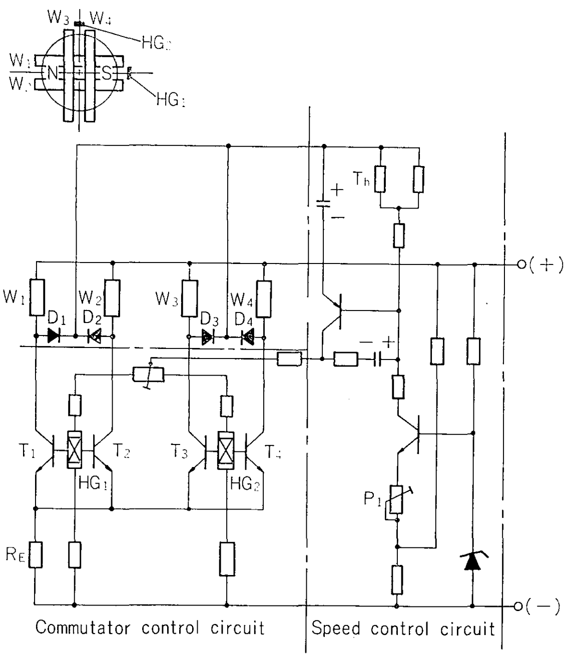
2. Fundamental Construction of Electronic Motor

The fundamental construction of an electronic motor is shown in *Fig. 2* in which it is compared with a permanent magnet-excited DC motor. In the DC motor, commutation is undertaken by brushes and commutator to drive a wound rotor. In the case of electronic motor, a permanent magnet rotor runs, and the current flows through the stator windings. Referring now to *Fig. 2* (*b*) in which windings (1) and (2) and a Hall element are arranged, if the permanent magnet is situated as illustrated, transistor T_1 will be turned on by the Hall voltage generated at H_1 terminal to force current through the winding (1) in the arrow direction, while the winding (2) remains dead. With this, a clockwise turning torque is generated until the angle (a) reaches 90°, driving the magnet in the clockwise direction. On the other hand, when the angle exceeds 90°, the magnetic field is reversed, turning the Hall voltage at terminal H_2 positive instead of terminal H_1. Accordingly, transistor T_1 is turned off, while transistor T_2 turns on, forcing current through the winding (2) in the direction of dotted line, and not through the winding (2). Thus, the rotation direction of the magnet still remains the same. In this way, the commutation is carried out electronically. Here, the commutation by brushes and commutator in the DC motor is replaced by the combination of Hall element and transistors. In actuality, however, an additional set of windings and Hall element is arranged at a position 90° apart from the original set as no driving torque is generated at an angle of 90° if only a single set is used. Since the stator winding current is changed over sequentially according as the rotor magnet position changes, the rotor can be driven smooth. Considering the current direction, this four-winding system is regarded as having four windings arranged at an interval of 90° in electrical angle. Although a three-winding system in which three windings are placed at an interval of 120° in electrical angle is also conceivable, the four-winding system is better because the torque ripple becomes smaller and because the commutation control can be accomplished with two Hall elements by taking the advantage of the point where the Hall element generates reverse electromotive force across it. For this reason, the four-winding system is preferred for the electronic motor. The magnet is also an important element, and in view of cost and performance, isotropic or anisotropic barium ferrite magnet or high-quality Alnico magnet is employed. Where a cheap motor of small output and high moment of inertia is required, outer rotor type is also available. Usually, windings are provided in four slots in the stator core, but slotless type in which ring-shaped yoke alone is used is also available. This type does not generate higher harmonics due to slots, and is best suited to information-related equipment and for high-speed purposes as its rotation is accompanied by less vibration and wow.

The electronic motor performs commutation electronically, and there is no mechanical wearing part other than bearings. Since the bearing load is also less than in other motors, the electronic motor can serve for an extended period with high reliability.

3. Control Circuit for Electronic Motor

The 180° conduction system is the simplest and fundamental. Each winding phase conveys a small sinusoidal current over a period of 180° in electrical angle in proportion to the Hall electromotive force. An example is shown in *Fig. 3*. The illustrated system is suitable for a costless, small output drive. By commutation, there happens to be a period during which no current flows through each winding phase, and there is no need of using a tachometer generator as the motor itself as a tachometer generator. mamely, the counterelectromotive force during non-conductive periodis taken out through a diode and rectified to represent the rotation speed of the motor. This voltage is com-

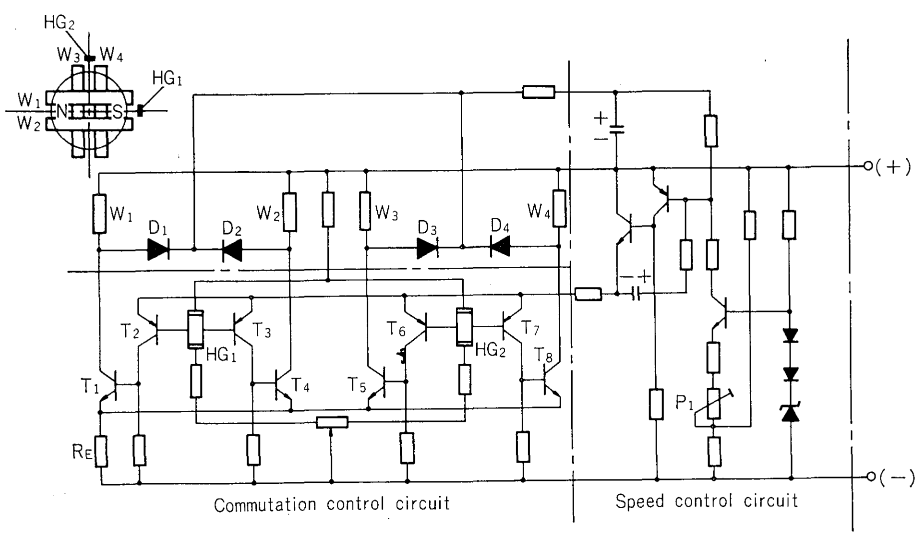


$W_1 \sim W_4$: Stator windings
HG_1, HG_2 : Hall elements
Th : Thermistor
R_E : Emitter common resistor
$T_1 \sim T_4$: Main transistors
$D_1 \sim D_4$: Diodes
P_1 : Speed adjusting resistor

Fig. 3 **Control circuit of electronic motor (180° conduction type)**

pared with say a reference voltage obtainable from a zener diode and amplified to control the control current of the Hall element in order to keep the motor speed at a specified value. The regulation of the speed can be accomplished by adjusting the variable sesistor, *P*. In the case of a barium ferrite rotor, the counterelectromotive force falls prey to the influence of a large temperature coefficient (−0.2%/°C), and it is devised to attach a thermistor to the winding for the temperature compensation of the circuitry (See *Fig. 3*).

Where a larger torque and a wider speed control range, together with higher controllability and higher efficiency, are prerequisite, the so-called 90° conduction system is employed as shown in *Fig. 4*. The prestage transistor is controlled by the Hall electromotive force in order to control the main transistor. Namely, the current is forced for a period of 90° in electrical angle through the main transistor only which is located at a position where the Hall electromotive force can generate the maximum voltage. Unlike the 180° conduction system, this system can handle larger winding current at a high efficiency, and is able to control speed over more than a ratio of 10 to 1. Just as with the 180° conduction system, the speed control is carried out by regulating the emitter current of the prestage transistor. Where it is required to carry out the temperature compensation of Alnico magnet, whose characteristics are adrift slightly depending on temperature, and of zener voltage, a diode may be connected in series with the zener diode as illstrated in the circuit diagram. Where the efficiency in a low speed range under high torque conditions is of importance or where wider speed control range is necessitated, there is a system (for which there is no space to spare here for detailed discussion) in which: Hall elements are arranged at an interval of 45°, and the Hall voltage is amplified; with reference to the time when the Hall voltage clears zero point, the main transistor is driven for a period of 90° with the help of a logic circuit, and the current is supplied to the electronic motor through a transistor chopper.



$W_1 \sim W_4$: Stator windings
$D_1 \sim D_4$: Diodes
HG_1, HG_2 : Hall elements
P_1 : Speed adjusting resistor
T_1, T_4, T_5, T_8 : Main transistors
R_E : Emitter common resistor
T_2, T_3, T_6, T_7 : Prestage transistors

Fig. 4 **Control circuit of electronic motor (90° conduction type)**

Table 1 **Outlines of characteristics on electronic motor**

Item \ Type		Unit	GCG143A	GCG246A	GCG256A	GCG341	1AD2001	1AD3101	1AD5000	1AD8050
Rated voltage	(V)	V	12	24	24	24	12	24	24	60
Rated speed	(N)	rpm	3,000 (1,000~ 3,600)	1,800 (1,000~ 3,600)	3,600 (400~ 4,000)	20,000~ 60,000	3,000	600~ 6,000	600~ 6,000	600~ 6,000
Rated torque	(T)	gr•cm	30	90	200	33	12	120	500	2,000
Rated current	(I)	A	0.35	0.34	1.1	1.57	0.16	0.7	3	3.2
Moment of inertia of rotor	(J)	gr•cm•sec^2	0.184	0.021	0.052	0.017	0.0045	0.033	0.416	2.30
Efficiency	(η)	%	22	20	29	52	20	44	42	63
Motor weight	(W)	gr	170	290	430	510	70	210	750	1,500
Ambient temperature		°C	−10°~55°C							

Notes : 1. The speed ranges appearing in the row, "Rated Speed", refer to variable speed ranges.
2. The ratings above refer to continuous duty.

Even for the same motor, the electronic circuit can assume a variety of arrangements and constants depending on cost requirements and on what the control objects demand.

IV. STRUCTURAL DESIGN AND CHARACTERISTICS OF ELECTRONIC MOTOR

The following is a list of typical examples of three basic types, GCG 1, GCG 2 and GCG 3, and 1AD series, and a brief explanation of each. All these products, developed by FUJI, are on a mass production line.

Table 1 shows the main particulars of electronic motors. The basic structure of the electronic motor is composed of a radially bipolarized rotor and four groups of stator windings. There are many variations, both in structure and characteristics, depending on application purposes.

1. GCG 1 (Outer Rotor Type)

The external view, structural design and characteristic curves of Type GCG 143 A are shown in *Figs. 5, 6* and *7*, respectively. A ring-shaped isotropic ferrite magnet is used, and two Hall elements are set 90° apart from each other in the respective grooves in the salient part of the core. This type of motor is mainly used for civil equipment, for which inexpensiveness is of the paramount importance, such as data recorder, desk-top printer, dictation machine, etc.

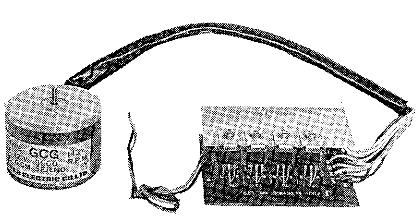
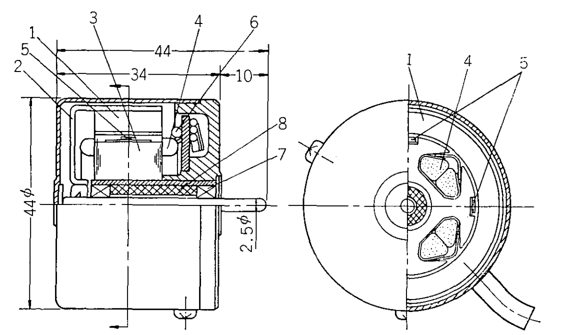


Fig. 5 Outerview of electronic motor type GCG 143A



1. Rotor (isotropic ferrite magnet)
2. Rotor frame
3. Stator core
4. Stator coil
5. Hall element
6. Thermistor
7. Sintered metal
8. Oil reservoir

Fig. 6 Sectional view of electronic motor type GCG 143A

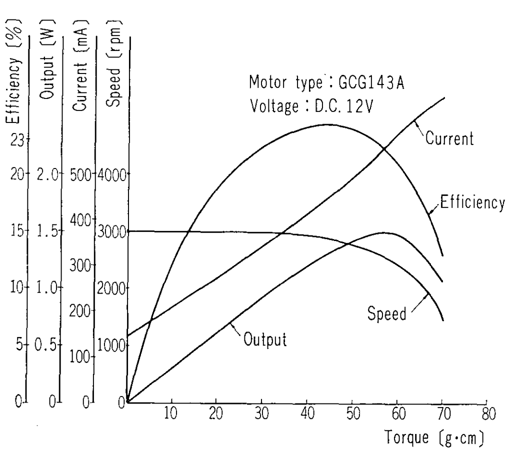


Fig. 7 Characteristics curve of electronic motor type GCG 143A

2. GCG 2 (Inner Rotor Type)

The external view and structural design of Type GCG 246 are shown in *Figs. 8* and *9*, respectively. A cylindrical anisotropic barium ferrite magnet is used, and two Hall elements are set in the grooves of salient part of the core while being set 90° apart from each other. Even with the same dimensions,

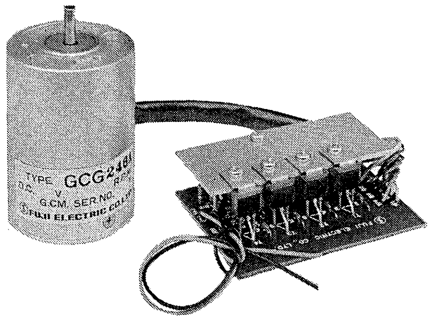
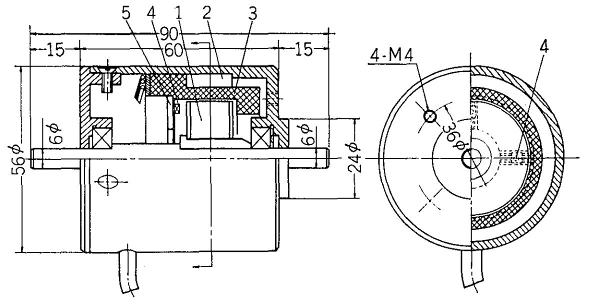
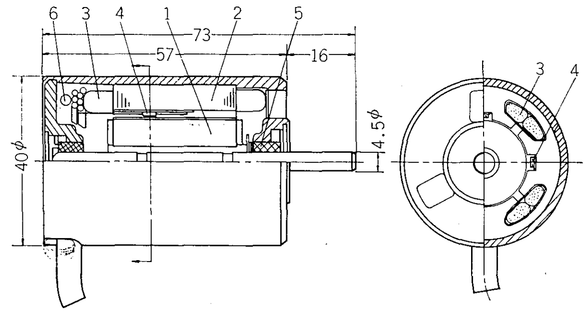


Fig. 8 Outerview of electronic motor type GCG 246A



1. Rotor (Alnico magnet)
2. Slotless stator core
3. Molded coil
4. Hall element
5. Hall element holder

Fig. 11 Sectional view of electronic motor type GCG 256A



1. Rotor (anisotropic ferrite magnet)
2. Stator core
3. Stator coil
4. Hall element
5. Sintered metal
6. Thermistor

Fig. 9 Sectional view of electronic motor type GCG 246A

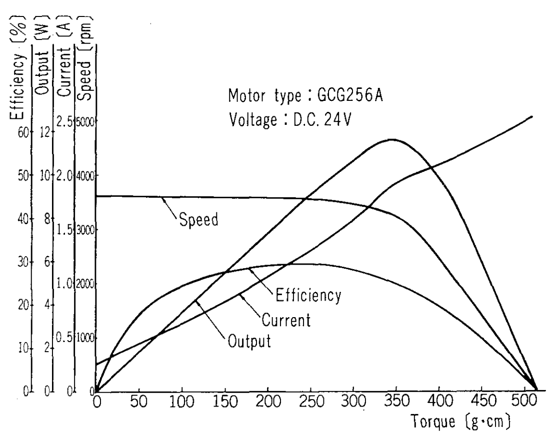
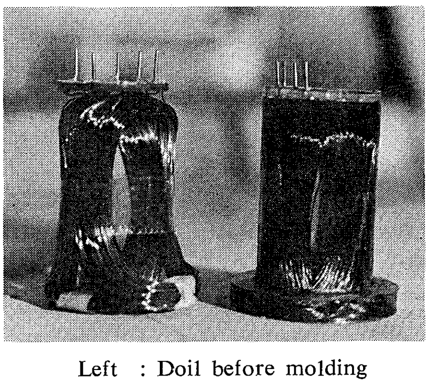


Fig. 12 Characteristics curve of electronic motor type GCG 256A

the motor can provide more powerful torque if Alnico magnet is used in place of barium ferrite magnet. This type of motor is suitable for information-oriented equipment and computer terminals and especially for the direct capstan drive of highly sophisticated dictation machine, motor-driven typewriter, digital cassette, etc. Sometimes it is important to dynamically tune the motor with the machine with which it is to be combined. For the high-quality picture machine and high-quality acoustic machine where vibration and wow are most abominable, Type GCG256A which is of the slotless type is useful. Its external view, structural design and characteristic curves are shown in *Figs. 10, 11* and *12*, respectively. A cylindrical Alnico magnet is used, and the stator winding is a newly developed epoxy resin molding. The core is of the intrinsic ring form of the slotless type. *Fig. 13* shows the coils before and after molding. Two Hall elements are mounted on the carrier arranged in the vicinity of the rotor. The carrier is made of ring-shaped thin iron sheet on which the Hall elements are arranged 90° apart from each other. In this arrangement, the Hall elements can detect rotor leakage flux in the axial direction, and can be little influenced by the flux originating from the stator winding. As a result, stabilized control is possible.



Left : Doil before molding
Right : Coil after molding

Fig. 13 Outerview of resin casted coil

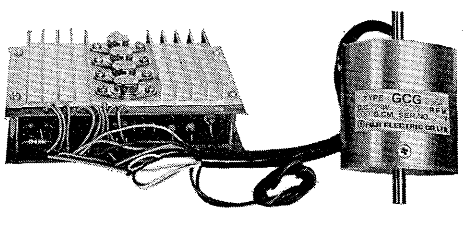


Fig. 10 Outerview of electronic motor type GCG 256A

3. GCG 3 (High-Speed Type)

The external view and structural configuration of Type GCG 341 are shown in *Figs 14* and *15*, respectively One of the features of this type is that the rotor is supported with high-precision, grease-lubricated ball bearing units in an overhang form. The rotor is made of high-quality Alnico magnet. It is found on an overspeed test that the motor can run at a speed of more than 75,000 rpm. Also a life test has proved that it can stand more than 10,000 hrs. Another feature is the slotless core structure using molded coils. This type of motor finds itself in optical equipment, textile industry and small-capacity centrifugal separator, etc. It is particularly useful when applied to high-speed mirror drive.

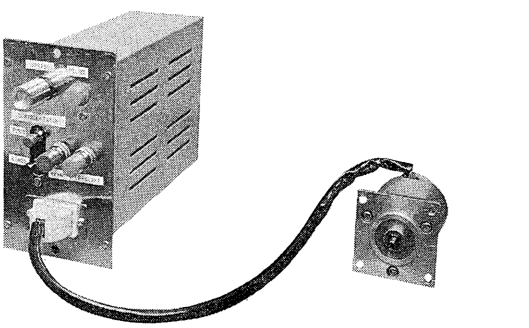
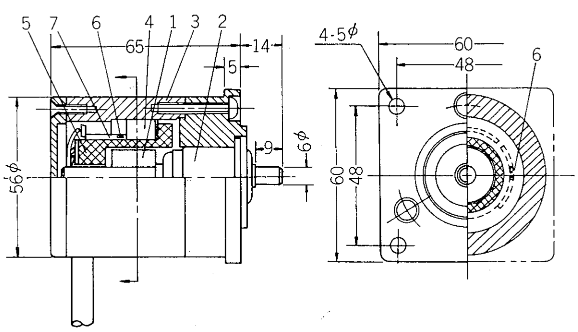


Fig. 14 Outerview of electronic motor type GCG 341



1. Rotor (Alnico magnet)
2. Bearing unit
3. Erame
4. Slotless stator core
5. Molded coil
6. Hall element
7. Hall element holder

Fig. 15 Sectional view of electronic motor type GCG 341

4. 1AD Series

The external view and fundamental structure of the motor are shown in *Figs. 16* and *17*, respectively. A cylindrical high-quality Alnico magnet is used, and the slotless core structure uses windings wound on a plastic frame. It is satisfactorily applicable to precision machinery industry and computer peripherals.

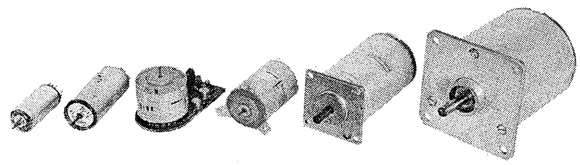
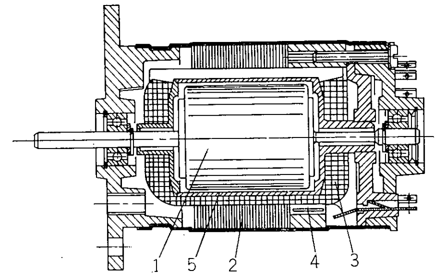


Fig. 16 Outerview of electronic motor type 1AD series



1. Rotor (High-quality Alnico magnet)
2. Slotless stator core
3. Stator coil
4. Hall element
5. Winding frame

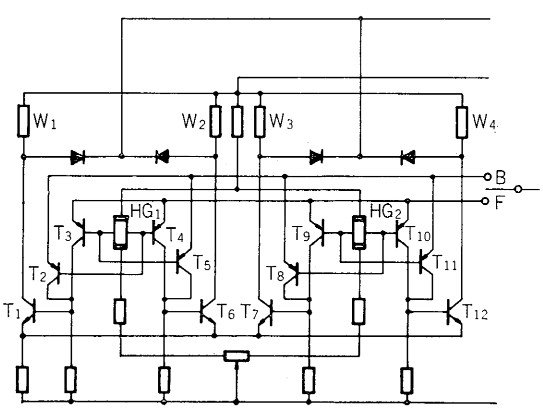
Fig. 17 Sectional view of electronic motor type 1AD series

V. SPECIAL FUNCTIONS BY ADDITIONAL CIRCUITS

Various functions are required of electronic motor depending on purposes. In such a case, functional circuits are available to achieve the required modes of operations stably and reliably. A few examples are given below. It is possible to supply contactless DC step voltage as a control input signal of the following circuits. Also, they can easily be combined with logic circuits.

1. Reversible Circuits

Changeover of the connections of transistors and windings or of the connections of Hall elements and transistors enables reversible operation of the electronic motor. As illustrated in *Fig. 18*, the forward



$W_1 \sim W_4$: Stator windings
T_3, T_4, T_9, T_{10} : Prestage transistors for forward running
T_2, T_5, T_8, T_{11} : Prestage trensistors for reverse running
T_1, T_6, T_7, T_{12} : Main transistors
F, B : For/Rev changeover switch

Fig. 18 Fundamental circuit of reversible operation

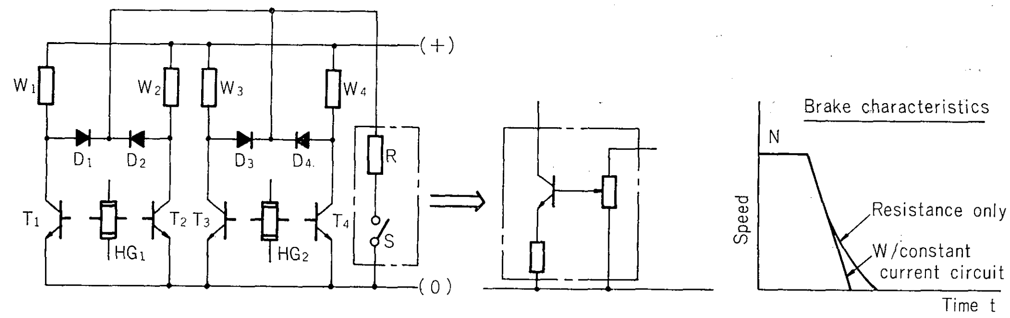


Fig. 19 **Fundamental circuit of braking operation and braking characteristics**

and reverse prestage transistors are grouped into two, and the transistor groups are changed over for reversible operation. This contactless method of changeover is verified to be workable. Also, a reversal braking circuit can be made of this circuit.

2. Brake Circuit

There are many ways for the braking of electronic motor. The most typical among them are special regenerative braking methode and reversal braking method. These two methods should be selected to suit specific purposes, however.

The special regenerative braking method can provide stable and highly reliable braking. Its operating principle is shown in *Fig. 19* in which braking signal, if given, turns off the prestage transistor to stop commutation for the windings, and at the same time, the switch *S* is closed to forcibly carry current again through the windings via diode, resistor *R* and switch *S* by the combined effort of counterelectromotive force and motor drive voltage. It should be noted however that in this case all the windings cannot be conductive at a time, but the only one which is subjected to the highest induction voltage can carry. Thus, four windings are sequentially ignited. The magnetic field developed by the windings is some 90° behind that by the rotor, and serves as a braking force. The switch *S* and resistor *R* can be passivated into a contactless form for constant current operation. An example of braking current is shown in *Fig. 20*. In the reversal braking method, the motor circuit is changed to reversal circuit on a braking signal from the reversible control circuit (explained under item 1), and when the motor speed is reduced to nearly zero, which is detected by knowing the counterelectromotive force, the reversal circuit is cut off to stop the motor.

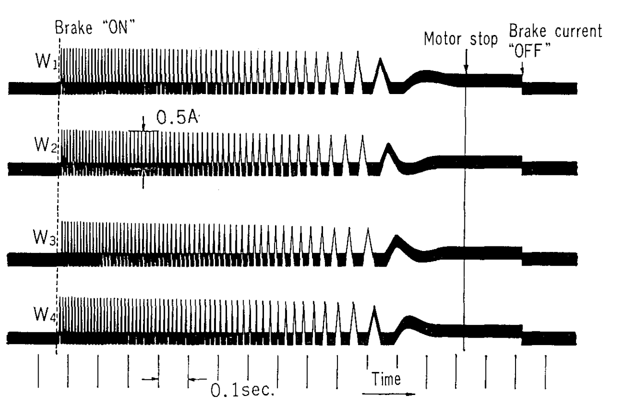


Fig. 20 **Braking current waveform**

3. Soft-Start Circuit

As illustrated in *Fig. 21*, a bootstrap circuit is arranged in parallel with a zener diode used for speed setting, and by increasing the speed reference voltage by degrees, soft-start can be accomplished.

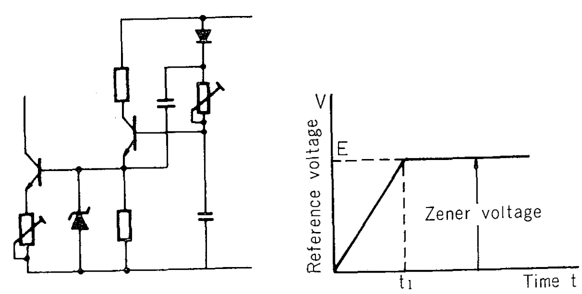


Fig. 21 **Fundamental circuit of soft-start operation**

4. Overspeed Protection Circuit

The speed reduction due to overload is detected by the counterelectromotive force of the motor or the voltage drop across the resistor common to the emitters shown in *Figs. 3* and *4* is detected to find the timing of cutting off the motor circuit. These methods are practically recognized.

VI. POSTSCRIPTS

We have described an outline of the electronic motor. With its excellent working reliability and controllability, the electronic motor will no doubt be used more and more wider fields for both civil and industrial purposes. In some specific fields, the electronic motor is said to be more economical than other drive systems. Although it leaves much to be desired at present, we do not care to say that the electronic motor will not become the most promising among the recent inventions if semiconductor technology and IC technology progress to refine the elements to be incorporated in the electronic motor.

References

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