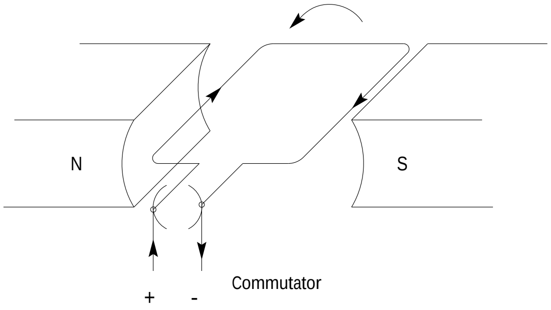
Brushless Motors

Before we talk about brushless motors in detail, let's clear up a few points about terminology. The term "brushless" has become accepted as referring to a particular variety of servo motor. Clearly a step motor is a brushless device, as is an AC induction motor (in fact, the step motor can form the basis of a brushless servo motor, often called a hybrid servo, which is discussed later). However, the so-called "brushless" motor has been designed to have a similar performance to the DC brush servo without the limitations imposed by a mechanical commutator.

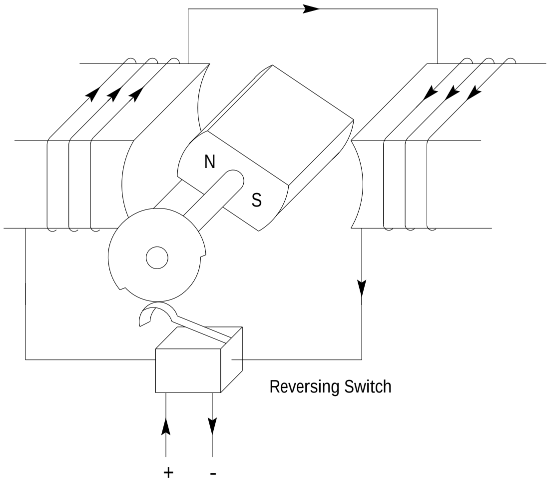
Within the brushless category are two basic motor types: trapezoidal and sine wave motors. The trapezoidal motor is really a brushless DC servo, whereas the sine wave motor bears a close resemblance to the AC synchronous motor. To fully explain the difference between these motors, we must review the evolution of the brushless motor.

Fig. 1.35 Conventional DC brush motor



A simple conventional DC brush motor (Fig. 1.35) consists of a wound rotor that can turn within a magnetic field provided by the stator. If the coil connections were made through slip rings, this motor would behave like a step motor (reversing the current in the rotor would cause it to flip through 180°). By including the commutator and brushes, the reversal of current is made automatically and the rotor continues to turn in the same direction.

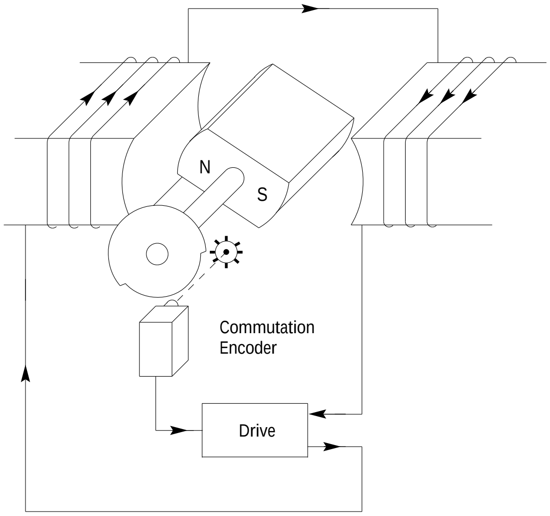
Fig. 1.36 "Inside out" DC motor



Brushless Motor Operation

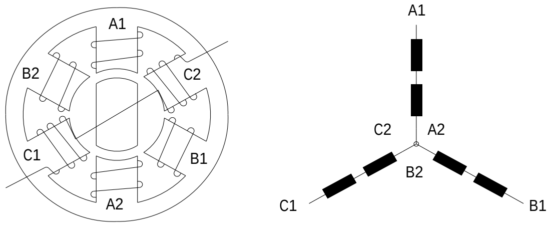
To turn this motor into a brushless design, we must start by eliminating the windings on the rotor. This can be achieved by turning the motor inside out. In other words, we make the permanent magnet the rotating part and put the windings on the stator poles. We still need some means of reversing the current automatically – a cam-operated reversing switch could be made to do this job (Fig. 1.36). Obviously such an arrangement with a mechanical switch is not very satisfactory, but the switching capability of non-contacting devices tends to be very limited. However, in a servo application, we will use an electronic amplifier or drive which can also be used to do the commutation in response to low-level signals from an optical or hall-effect sensor (see Fig. 1.37). This component is referred to as the commutation encoder. So unlike the DC brush motor, the brushless version cannot be driven by simply connecting it to a source of direct current. The current in the external circuit must be reversed at defined rotor positions. Hence, the motor is actually being driven by an alternating current.

Fig. 1.37 Brushless motor



Going back to the conventional brush motor, a rotor consisting of only one coil will exhibit a large torque variation as it rotates. In fact, the characteristic will be sinusoidal, with maximum torque produced when the rotor field is at right angles to the stator field and zero torque at the commutation point (see Fig. 1.38). A practical DC motor has a large number of coils on the rotor, each one connected not only to its own pair of commutator segments but to the other coils as well. In this way, the chief contribution to torque is made by a coil operating close to its peak-torque position. There is also an averaging effect produced by current flowing in all the other coils, so the resulting torque ripple is very small.

Fig. 1.38 3-phase brushless motor



We would like to reproduce a similar situation in the brushless motor; however, this would require a large number of coils distributed around the stator. This may be feasible, but each coil would require its own individual drive circuit. This is clearly prohibitive, so a compromise is made. A typical brushless motor has either two or three sets of coils or “phases” (see Fig. 1.38). The motor shown in Fig. 1.38 is a two-pole, three-phase design. The rotor usually has four or six rotor poles, with a corresponding increase in the number of stator poles. This doesn’t increase the number of phases—each phase has its turns distributed between several stator poles.

Fig. 1.39 Position-torque characteristic

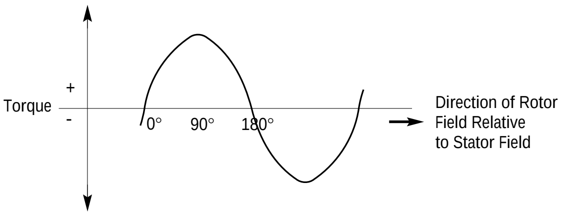
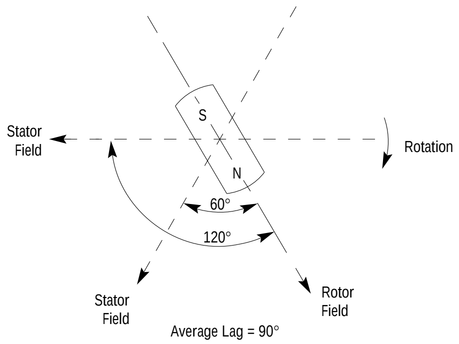
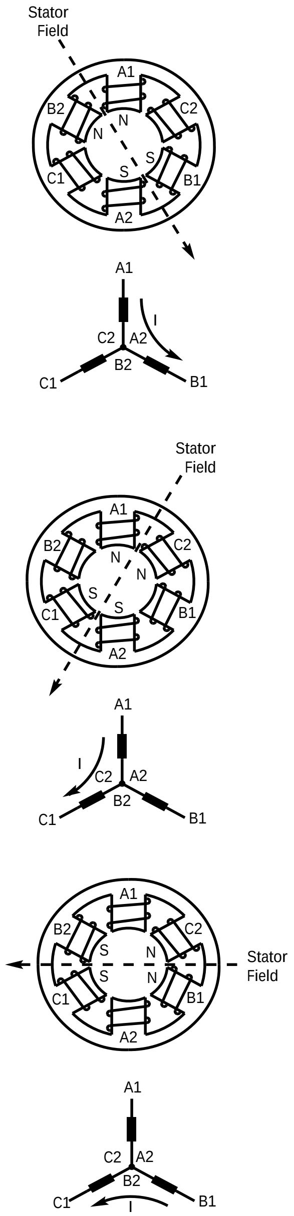


Fig. 1.40 Stator field positions for different phase currents



The torque characteristic in Fig. 1.39 indicates that maximum torque is produced when the rotor and stator fields are at 90° to each other. Therefore, to generate constant torque we would need to keep the stator field a constant 90° ahead of the rotor. Limiting the number of phases to three means that we can only advance the stator field in increments of 60° (Fig. 1.40). This means we must keep the stator field in the same place during 60° of shaft rotation. So we can’t maintain a constant 90° torque angle, but we can maintain an average of 90° by working between 60° and 120°. Fig. 1.41 shows the rotor position at a commutation point. When the torque angle has fallen to 60°, the stator field is advanced from 1 to 2 so that the angle now increases to 120°, and it stays here during the next 60° of rotation.

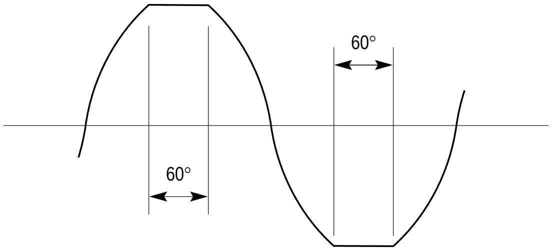
Fig. 1.41 Position of rotor at commutation point



The Trapezoidal Motor

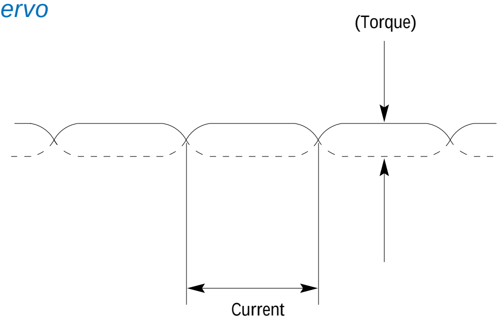
With a fixed current level in the windings, the use of this extended portion of the sinusoidal torque characteristic gives rise to a large degree of torque ripple. We can minimize the effect by manipulating the motor design to “flatten out” the characteristic – to make it trapezoidal, (Fig. 1.42). In practice, this is not very easy to do, so some degree of non-linearity will remain. The effect of this tends to be a slight “kick” at the commutation points, which can be noticeable when the motor is running very slowly.

Fig. 1.42 Trapezoidal motor characteristic



Torque ripple resulting from non-linearity in the torque characteristic tends to produce a velocity modulation in the load. However, in a system using velocity feedback the velocity loop will generally have a high gain. This means that a very small increase in velocity will generate a large error signal, reducing the torque demand to correct the velocity change. So in practice, the output current from the amplifier tends to mirror the torque characteristic (Fig. 1.43) so that the resulting velocity modulation is extremely small.

Fig. 1.43 Current profile in velocity-controlled servo



The Sine Wave Motor

In the sine wave motor (sometimes called an AC brushless servo), no attempt is made to modify the basic sinusoidal torque characteristic. Such a motor can be driven like an AC synchronous motor by applying sinusoidal currents to the motor windings. These currents must have the appropriate phase displacement, 120° in the case of the three-phase motor. We now need a much higher resolution device to control the commutation if we want smooth rotation at low speeds. The drive needs to generate 3 currents that are in the correct relationship to each other at every rotor position. So rather than the simple commutation encoder generating a handful of switching points, we now need a resolver or high-resolution optical encoder. In this way, it’s possible to maintain a 90° torque angle very accurately, resulting in very smooth low-speed rotation and negligible torque ripple. A simplified explanation of why the sine wave motor produces constant torque is given in the next section.

The drive for a sine wave motor is more complex than for the trapezoidal version. We need a reference table from which to generate the sinusoidal currents, and these must be multiplied by the torque demand signal to determine their absolute amplitude. With a star-connected three-phase motor, it is sufficient to determine the currents in two of the windings—this will automatically determine what happens in the third. As previously mentioned, the sine wave motor needs a high-resolution feedback device. However, this device can also provide position and velocity information for the controller.

Why constant torque from a sine wave motor?

To understand this, it’s easier to think in terms of a two-phase motor. This has just two sets of windings that are fed with sinusoidal currents at 90° to each other. If we represent shaft position by an angle θ, then the currents in the two windings are of the form $I\sin\theta$ and $I\cos\theta$.

Going back to our original motor model, you’ll remember that the fundamental torque characteristic of the motor is also sinusoidal. So for a given current I, the instantaneous torque value looks like:

$$T = I\,K_T \sin\theta$$

Where K_T is the motor torque constant

By making the motor current sinusoidal as well, and in phase with the motor torque characteristic, the torque generated by one phase becomes:

$$T_1 = (I\sin\theta)\,K_T \sin\theta$$
$$= I\,K_T \sin^2\theta$$

Similarly, the torque produced by the other phase is:

$$T_2 = I\,K_T \cos^2\theta$$

The total torque is:

$$T_1 + T_2 = I\,K_T (\sin^2\theta + \cos^2\theta)$$

but: $\sin^2\theta + \cos^2\theta = 1$ for any value of θ

therefore: $T_1 + T_2 = IK_T$

So for sinusoidal phase currents with a constant amplitude, the resultant torque is also constant and independent of shaft position.

For this condition to remain true, the drive currents must accurately follow a sine-cosine relationship. This can only occur with a sufficiently high resolution in the encoder or resolver used for commutation.

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