Getting to grips with brushless drives

The costs of permanent magnet brushless motor drives have dropped in recent years and they offer several advantages over brushed machines. Dr Sab Safi* outlines the technologies involved and how to use them.

Brushless permanent magnet (PM) motors offer a viable and competitive alternative to AC and DC motors in performance- and size-driven applications. In recent years, brushless PM motor technology has benefited significantly from the evolution of drive electronics and reductions in the costs of magnetic materials and semiconductors. These have led to dramatic drops in the price of brushless motors. Today, the cost differential between brushed and brushless motor technologies is only around 10 %.

A brushless PM motor drive consists of four basic sub-assemblies: the motor, an inverter, a controller and a position sensor. The components are connected together as shown in Fig. 1. The circuit topology and a cross-sectional view of a typical brushless PM motor are shown in Figs. 2 and 3.

A PM motor has three stator windings and permanent magnets on the rotor to produce the air gap magnetic field. The stator is essentially the same as an AC induction stator. The phase windings are connected either in Y or delta configurations, almost always three-phase. Fewer than three phases results in inefficient electromagnetic utilisation of the machine, while more phases require additional power electronic devices for little gain.

> Two types

PM brushless drives are classified on the basis of the flux density distribution and the shape of current excitation. They are split generically into two types:

- those with sinusoidal back-emfs and current, known as PM sinewave machine drives (sometimes also called PM synchronous machine drives); and
- those with trapezoidal back-emfs and DC pulses of current, known as brushless DC (or BLDC) drives.

The former are based on fixed-frequency AC synchronous machine principles, and the latter on DC machine ideas. In practice, the two types of drive have much in common. A trapezoidal surface PM motor is the same as a sinusoidal PM motor except that the three-phase winding has a concentrated full-pitch distribution, instead of a sinusoidal distribution.

PM motors are classified broadly by the direction of the field flux. In axial-flux motors, the magnetisation of the permanent magnets is oriented axially. In radial-flux motors, it is oriented radially.

Radial-flux PM motors can be categorised according to the way the magnets are mounted – either on the surface of the rotor, or inside it. Surface-mounted PM motors are used for low-speed applications. Buried or interior magnet topologies give added mechanical strength to the assembly, allowing higher operating speeds and, because of increased armature inductance, are amenable to flux weakening. Considerable saliency exists, leading to substantial saliency torque.

PM machines need position sensors to operate. The most common position detectors for brushless DC motors are Hall Effect and optical sensors. A sinewave PM drive needs high-resolution measurement of the rotor position to orient the sinusoidal armature phase voltages correctly. Sinewave machines therefore need more sophisticated position detection.

> Inverters and control

Three-phase BLDC motors and PM synchronous motors (PMSMs) share a similar motor drive topology – called inverters, power stages, or amplifiers (see Fig. 2). Inverters use power switches to deliver power by converting a DC voltage to AC voltage of variable frequency and magnitude. The inverter switches must be chosen carefully. Common switching devices include power Mosfets, IGBTs and bipolar transistors. The choice of power switch depends largely on the requirements of the application, such as the voltage, peak current, PWM frequency, and the operating characteristics of the machine.

Commutation is the process of switching current in the phases of a motor to generate motion. The commutation method depends on the type of motor: trapezoidal brushless inverters are used for BLDC motors; and sinusoidal brushless inverters for PMSMs. In both cases, the effective value of the voltage is adjusted by the duty cycle of pulse width modulation (PWM) signals.

The relationship between the stator winding energising sequence, the commutation sequence for the BLDC motor and PMSM, and the position sensor signal states, is shown in Fig. 4.

In trapezoidal commutation (also known as six-step commutation), current is controlled through motor terminals one pair at a time, with the third motor terminal always being disconnected electrically from the source of power. Three Hall Effect devices provide digital signals which measure the rotor position within 60-degree sectors. As the motor turns, the current to the motor terminals is switched electrically (commutated) every 60 degrees of rotation. The phase voltages can only be zero or positive or negative.

In sinusoidal commutation, a continuous shaft sensor (commonly a resolver) is used to synthesize sinusoidal phase voltages and currents. In this scheme, the three motor windings are commutated with three currents that vary sinusoidally. By switching each transistor pair for each phase to control precisely the on and off times during each cycle of the fundamental output frequency, a truly sinusoidal current results due to the inductance of the motor windings.

Compared to sinusoidal drives, brushless DC drives need less sophisticated rotor positioning and less complex controls, and produce slightly higher torque per unit volume and, usually, higher torque ripple. For applications where low speeds are not critical, the trapezoidal technique may be an economic choice.

> Current controller

There are two main methods of current control: PWM and hysteresis current controllers. Today, most motors use PWM in which an analogue input voltage is converted into a variable duty-cycle drive signal. PWM is based on the principle of comparing a triangular carrier wave at the required switching frequency with the error of the controlled signal. The error signal comes from the sum of the reference signal and the negative of the motor current.

The comparison results in a voltage control signal that goes to the gates of the inverter to generate the desired output. Its control will respond according to the error. If the error command is greater than the triangle waveform, the inverter leg is held switched to the positive polarity (upper switch on). When the error command is less than the triangle waveform, the inverter leg is switched to the negative polarity (lower switch on). This will generate a PWM signal as shown in Fig. 5. The inverter leg is forced to switch at the frequency of the triangle wave and produces an output voltage proportional to the current error command.

> Sensorless operation

If position can be detected by monitoring signals in the motor windings, then the need for position sensing devices can be avoided (although extra signal processing is needed). Almost all such schemes are based on monitoring the variation of either motional emf or winding inductance with rotor position. The latter method is not applicable in machines where there is no rotor saliency, while the former cannot be operated at standstill where motional emfs are zero. Neither method is easy to implement, but the technology is now advanced enough for commercial sensorless drives to be entering the market, particularly in applications that do not need the motor to start and stop. D&C

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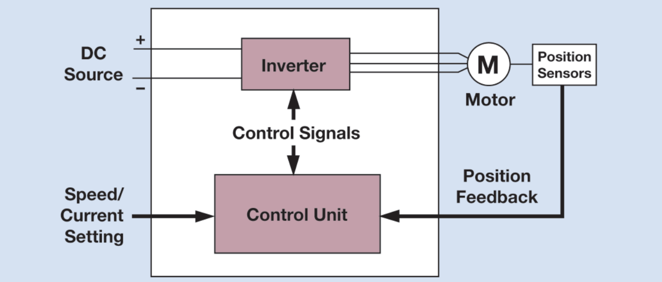

Fig. 1: The key elements in a brushless DC drive

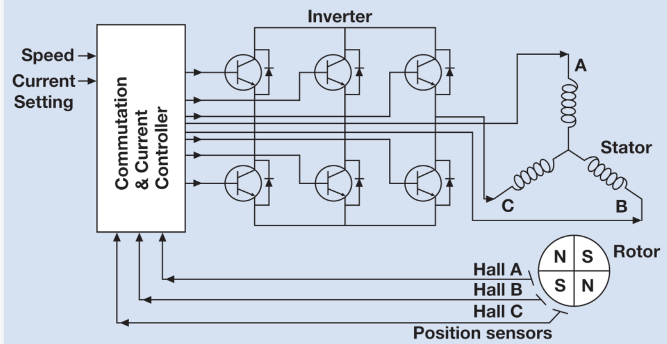

Fig. 2: A block diagram of a brushless PM machine

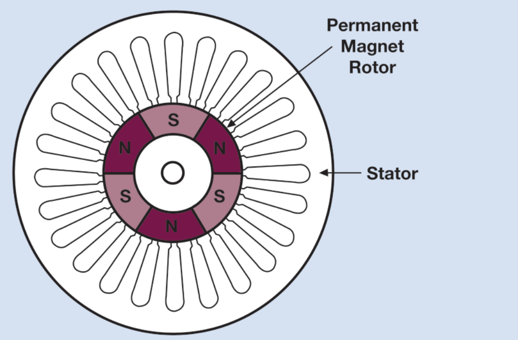

Fig. 3: A cross-sectional view showing the structure of a brushless DC motor

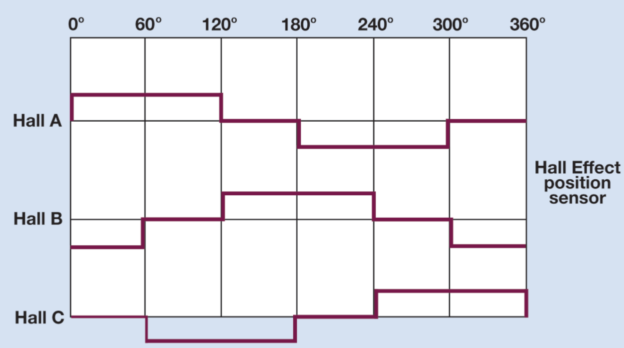

Fig. 4: Signals generated by the three Hall Effect sensors shown in Fig. 2

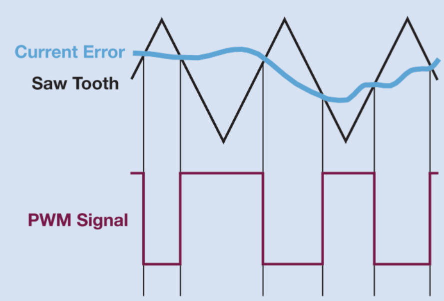

Fig. 5: The waveform produced by a PWM controller