On the Brushless dc Motors

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Abstract

Incremental motion devices are becoming very important in various industrial applications from a sophisticated control system to driving a powerful work machine [1]. Among a variety of incremental motion devices brushless dc motors have gained the attention of many users and manufacturers as a possible replacement of conventional dc and other types of motors [2]. Therefore, in this paper an overview of brushless dc motors is presented.

Introduction

It is a well-known fact that a conventional, permanent-magnet, dc motor is an excellent motor to driving a system where the control of speed or torque is critical. Another important characteristic of a permanent-magnet dc motor is that the variation of speed is very small with torque. However, the disadvantages of a conventional dc motor are discouraging. Some of these disadvantages are, erosion of the commutator and/or brush surface which requires frequent replacement, brush and commutator heating due to $I_a^2R_{bc}$ losses, and electric arcs occurring between the brushes and commutator which may possibly lead to radiating emissions. Thus, the overall performance of a motor may suffer seriously because of these unfavorable circumstances. Therefore, there has been a desire to replace a conventional dc motor with a motor having similar performance characteristics but without brushes, commutator and slip rings.

With the development of power electronic devices it seemed to be feasible that the mechanical switching parts of a brush-type dc motor could be replaced by electronic switching. However, a simple translation of a brush-type motor designed to operate as a brushless type is impractical since the use of semiconductor devices will be very inefficient. Thus the problem has to be solved in a different way to achieve cost effective performance.

In essence, a brushless dc motor system is an electromechanical system that has the speed-torque characteristic of a conventional permanent-magnet dc motor.

Initially brushless dc motors were employed in servo applications. However, with the advancements in power semiconductor devices and permanent magnets [2], brushless dc motors have gained more importance in different areas such as, disc drives, pumps, laser systems, automotive systems, robotics, air-conditioning and ventilation systems, slow-speed, direct-drive applications where gear backlash is unacceptable, etc. Brushless dc motors can also be used in applications where traditionally induction motors have been employed.

A Brushless dc Motor System

In a brushless dc motor system, the design of the motor should be in such a way that the controller would require the least number of semiconductor switching devices [3]. Moreover, in order to avoid slip rings in the motor it is necessary to use permanent magnets to set up the magnetic field.

A brushless dc motor is very similar to a polyphase, permanent-magnet synchronous motor with no damper winding. It also differs from the conventional synchronous motor in a way that the current into the windings is electronically switched similar to a step motor. This switching is often referred to as commutation and serves a function similar to the commutation in a conventional dc motor. A brushless dc motor system contains the following elements:

A motor built with a permanent magnet rotor and a polyphase stator winding; permanent magnets in the rotor are responsible for setting up the magnetic field in the motor, whereas stator winding develops a revolving field in the air gap when the windings are switched in a certain pattern. The interaction between the two fields results in a torque development in the motor.

A position sensing system (a Hall-effect device or an optoelectronic system) senses the absolute position of the rotor so that based on that information electronic controller would switch windings on in the correct sequence and at the proper time.

A controller acquires information from the position sensors and processes it with the preprogrammed commands in order to make the motor operate for a given condition. The control circuits handle very low currents and switch the power semiconductor devices.

A set of semiconductor switching devices is used to switch the right stator winding on at the right time and in the right sequence based on the information received from the controller. The switching semiconductors are usually power transistors.

Motor Construction

Due to practical advantages armature of a brushless dc motor is the stationary member (stator) and is made by stacking thin-slotted, highly permeable steel laminations. Identical windings are placed into the stator slots and connected to form a balanced polyphase winding as shown in Figure 1. The rotating member, rotor, on the other hand is made of radially-magnetized permanent magnets as indicated in Figure 1. The rotor also carries the shaft and a hub assembly.

It can be easily seen that there are significant differences in winding and magnet locations between a brushless dc motor and a brush-type dc motor shown in Figure 2. As a consequence, the removal of heat produced in the armature winding is easier in a brushless dc motor since the thermal path to the outside of the motor is shorter than the conventional dc motor. Thus the thermal stability of a brushless dc motor is better than a conventional dc motor. In spite of the thermal advantages, there are, nevertheless, certain applications where a brushless dc motor has the configuration of a conventional dc motor. However, in such a configuration in contrast to a conventional dc motor, armature winding remains stationary and the permanent magnets rotate as shown in Figure 3. This construction results in a high rotor moment of inertia, and is especially useful in applications where high mechanical time constant is required. However, in such a configuration the thermal advantage is obviously compromised.

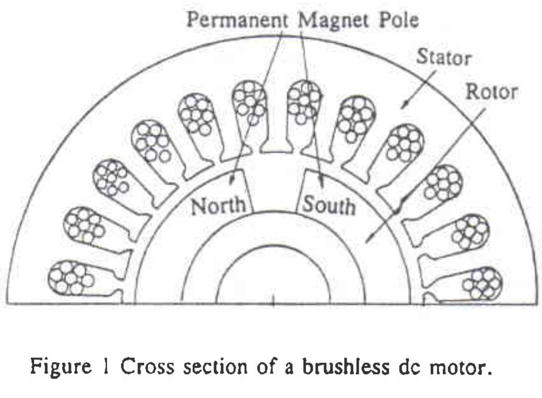

Figure 1 Cross section of a brushless dc motor.

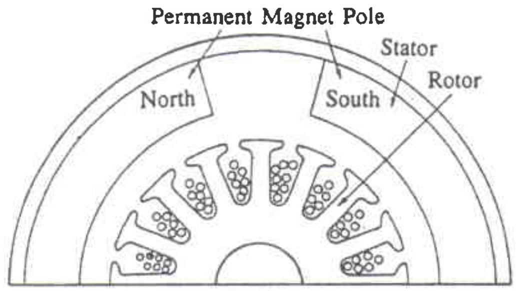

Figure 2 Cross section of a brush-type dc motor.

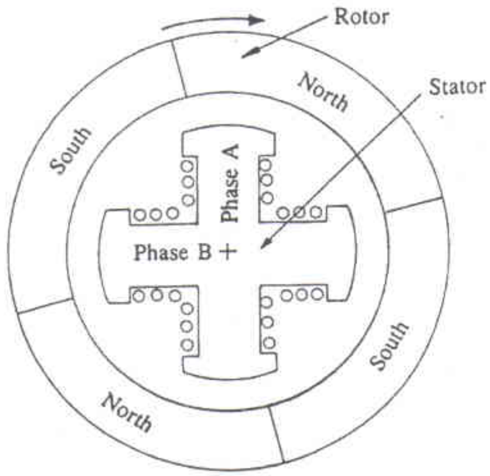

Figure 3 Cross section of a brushless dc motor with rotating permanent magnet poles.

Operating Principle

The principle of operation of a brushless dc motor is based on synchronizing the magnetic field produced by the stator winding with the magnetic field of the rotor. In relation to the rotor position, the stator windings are switched on and off so that the magnetic fields generated by the rotor and stator will be synchronized. The switching of the windings is done electronically by using power transistors to produce a rotating magnetic field in the air gap that stays at a fixed position with respect to the field produced by the rotor. The applied voltage to the electronic switching circuit may be direct or alternating voltage. However, the frequency of the voltage applied to the stator windings varies with the load leading the motor to operate always as a synchronous motor at that frequency. The torque developed by the motor increases with the armature current.

Winding and Switching Patterns

In a brushless dc motor, the winding configuration and its switching pattern are two critical issues and usually selected based on the performance and cost requirements of the overall system. Some of the winding configurations of brushless dc motors are, two- phase, three-phase, four-phase and six-phase windings with a unipolar or a bipolar switching pattern. However, the most widely used winding configurations are three-phase and two-phase with unipolar or bipolar switching. Thus the discussion is confined only to these configurations.

Three-phase, unipolar brushless dc motor

In three-phase, unipolar brushless dc motors phase currents are unipolar. In other words, currents do not reverse. A unipolar operation is primarily used due to economic reasons since the switching is simpler and the cost of the electronic system is lower.

The stator winding is Y-connected with its neutral point grounded as shown in Figure 4. When the switching takes place there is only one phase winding in the circuit, and the conduction occurs only during the positive part of the back electromotive force. With the unipolar operation, the motor is under-utilized for performance.

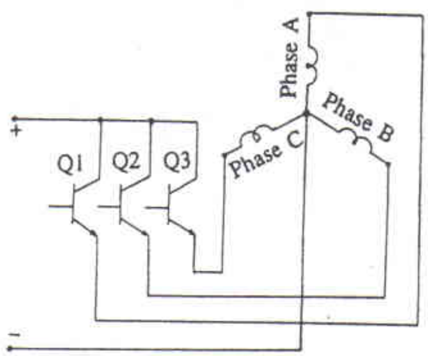

Figure 4 Circuit of a three-phase, unipolar brushless dc motor.

Three-phase, bipolar brushless dc motor

The stator windings are Y-connected and each winding is subjected to a dc voltage in a certain sequence as shown in Figure 5. Always two phases are energized and the currents reverse in each phase winding during one complete cycle. Because the conduction takes place during positive and negative half-cycles, the mode of operation in such a brushless dc motor is referred to as bipolar operation.

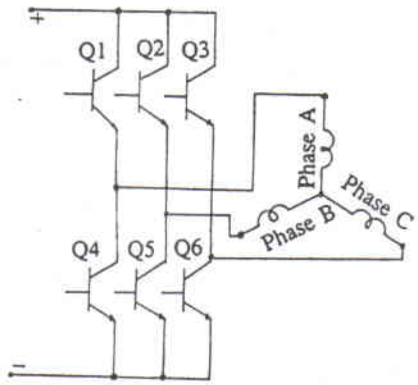

Figure 5 Circuit of a three-phase, bipolar brushless dc motor.

Two-phase, unipolar brushless dc motor

The main advantage of a two-phase system over a three-phase system is that the electronic switching requires less number of semiconductor devices as shown in Figure 6. During the conduction, only one phase winding is in the circuit. The conduction lasts 90° (electrical) in a two-phase brushless dc motor.

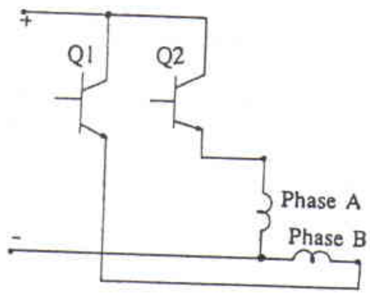

Figure 6 Circuit of a two-phase, unipolar brushless dc motor.

Armature Reaction

The interaction between the magnetic field developed by the stator current and the magnetic field set up by the permanent magnets may distort the developed torque in the motor. The amount of distortion is dependent upon the magnitude of the armature current and the magnetic properties of the steel lamination in the stator. Especially, if the magnetic steel of the stator saturates, a net loss of magnetic flux may take place in the motor leading to a drop in developed torque. The effect of armature reaction is the highest when the motor is under blocked-rotor condition. Above a certain current level, the armature magnetic field becomes so high that it may completely demagnetize the magnets of the motor. Thus, a special care should be given not to exceed the rated operating current of a brushless dc motor [4].

Minimizing the Armature Reaction

The armature reaction can be minimized to a certain degree by advancing or retarding the phase switching with respect to the rotor position just like adjusting the brush position in a conventional dc motor [4]. The switching of the semiconductors can be done accurately by a microprocessor that continuously monitors the armature current and determines the correct switching instant.

Effect of Winding Resistance and Inductance

For an effective semiconductor switching circuit, it is a common practice to keep the time constant and the inductance of the winding to a minimum. The electrical time constant is an indication to quantify as to how fast the current reaches to its maximum after the switching takes place. The electrical time constant is

$$\tau = L / R$$

where L and R are the inductance and resistance of the winding being energized, respectively.

As an example, consider a three-phase, four pole, bipolar, Y-connected brushless dc motor operating at a speed of 15,000 rpm. The question is whether the motor current will reach its maximum during the switching if the terminal resistance and inductance of the motor are 2.0 Ω and 1.0 mH.

Time constant: $\tau = 1.0\text{x}10^{-3} / 2.0 = 0.5$ ms

Duration for one revolution: 60/15000 = 4 ms

Duration per one degree of rotation:

$$4\text{x}10^{-3}/360^{\circ} = 1.11\text{x}10^{-5} \text{ s/deg}$$

On duration of semiconductors:

$$60^{\circ}\text{x}1.11\text{x}10^{-5}=0.67\text{x}10^{-3}\text{s}$$

Time-to-peak current:

$$5 \text{ x } 0.5 = 2.5 \text{ ms} > 0.67 \text{ ms}$$

Therefore, before the current reaches its maximum, switching takes place leading to a reduction in developed torque in the motor. If we insert a resistance of 8 Ω in series with the winding, the new time constant becomes

$$\tau = 1.0\text{x}10^{-3} / (2 + 8) = 0.1\text{x}10^{3} \text{ s}$$

and time-to-peak is

$$5 \text{ x } 0.1 = 0.5 \text{ ms} < 0.67 \text{ ms}$$

Hence, the current reaches the maximum value before the switching occurs. However, with this approach the overall efficiency of the system will be lower because of the power loss in the additional resistance.

On the other hand, the stored energy in the inductance of the winding causes a high-voltage problem during the switching. When the semiconductor device turns off, the device junction will immediately experience a voltage rise (almost twice the operating voltage) which may lead to a junction breakdown. In order to avoid such an event, a diode can be connected across the phase winding of a brushless dc motor. That way, the stored energy is well handled by the diode arrangement without damaging the switching transistor.

Operation With a Hall-Effect Sensor

Figure 7 illustrates the principle of operation of a brushless dc motor with a Hall-effect device being the rotor position sensor. When the Hall-effect device senses the ***North*** pole of the rotor, ***Winding 2*** is energized to produce ***South*** pole that leads to a counterclockwise displacement. Later, the Hall-effect device detects nothing, but the rotor continues to rotate due to its inertia. When the Hall-effect device senses the ***South*** pole of the rotor, ***Winding 1*** is energized to generate ***South*** pole so that the rotor continues to rotate in the counterclockwise direction. Thereafter, the operation repeats itself.

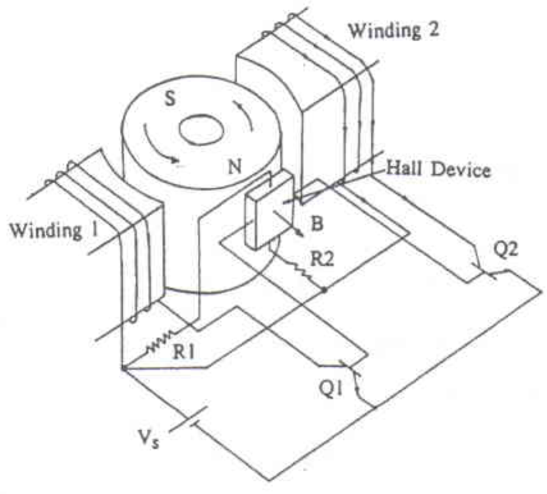

Figure 7 A brushless dc motor operating with Hall-effect device.

Modeling

Direct modeling of a brushless dc motor is quite complicated [3] due to its complex nature where the motor parameters are position dependent (time varying), and the governing equations are time-varying. However, by considering similarities of a conventional dc motor and a brushless dc motor, a simplified, linear, time-invariant model can be developed for practical applications. In the following, the electrical circuit of a brushless dc motor can be represented as

$$K\omega_m + R_a i_a + L_a \frac{di_a}{dt} = V_a \qquad (1)$$

where R_a is the resistance of a phase winding, L_a is the inductance of a phase winding, ω_m is the angular velocity of the motor shaft, i_a is the sum of phase currents K is the motor constant of a phase winding for a certain conduction period, and V_a is the supply voltage. The mechanical behavior of a brushless dc motor can be modelled as

$$T_L + D\omega_m + (J_m + J_L)\frac{d\omega_m}{dt} = Ki_a \qquad (2)$$

where, ω_m is the angular velocity of the shaft [rad/s], J_m is the moment of inertia of the rotating member of the motor [$kg.m^2$], $J_L$is the moment of inertia of the load [$kg.m^2$], D is the viscous friction coefficient [N.m.s], and T_L is the load torque [N.m]. Solving Equations (1) and (2) simultaneously yields the armature current and the angular velocity of the motor.

Conclusions

In this paper an overview of brushless dc motors is presented due to their rapid emerge into a wide variety of applications over the past decade. This is mainly because of the reduction of cost, advances in permanent magnets and electronic devices. In the future the decreasing trend of the cost of brushless dc motors will continue.

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