

- [54] **THREE PHASE BRUSHLESS DC MOTOR**
- [75] Inventors: **Harold V. Clark**, Palo Alto; **Peter Skalon**, Redwood City; **Lawrence D. Emmons**, Grass Valley, all of Calif.
- [73] Assignee: **Ampex Corporation**, Redwood City, Calif.
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FOREIGN PATENTS OR APPLICATIONS

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Primary Examiner—James R. Scott
Assistant Examiner—John J. Feldhaus

- [52] U.S. Cl. **318/254; 318/138; 318/313**
- [51] Int. Cl.² **H02P 5/06; H02K 29/02**
- [58] Field of Search **318/138, 254, 313**

[56] References Cited

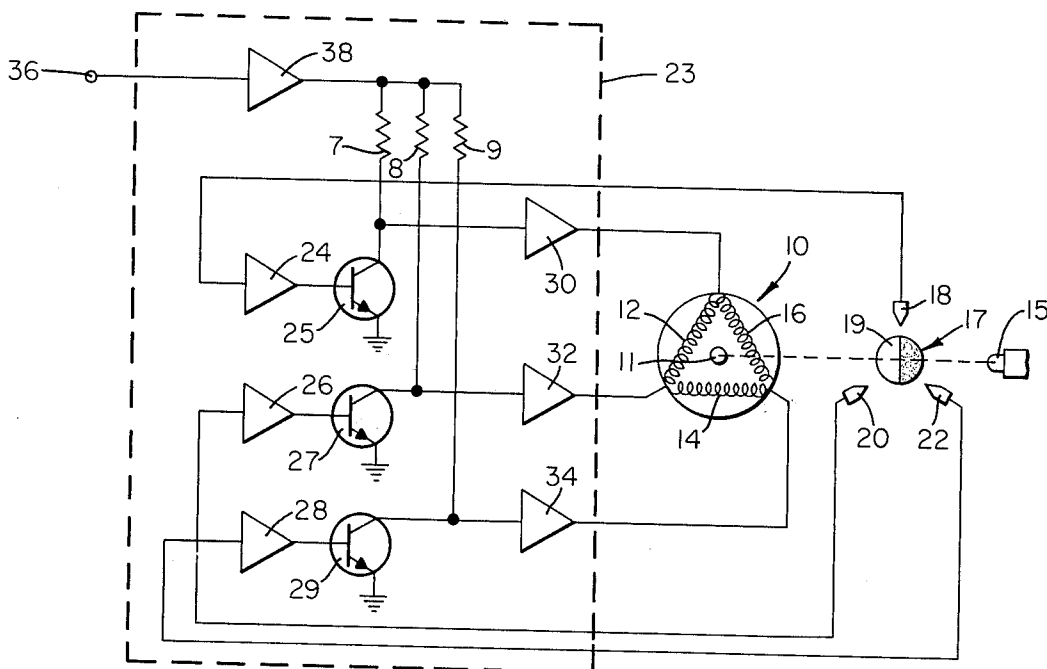
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[57] ABSTRACT

A three phase brushless DC motor incorporates a stationary armature having three symmetrically positioned sets of windings, a two pole permanent magnet rotor having photoelectric self commutation means for producing three switching signals, and square wave generation circuitry which produces a three phase square wave e.m.f. in response to said switching signals to energize the windings.

4 Claims, 9 Drawing Figures



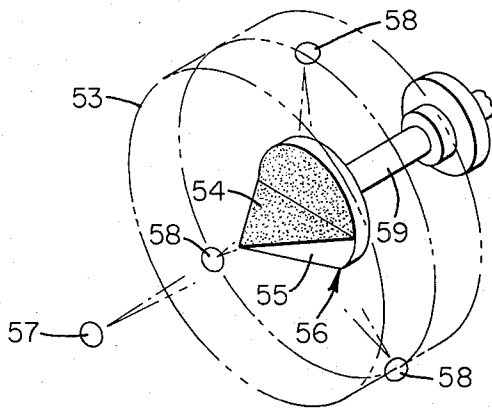


FIG. 3A

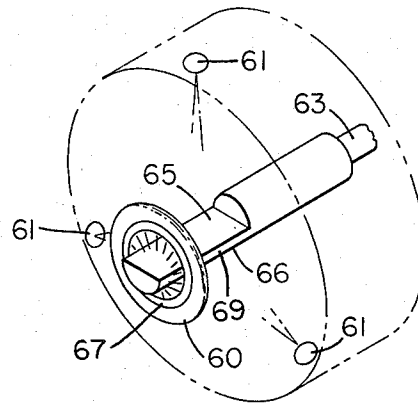


FIG. 3B

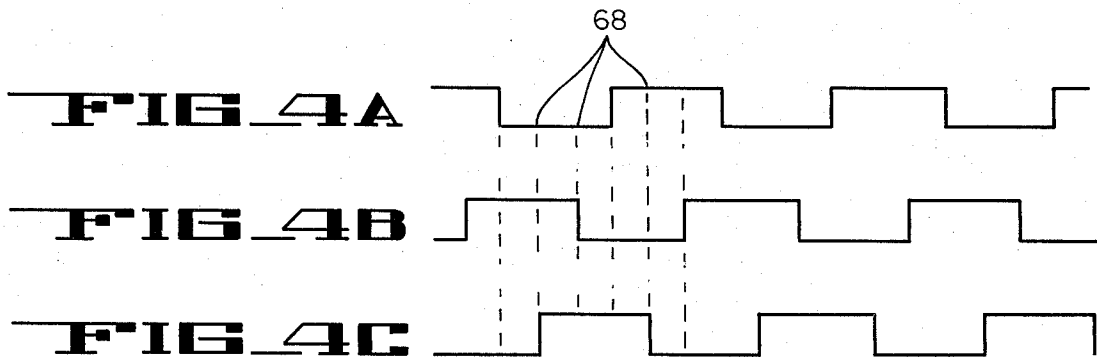


FIG. 4A

FIG. 4B

FIG. 4C

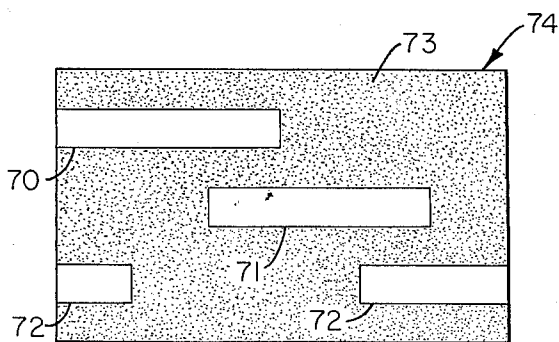


FIG. 5

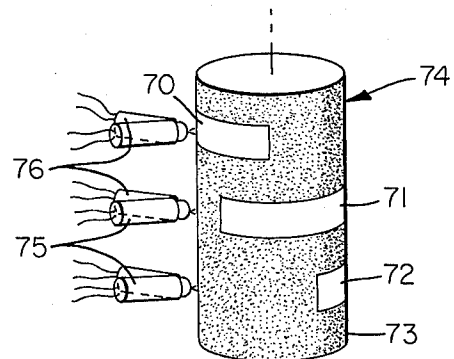


FIG. 6

THREE PHASE BRUSHLESS DC MOTOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a brushless DC motor, and more particularly, relates to a three phase brushless DC motor.

2. Description of the Prior Art

Direct current motors are often preferred for applications in which smooth, stable operation is required and in which it is desired to avoid AC ripple or complex current stabilization circuitry. Commutation, however, is required in order to selectively energize the windings; brushes which make electrical contact between the stator and rotor are typically used.

Self commutated (commonly called brushless) motors of various types have been developed to avoid the problems of rapid degradation and radio frequency interference which have been produced by the sparking of the commutator brushes. These brushless motors typically have incorporated self commutators such as Hall generators which are mounted on a stator so as to receive an indication of the instantaneous position of the rotor. This type of device is illustrated by the subject matter of U.S. Pat. No. 3,663,877 which was designed to be used in sensitive servo systems in which generation of mechanical jitter and radio frequency noise due to the action of the brushes is intolerable. The incorporation of Hall effect generators, however, has rendered the motors subject to erratic behavior due to temperature responsive zero drift; this problem is enhanced by the proximity of the generators to the motor which can become heated while operating. The generators also have been fragile and have required complex circuitry.

For precision servo operations, e.g. in a magnetic tape recorder of the type adapted for recording and reproducing wide-band signals by rotating a magnetic record/reproduce head assembly at high speeds to scan longitudinally moving magnetic tape, it is essential that the rotational velocity of the head be precisely controlled. For such applications it has been found that the employment of motors which utilize one or more pairs of coils with each pair operating as a discrete winding have not been wholly suitable. Brushless motors generally have incorporated these standard motor fabrication techniques. See Machine Design, 1970 Electric Motors Reference Issue, pp 17 et. seq.; see also Kreutzer, U.S. Pat. No. 3,204,165. The unsuitability of standard brushless motor fabrication techniques for precision servo applications stems from the need to use a switching type of driver producing square wave commutation in order to obtain efficiency. The apparently straightforward approach of using a linear or sinusoidal driver directly controlled by a self commutation means in fact introduces inefficiency as even the best amplifier operates with less than complete efficiency. A switching driver simply turns the current source on and off, in sequence, to the respective windings. Unfortunately, square wave driving currents possess odd harmonics when paired coil configurations are employed. These odd harmonics are undesirable since they produce ripple torque and heat in the armature windings. Consequently, in order to prevent distortion in precision servo applications, e.g. video applications, filters and heat sinks have to be employed to dissipate the odd

harmonics. Such add-on components add to the complexity of video recorder circuitry.

Three phase synchronous-hysteresis motors have been developed for precision applications; such motors, however, require sophisticated driving circuitry. Magnetically commutated three phase DC motors have been developed but inherently provide only tachometer information and do not identify which magnetic marker on the rotor is passing the pick-up sensor at any point in time; this ambiguity must be clarified by a once-around sensor. Such a commutation system also does not provide an indication of position when the motor is not operating; the absence of static positional information necessitates a separate start up oscillator circuit.

Accordingly it is an object of the present invention to provide a three phase brushless DC motor for smooth, stable operation which does not require a once-around sensor.

It is another object of the present invention to provide a three phase brushless DC motor which provides positional information when the motor is not running so that the motor may be started without a separate starter.

It is a further object of the present invention to provide a three phase brushless DC motor with a self commutation means which permits the position of the rotor to be determined within an arc of about 60°.

It is a still further object of the present invention to provide a three phase brushless DC motor having a photoelectric self commutation means.

SUMMARY OF THE INVENTION

A three phase brushless DC motor is provided with a cylindrical stationary armature having three symmetrically positioned sets of windings, each set of windings occupying 120° of the armature surface. A two pole permanent magnet rotor is positioned within the stationary armature and is provided with a self commutation means. The self commutation means produces three switching signals, the ON/OFF variations in the signals indicating the passage of a reference radius on the rotor by each of three equiangularly spaced reference points about said rotor. The three switching signals are introduced to square wave generation circuitry which produces a three phase square wave e.m.f. to energize the three sets of windings in sequence to produce the continuous operation of the motor.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more thorough understanding of the three phase brushless DC motor of the present invention reference may be had to the accompanying drawings which are incorporated herein by reference and in which:

FIG. 1 is a circuit schematic of the three phase brushless DC motor incorporating a photoelectric self commutation means;

FIG. 2 is a perspective view of the three phase brushless motor whose circuit schematic is shown in FIG. 1;

FIG. 3A is a pictorial illustration of a reflector means with a reflective side in the shape of a half cone in combination with a point light source and three symmetrically disposed photodetectors;

FIG. 3B is a pictorial illustration of a reflector means with a reflective side in the shape of an inclined plane in combination with a shielded circular light source and three symmetrically disposed photodetectors;

FIGS. 4A-4C are graphs of voltage versus time for the three phase square wave e.m.f. produced by the square wave generation circuitry of the present invention;

FIG. 5 is an exploded view of a self commutation cylinder illustrating three reflective strips on a nonreflective background; and

FIG. 6 is a perspective view of a self commutation cylinder illustrating three light source/photodetector pairs in registration with specific reflective strips.

DESCRIPTION OF THE PREFERRED EMBODIMENT

By reference to the schematic diagram of FIG. 1 it can be seen that the preferred embodiment of the brushless DC motor of the present invention employs a photoelectric self commutation means to produce the three-phase square wave e.m.f. shown in FIGS. 4A-4C which produce smooth, constant speed motor operation free from objectionable ripple torque and heating.

A reflector means 17 is mounted on the rotor shaft 11 so that it rotates in synchronization therewith. Reflector means 17 has a reflective side 19 and a nonreflective side 13. A light source 15 is positioned on or near the axis of rotation of rotor shaft 11 and reflector means 17. Light emitted by light source 15 is reflected off reflective side 19 of reflector means 17 and is received by photodetectors, e.g. phototransistors, 18, 20 or 22 as they fall within the arc of light reflected from reflective side 19 of reflector means 17. The photodetectors 18, 20 and 22 are positioned symmetrically 120° apart about rotor 11. Since reflective side 19 of reflector means 17 sweeps a 180° arc, each photodetector receives reflected light half the time and receives no light half the time. Each photodetector is exclusively lighted one-sixth of the time and lighted simultaneously with another photodetector one-third the time; similarly, each photodetector is exclusively darkened one-sixth the time and darkened simultaneously with another photodetector one-third the time. The outputs of the photodetectors 18, 20 and 22 are switching signals whose ON/OFF variations coincide with the passage of a part of the rotor, e.g. a reference radius, past six equiangularly spaced reference points around the rotor.

When each of the respective photodetectors 18, 20 and 22 is activated by light reflected from reflective side 19 of reflector means 17, their output is transmitted, respectively, to control amplifiers 24, 26 and 28 in square wave generation circuit 23. When an input is received by one of the control amplifiers the instantaneous output is introduced as an input to the bases, respectively, of transistors 25, 27 and 29. Thus, when a given photodetector is in the ON mode the associated transistor is rendered conductive so that the voltage received at the emitter is transmitted through the collector to ground; otherwise the control voltage from terminal 36, amplifier 38 and resistors 7, 8 or 9 will pass to gain amplifiers 30, 32 or 34, respectively. Consequently, the signal generated by a photodetector will determine whether or not a driving signal is received by one of the gain amplifiers.

The gain in amplifiers 30, 32 and 34 is set so that the input control voltage will produce a DC voltage of appropriate magnitude to energize the three sets of windings in motor 10. An alternative square wave generation circuit employs the well known slicing technique wherein selected sections of the ON/OFF variations in the switching signals are amplified.

In the preferred embodiment of FIG. 1 a delta configuration for the armature windings is shown; a standard Y configuration, although requiring greater voltage, could also be employed. The character of the three current phases in the embodiment of FIG. 1 is clearly shown in FIGS. 4A-4C. The physical generation and application of the three phases can be visualized in conjunction with the partial broken-away view of FIG. 2 which illustrates a sequence of discrete windings 49 positioned in slots defined by ridges 48 which are configured in the peripheral surface of the stationary armature 50. The active permanently magnetized portion of rotor 51 corresponds to the length of windings 49 on armature 50; nonmagnetized segments of rotor 51 form an air bearing with the inner surface of ends 47 of armature 50. The windings 49 comprise three discrete sets of windings, each set occupying 120° of the circumference of the stationary armature and each set having the same number of windings. Since a delta configuration is employed each phase is connected to one of the triangular intersections. Thus, each winding is energized by the current differential between the adjacent phases. If a Y configuration were employed, as discussed above, each winding could be directly connected to one of the phases; here also each winding is energized by the current differential between adjacent phases. It is in this current differential and associated voltage that third harmonic cancellation occurs, as set out infra.

The manner in which the self commutation means produces the three switching signals may be further understood by reference to FIGS. 2, 3A, 3B, 5 and 6. Two pole permanent magnet rotor 51 has an axial extension on which the particular photoelectric self commutation means is mounted. The self commutation criteria is that three switching signals be produced which have ON/OFF variations which indicate the passage of a reference point on the rotor, e.g. a reference radius, past each of six angularly spaced reference points located about the rotor; in the preferred embodiment the points are equiangularly spaced. The six reference points provide information to the square wave generation circuitry so that a single cycle of the three phase e.m.f. may be generated. With such explicit positional information a once-around sensor need not be employed. Also, the position of the rotor is uniquely determined within 60° even when the motor is not operating so that the motor may be started without any special startup circuitry.

In FIG. 2 the self commutation means is shown as light source 41 positioned in assembly 52 slightly beyond the end of a reflector means (not shown) mounted on rotor 51. Photodetectors 42, 44 and 46 are positioned, 120° apart, in assembly 52 in a symmetrical manner about the end of rotor 51; the outputs from the photodetectors are taken at terminals 43 and communicated to square wave generation circuitry (not shown). The light transmission path of the embodiment of FIG. 2 is shown clearly in FIG. 3A to be from light source 57 to the reflective surface 55 of half-cone 56 mounted on rotor 59 and thence to one of the photodetectors 58 mounted on housing 53. Light from light source 57 incident on blackened surface 54 of cone 56 will not be reflected.

In another embodiment, illustrated in FIG. 3B, a cylinder 66 has an inclined planar surface 65 cut out on one side and oriented obliquely with respect to the axis of the cylinder 66. As a result of the oblique orienta-

tion, light from circular light source 67 which impinges on inclined planar surface 65 will be reflected to the photodetectors 61; any light incident on cylindrical surface 69 will be reflected directly back in the direction of the circular light source. Circular light source 67 is provided with a shield 60 so that light which is incident on either inclined surface 65 or cylindrical surface 69 will come only from a circular strip source and no spurious light will be received by photodetectors 61. The light reflected from inclined surface 65 will describe a rotating 180° arc. Thus, as with the self commutation of FIG. 3A, each photodetector receives reflected light half the time and receives no light half the time. The interconnection with the square wave generation circuitry is the same as described above.

An additional embodiment for the self commutation means is shown in FIGS. 5 and 6. A cylindrical reflector means 74 is attached axially to the end of the rotor. Three reflective strips 70, 71 and 72 are applied to the surface of reflector means 74 and are displaced in the axial direction from each other. Each strip describes a 180° arc on the surface of the cylinder and covers one-half of the cylinder circumference as shown in the expanded view of FIG. 5. For each reflective strip there is an associated pair of light sources 75 and photodetectors 76 positioned in registration so that light to the respective light source 75 will be reflected from the respective photodetector 76. Thus, since area 73 is non-reflective, each photodetector will be in the ON mode half the time as with the other commutators described above. If the strips are displaced with angular symmetry about cylindrical reflector means 74 and the paired light sources and photoreceptors are at the same angular position the three switching signals will have ON/OFF variations which indicate the passage of a reference rotor radius past six equiangularly spaced reference points about the rotor. The same switching signals can also be produced by various combinations of strip angular position and light source/photoreceptor location.

In addition to the typical advantages of the brushless motors set out in the background discussion above, it has been found that the three phase brushless DC motor of the present invention eliminates a significant portion of the ripple torque which is associated with the odd harmonics which necessarily are present when a switching type of square wave e.m.f. is employed. Specifically, the voltage and current sensed by any winding at any point in time will be a composite square wave produced by two of the three phases of FIG. 4. A Fourier analysis of this composite square wave indicates that the fundamental sine wave equivalent is present, all even harmonics are absent and the only odd harmonics present are the fifth, seventh, and other lesser orders; the third harmonic cancels. The absence of this third harmonic significantly reduces ripple torque and heating. The fifth harmonic causes negligible ripple torque and heating and lesser orders have not visible effect. For precision video applications the absence of significant ripple torque obviates the necessity of complex filtering schemes to produce smooth operation. Furthermore, there is less generation of heat so cooling is not necessary.

The generation of three switching signals by the self commutation means permits the position of the rotor to be located at any point in time within a particular angular range. If the ON/OFF variations in the switching signals are produced as described above, i.e. if each

switching action denotes the passage of a reference rotor radius past one of six equiangularly spaced reference points external to said rotor, the position of the rotor will be known at any time to be between two of the reference points. While the points need not be equiangularly spaced the achievement of complete cancellation for certain odd harmonics requires symmetry; slight variations only (on the order of less than 5°) could be tolerated. As recited above this positional information eliminates the need for a once-around sensor and a separate startup oscillator circuit.

While specific embodiments of the three phase brushless DC motor of the present invention have been set out herein, it is not intended that the descriptions should limit the scope of this invention; rather the present invention is intended to be limited solely by the scope and spirit of the appended claims.

What is claimed is:

1. A three phase brushless DC motor for precision servo applications, comprising,
 - a stationary armature having three sets of windings symmetrically positioned thereon;
 - a two pole permanent magnet rotor mounted for rotation relative to said armature;
 - photoelectric self commutation means including a square wave generation circuit connected to said sets of windings, half cone reflector means axially mounted to rotate with said rotor for reflecting light projected thereon by a source, a light source for projecting light on said half cone reflector means, three photodetectors connected to said circuit positioned symmetrically about said rotor so as to receive the reflected light, said reflector means and said photodetectors being relatively positioned and said reflector means having a 180° arc of reflection to produce signals in said sets of windings without odd harmonic distortion.
2. A three phase brushless DC motor according to claim 1 wherein:
 - said photodetectors comprise phototransistors;
 - and said light source comprises a light emitting diode.
3. A three phase brushless DC motor for precision servo applications, comprising,
 - a stationary armature having three sets of windings symmetrically positioned thereon;
 - a two pole permanent magnet rotor mounted for rotation relative to said armature;
 - photoelectric self commutation means including a square wave generation circuit connected to said sets of windings, reflector means comprising a planar surface inclined with respect to the axis of said rotor axially mounted to rotate with said rotor for reflecting light projected thereon by a source, a circular light source for projecting light on said planar surface reflector means, three photodetectors connected to said circuit positioned symmetrically about said rotor so as to receive the reflected light, a shield mounted about said circular light source to prevent spurious light from being received by said photodetectors, said reflector means and said photodetectors being relatively positioned and said reflector means having a 180° arc of reflection to produce signals in said sets of windings without odd harmonic distortion.
4. A three phase brushless DC motor for precision servo applications, comprising,
 - a stationary armature having three sets of windings symmetrically positioned thereon;

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a two pole permanent magnet rotor mounted for rotation relative to said armature;
photoelectric self commutation means including a square wave generation circuit connected to said sets of windings, reflector means comprising a cylindrical reflector mounted axially with respect to said rotor having three reflective strips displaced from one another in the axial direction each describing a 180° arc, three light sources respectively

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positioned adjacent said three reflector strips, three photodetectors positioned so as to receive, respectively, light reflected from each light source by its adjacent strip, said reflector strips, said light sources and said photodetectors being relatively positioned to produce signals in said sets of windings without odd harmonic distortion.

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