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TND6041/D

DC Motor Driver Fundamentals

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TECHNICAL NOTE

INTRODUCTION

Electric motors have been with us since the early 19th century, when Hungarian physicist Ányos Jedlik produced the first continuously rotating DC motor, made possible by his invention of the commutator. By the early 20th century electric motors revolutionized industry and agriculture and made possible such labor saving consumer applications as washing machines and refrigerators. Today electric motors power everything from giant cruise ships to implantable medical devices.

There are many different types of motors, but they all contain three basic elements: an *armature*, a *field* magnet, and a *commutator*. The *armature* is a conductive coil that in most cases is attached to a rotating shaft and surrounded by a *field* magnet, which can be either a field winding or permanent magnets. Current passing through the armature creates a magnetic field that is opposed to the field current, resulting in an electromotive force (EMF) that causes the shaft to rotate, generating mechanical torque. The *commutator* is a set of contacts attached to the armature shaft that keeps reversing the direction of current flow in the armature as it turns, thus ensuring that the motor continues to turn.

While motors are mechanically rather simple, the terms that describe them can be confusing. In *mechanical terms* the rotating part of motor is called the **rotor**; the stationary part is the **stator**. In *electrical terms* the power producing part of the motor is called the **armature**; depending on the design the armature can be either the rotor or the stator. The **field** is a magnetic field component of the motor; again this can be either the rotor or the stator and it can be either an electromagnet or a permanent magnet. In general literature these terms are often used interchangeably, which can be confusing.

There are two basic types of DC motors: brushed and brushless, with subsets of each (Figure 1). We'll discuss each in turn.

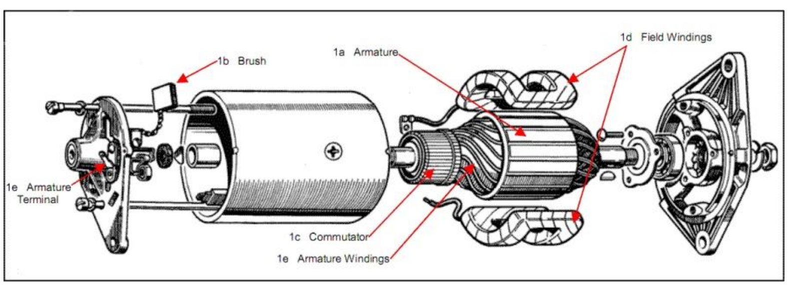

Figure 1. Motor Components

BRUSHED DC MOTORS

The brushed DC motor is the simplest and the earliest electrical motor design. While it has a number of disadvantages, is inexpensive and is still used widely for torque control and variable speed applications.

The brushed DC motor consists of a few simple components: stationary *stator* composed of field coils (wound field) or two hemispherical permanent magnets (PM); an internal rotating *armature* consisting of two or more coils connected to a segmented *commutator* which is contacted by brushes connected to the DC power supply (Figure 2).

DC power is conducted through the brushes and commutator, and the current through the coil creates a magnetic field. This field is opposite to the magnetic field of the permanent magnets in the stator, causing the armature to rotate. Mechanical commutation changes the direction of the current and a rotational motion is generated. With a two-pole motor the commutator causes the current to reverse in direction every half cycle, causing the motor to continue to rotate.

The speed of the motor is directly proportional to the voltage applied, while the torque is proportional to the current. You control the speed of a brushed DC motor by simply varying the voltage applied to it; to reverse it, just reverse the polarity of the applied voltage; and to stop it turn off the voltage.

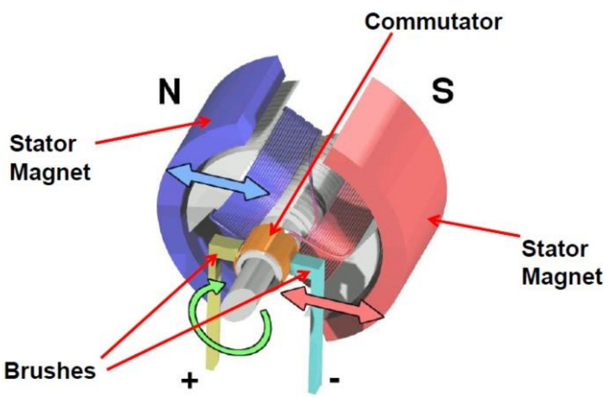

Figure 2. Brushed PM DC Motor

Brushed DC motors have some advantages over other designs:

- They are simple and inexpensive;
- They don't require complex drive electronics;
- Their speed is a direct, linear function of the armature voltage;
- Because of their simplicity and low cost − typically half the cost of brushless DC motors of the same size − design cycles are shortened.

However, they're not without some notable drawbacks:

- The brushes tend to wear out because of continuous friction. The brushes and springs need replacing from time to time;
- The commutator needs periodic cleaning or replacement;
- Arcing is ever present and causes EMI that can interfere with nearby electronics;
- The rotor's inertia may be an issue, and the commutator makes the motor larger than its brushless counterpart;
- Heat generated by coil rotation is always an issue.

The environment in which a brush DC motor is used can also greatly affect the lifetime of the motor. Dry, warm environments may increase the wear of the brushes and quicken the breakdown of the commutator and bearings. Running a brush DC motor in a cooler environment along with external cooling by forced air may cause the motor to perform better. However, extreme drops in temperature can potentially increase the viscosity of the lubricants, causing the motor to run at a higher current.

Wound-field Brushed DC Motors

There are two basic types of brushed DC motors: those whose stator consists of field coils and those that use permanent magnets in the stator instead. There are three types of wound-field coils (Figure 3):

- Shunt wound, in which the field coils are connected in parallel with the armature coils via the brushes (Figure 3A);
- Series wound, in which the field coils are in series with the coils in the armature (Figure 3B); and
- Hybrid, with separate field coils where one is in series and the other is in parallel with the armature coils (Figure 3C).

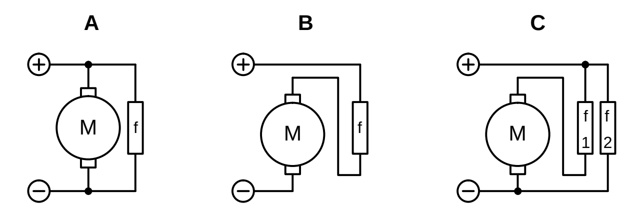

Figure 3. Field Coils: (A) Shunt, (B) Series, (C) Hybrid

Brushed PM DC Motors

Until the development of neodymium magnets brushed permanent magnet (PM) DC motors were only able to handle small loads. Today they are commonly used in fairly large commercial and industrial applications and are dominant in fractional-horsepower applications. In commercial use since 1886 they are still the most commonly used DC motors in the world.

Driving Brushed DC Motors

Driving brushed DC motors is straightforward in principle but not quite so simple in practice. For the simplest small applications you can run the motor directly from a power source and use a potentiometer to control the speed and a switch to reverse its direction. If the motor is to be part of an embedded application you need a driver IC and some control logic.

Figure 4 is a block diagram of ON Semiconductor's LB1938FA single-channel, forward/reverse brush motor driver IC that provides low-saturation outputs for use in low-voltage applications. The motor is driven by an H bridge that is protected by 'spark killer' diodes, since this is a brushed motor. The logic circuitry in the control block determines the speed and direction of the motor as dictated by the CPU. The LB1938FA provides forward, reverse, brake, and standby modes controlled by two input signals. It's designed for use in notebook computers, digital cameras, cell phones, and other portable equipment.

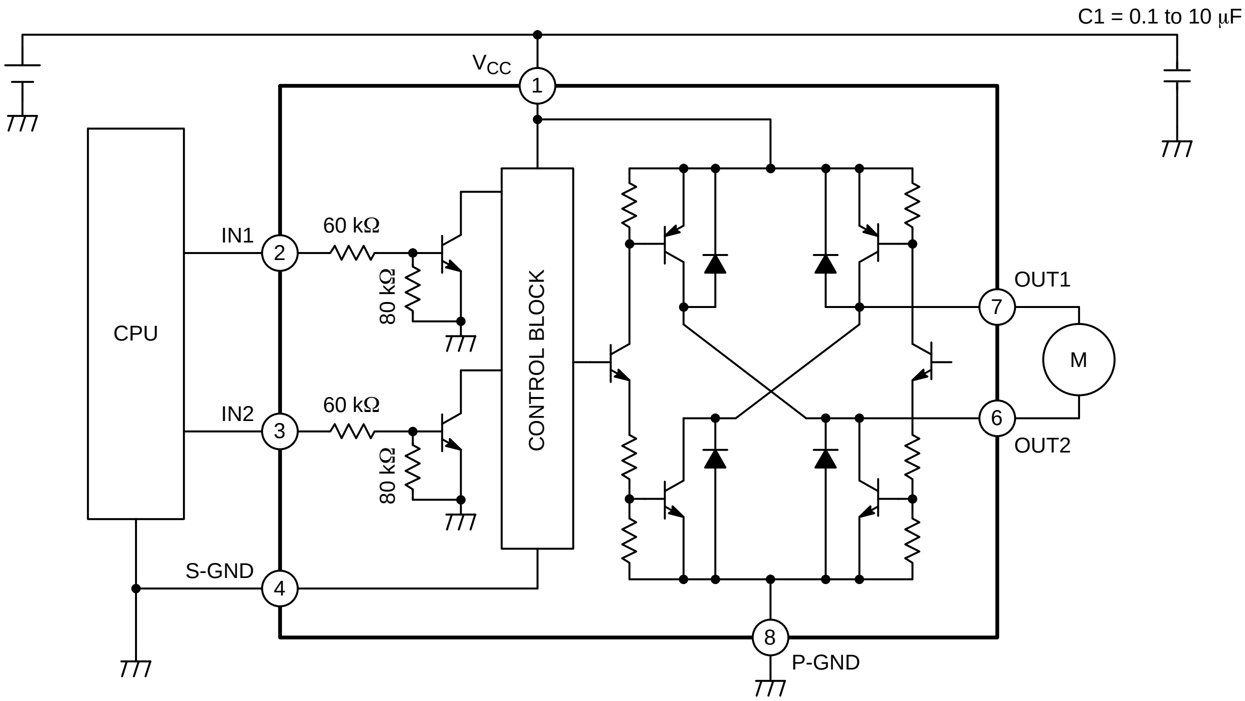

Figure 4. Motor Components

BRUSHLESS DC MOTORS

Where brushed DC motors have a very long history, BLDC motors only came into their own in the 1960s. BLDC motors are considerably more efficient than brushed DC motors; they last a lot longer; and they deliver more torque per weight.

By moving the permanent magnets to the rotor and driving the field coils with transistors you can eliminate the brushes in DC motors along with their disadvantages (inrunner configuration, the most common). Alternatively the armature coils can form a fixed core with the permanent magnets revolving around them and driving the motor shaft (outrunner). In either case the coils are stationary. BLDC motors are referred to as electronically commutative motors (ECMs) in contrast to mechanically commutative brushed motors.

BLDC motors need sophisticated electronic control circuitry as well as some way to continuously determine the position of the rotor. The position of the rotor can be determined either by a Hall effect sensor or by measuring changes in the back EMF (BEMF) at each of the armature coils as the motor rotates.

Whereas the speed of brushed DC motors is determined by the applied voltage, the speed of BLDC motors is determined by the frequency at which it is switched. The motors are driven by PWM pulses as shown in Figure 5.

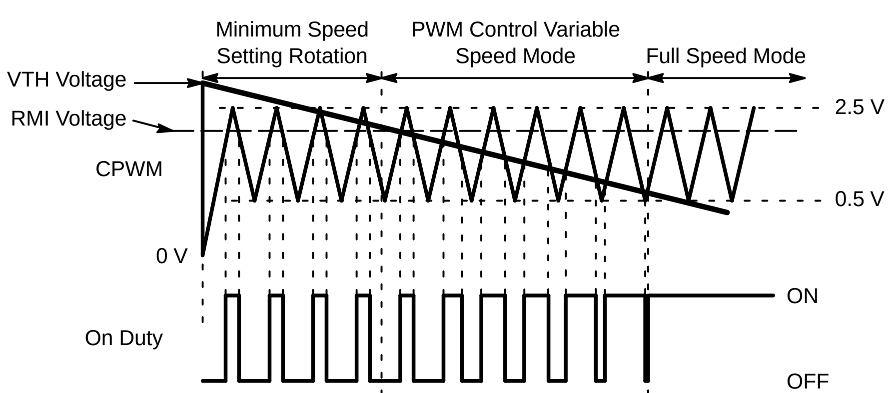

Figure 5. PWM Drive for a BLDC Motor

There are three basic types of BLDC motors: single-phase, 2-phase, and 3-phase. The operating principle in each case is the same. Instead of a mechanical commutator changing the magnetic polarity of the rotor coils, transistors continuously change the phase of the stator coils to keep the motor rotating. Single-phase BLDC motors are found in low-power applications; 2-phase motors are more often used in medium power ones. Three-phase BLDC motors are typically used to power disk drives and DVD players. Each type has different characteristics that best suits it to particular applications as shown in the Table 1.

Table 1. BLDC MOTOR CHARACTERISTICS

	Single-phase	2-phase	3-phase
Cost	Good	Excellen	Fair
Silent	Good	Fair	Excellent
Efficiency	Good	Fair	Excellent

Single-phase BLDC Motors

Single-phase BLDC motors consist of two parallel armature windings driven by an H bridge under PWM control. The output from a single Hall sensor continuously reverses the direction of the current flowing through the armature coil, keeping the motor rotating (Figure 6). Single-phase motors are simple to drive, requiring little more than a single chip such as the LB11970RV single-phase full-wave driver and a few capacitors.

2-phase BLDC Motors

Two-phase BLDC motors are slightly more complex. The armature now consists of four coils and the field contains four pairs of permanent magnets. The armature coils are paired, giving 2-phase motors more torque than their single-phase counterparts. Two-phase BLDC motors are typically used in low-end non-critical applications such large cooling fans, so they can dispense with sophisticated control circuitry in place of bipolar transistors and constant-voltage, constant-current drivers. As a result 2-phase BLDC motors are stronger and cheaper, if noisier and less efficient, than other BLDC architectures. The ON Semiconductor LB1868M is a good example of a 2-phase BLDC fan motor driver.

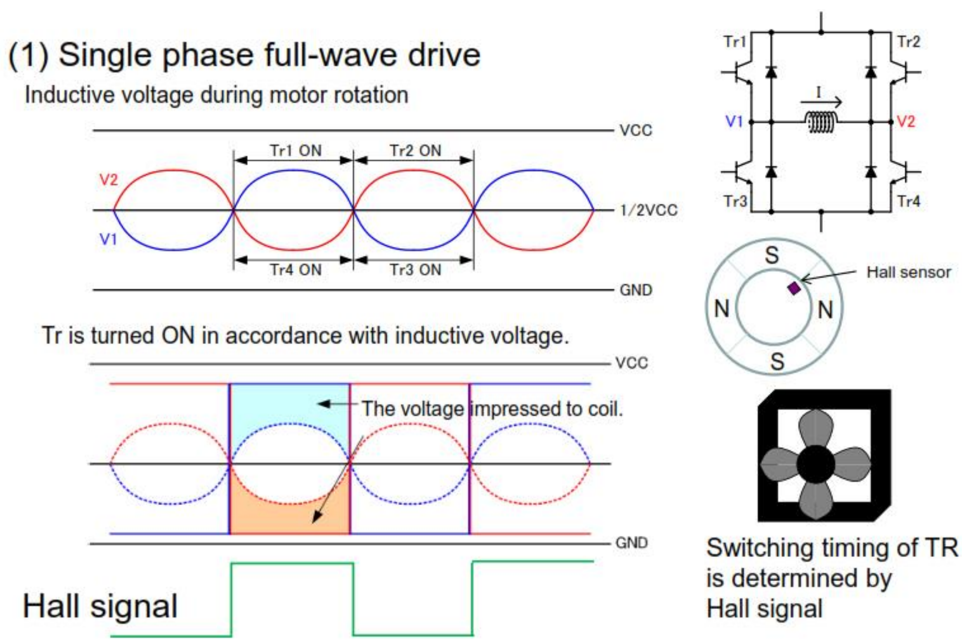

Figure 6. Single-phase BLDC Motor Control

3-phase BLDC Motors

With 3-phase BLDC motors there are six commutation states affecting three sets of armature coils. Three Hall sensors are typically placed on alternate stator coils that respond to the passage of the rotating permanent magnets on the rotor (Figure 7).

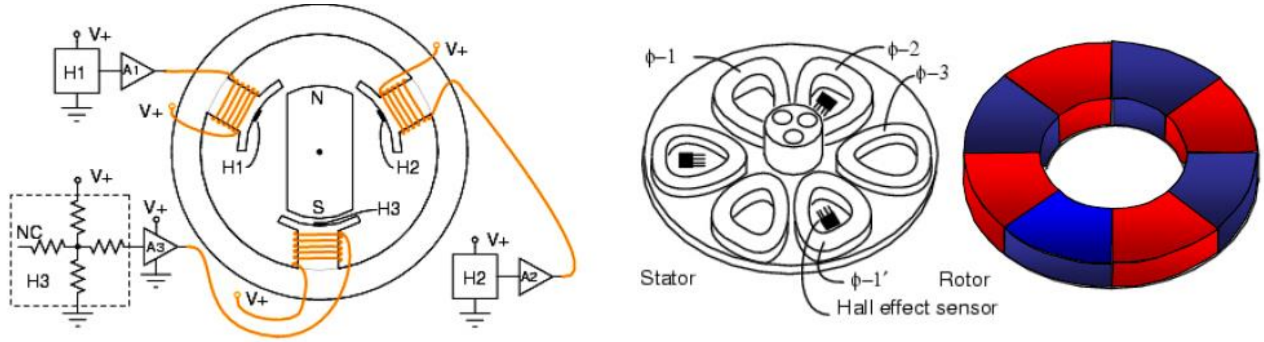

Figure 7. 3-phase BLDC Motor

Figure 8 shows how information from the Hall sensors is used to control the current going to the motor. The output from the Hall sensors drives logic circuitry that determines the switching timing; this is then passed through gate drivers to the power transistors that drive the motor. Since a 3-phase BLDC motor is pulsed more frequently than a single-phase motor, the motor displays less vibration and be controlled more precisely. ON Semiconductor's LB1976 is 3-phase brushless motor driver utilizing Hall sensors.

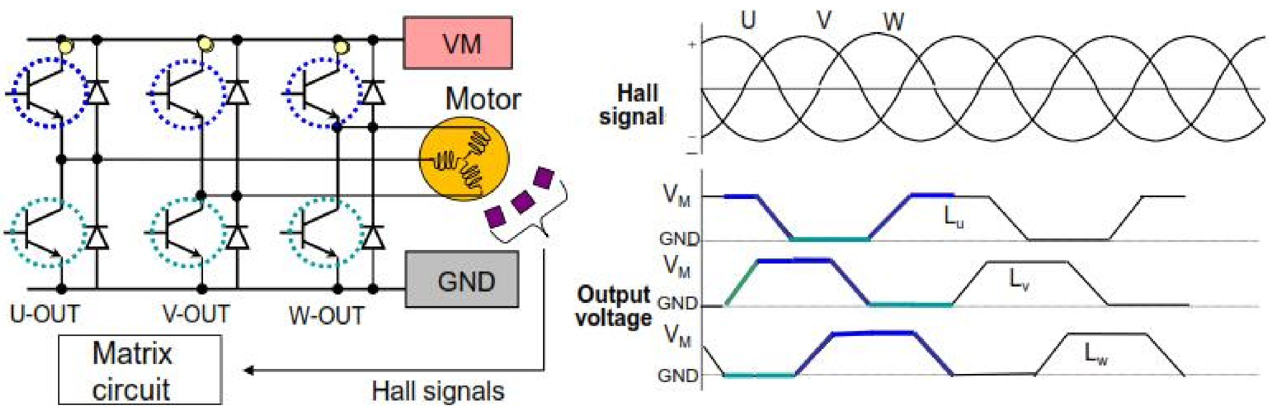

Figure 8. 3-phase BLDC Motor Drive with Hall Sensors

It is also possible to control a 3-phase BLDC motor without the use of sensors by determining the BEMF signal from each coil as shown in Figure 9. This is accomplished by comparing the motor's induction voltage with the midpoint of the voltage to each of the three coils. The results of this feedback is amplified, fed into a rotor position detection circuit, and each of the three sets of coils is then pulsed 120 degrees apart. Some controllers use simple comparators to determine the phase of each winding; others require the use of an external MCU. ON Semiconductor's LB11983 3-phase sensorless motor driver IC integrates rotor position detection with startup, timing, switching, thermal shutdown, and saturation control without the need for MCU control. For more complex circuits other drivers may outsource motor speed and acceleration to an MCU.

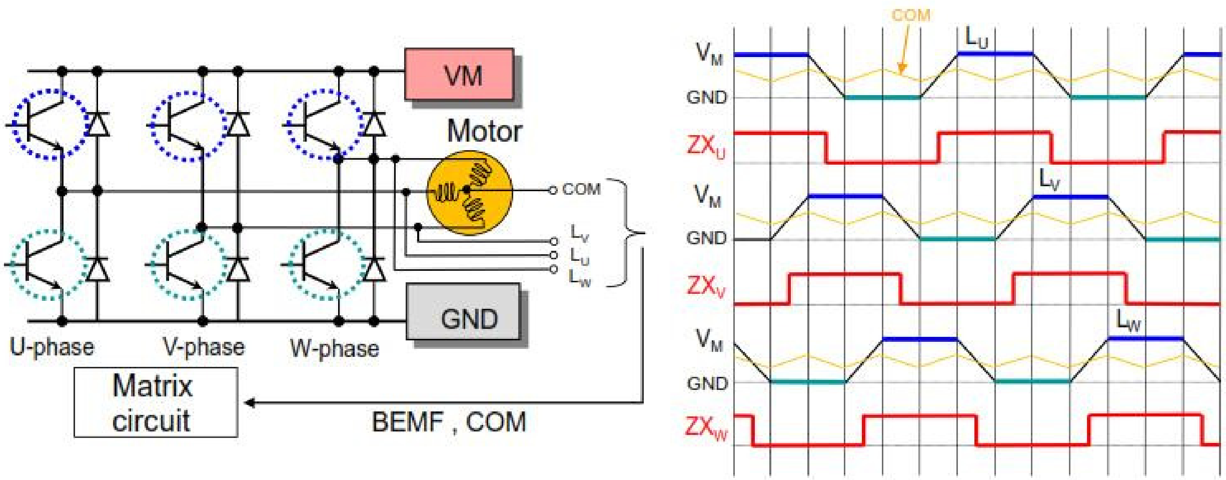

Figure 9. 3-phase Sensorless BLDC Motor Drive

BLDC circuits relying on BEMF to determine rotor position have a problem at startup when there is no BEMF. In this case they will typically start the motor from an unknown position and quickly get it operating in phase.

STEPPER MOTORS

Not all applications require the motor to rotate freely; *stepper motors* advance the rotor in finite increments and want the shaft to stay fixed until moved again. They have no brushes or contacts; they are synchronous DC motors with magnetic fields electronically switched to rotate the armature magnet around, converting digital pulses into mechanical shaft rotation. They are the mechanical equivalent of DACs, converting digital steps into analog angular displacement.

A stepper is a synchronous DC motor that divides a full rotation into a discrete number of steps; the number of steps or “phases” is equal to the number of electromagnets arranged around a central gear shaped core (Figure 10). By controlling the current to these magnets the motor can be turned by precise angle.

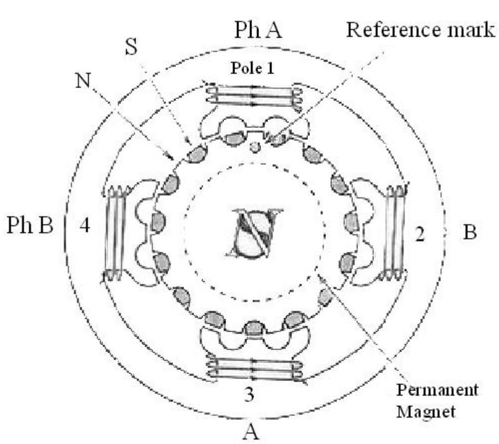

Figure 10. Hybrid Stepper Motor

There are three basic types of stepper motors: permanent magnet, variable reluctance, and hybrid.

- Permanent magnet stepper motors use permanent magnets for rotors and laminated steel stators. These are the lowest resolution steppers.
- Variable reluctance steppers offer high resolution but exhibit no detent torque; they are rarely used anymore.
- Hybrid steppers combine high-resolution of variable reluctance with the detent torque available and permanent magnet stepper motors. They might be considered the best of both worlds.

Two-phase stepper motors are the most commonly used configuration. They come with two types of windings − unifilar and bifilar:

- Unifilar steppers have two windings per phase. They’re difficult to drive because the coil current direction needs to be reversed; and one drawback is that only half the number of windings are energized at any time. Stepper motors with a unifilar winding have 4-5 lead wires.
- Bifilar steppers have one winding per phase. This gives them a size and weight advantage compared to unifilar motors since the amount of copper in the winding is roughly half the size. They are easy to drive because there is no need to change the current direction in the windings. This configuration simplifies transferring current from one coil to another. Stepper motors with a bifilar winding have 6-8 lead wires.

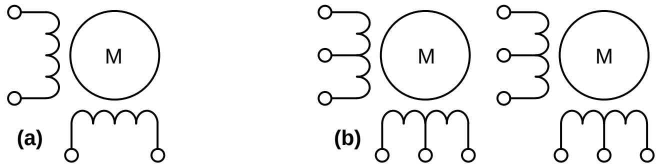

Figure 11. Unifilar (a) vs. Bifilar (b) Wings

Driving Stepper Motors

Stepper motors are typically driven by H bridges, one per winding, with the output being under PWM control. The rotation angle is proportional to the number of pulses, and the rotational speed is proportional to the frequency of the pulses.

Stepper motor applications are typically more stringent than those for continuously rotating motors, so tighter control is necessary. Stepper motors move from step to step by alternatively turning electromagnets on off in sync; this revolves the rotor around the stator tooth by tooth or step-by-step. By going full steps this can cause noise and vibration and possibly overshoot and skip steps (“step-out”), losing awareness of position. *Micro-stepping* addresses that issue, energizing the windings together in such a way that the rotor moves through several sub-positions or micro-steps for each step.

If an action such as quickly closing a valve requires the stepper motor to traverse numerous steps, then both *stall detection* and in *stop detection* become important. In this case *closed loop control* is highly desirable in contrast to open loop absolute positioning based on counting steps. Finally, *adaptive speed control* enables stepper motor to close the valve as quickly as possible despite the fact that the load may increase as it closes; this is made possible by sensing the increase in BEMF and increasing the frequency of the pulses to the motor accordingly.

The ON Semiconductor AMIS-30624 (Figure 12) is a single-chip micro-stepping motor driver that incorporates the features mentioned above. The position controller is configurable for different motor types, positioning ranges, and parameters for speed, acceleration, and deceleration. Integrated sensorless stall detection stops the motor when running into a stall; this enables silent yet accurate position calibrations during a referencing run and allows semi-closed loop operation when approaching mechanical and stops. Targeted for small positioning applications in the automotive, industrial, and building automation markets, the AMIS-30624 incorporates both high-voltage analog circuitry and digital functionality on the same chip.

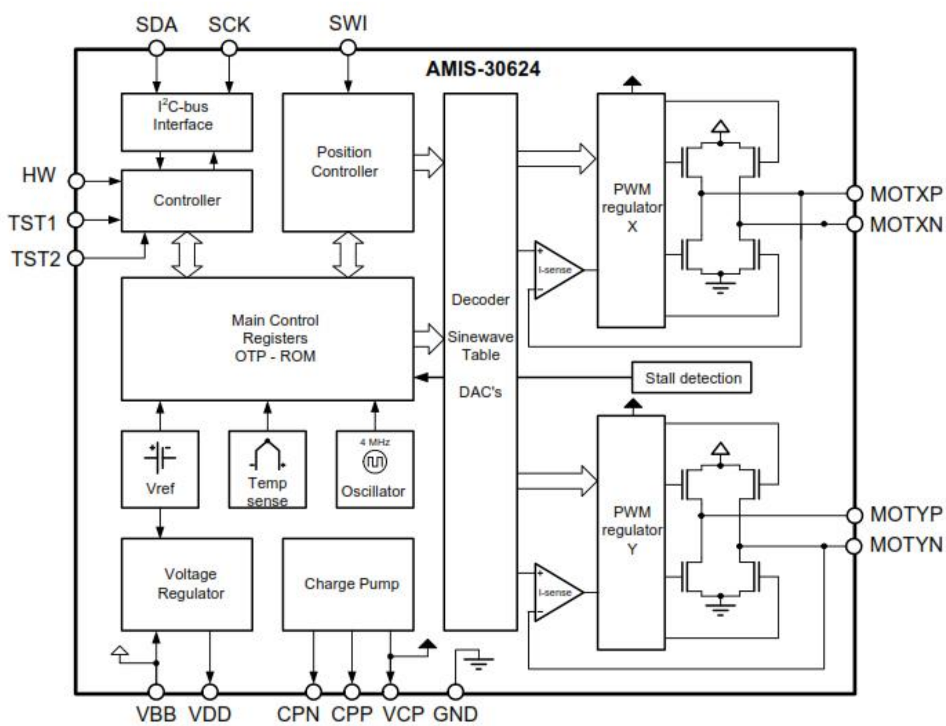

Figure 12. AMIS-30625-D Block Diagram

Advantages and Disadvantages

Like any other mechanical or electronic device stepper motors have both advantages and disadvantages. Among the advantages are:

- Position and speed are subject to open-loop control;
- They are easily controllable by a digital signal from an MCU;
- They are highly durable, without brushes or commutators.

On the other hand obtaining these advantages involves some trade-offs:

- If control is not optimized step-out may occur;
- Vibration and noise can be problematic;
- They're not as efficient as other BLDC motors.

The application will of course dictate whether or not a stepper motor is indicated; if so the proper choice of motor driver can alleviate or even effectively eliminate any potential problems.

SELECTING MOTOR DRIVERS

As with any other design choosing a motor driver is best done using a top-down approach. First ask yourself:

1. What is the intended application and purpose?
2. What is the most appropriate type of motor – single phase, 3-phase, 3-phase sensorless, stepper, DC brush, etc.?
3. What is the range of supply voltages?
4. What is the output or drive current?

Besides the range of supply voltage and output current you need to answer a few more questions before deciding on the appropriate type of motor for your intended application:

To select a brushed DC motor driver you need to determine:

1. First, find out whether speed control, or fixed forward/reverse drive is required. If yes, what is the method of speed control − by thermistor, voltage, or direct PWM?
2. What is motor driver power? Is it integrated or pre-drive type?
3. What are additional features −fault protection or current sense method?

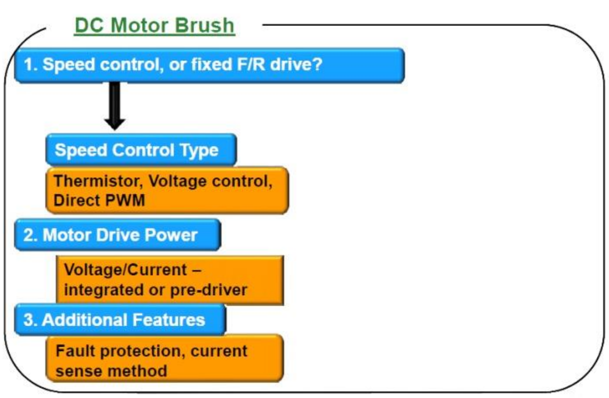

Figure 13. Selecting a Brushed Motor Driver

To select a BLDC motor driver you need to consider the following questions:

1. Is speed control by an external signal required? If yes, what is the method of speed control – by thermistor, voltage, or direct PWM?
2. What does the customer request for an output signal? The rotation detector (RD) signal is the error signal when the motor is locked. The frequency generator (FG) signal outputs the rotation count of a rotor.
3. What other functionality is requested – current limit control, Hall bias control, lock protection, etc.?

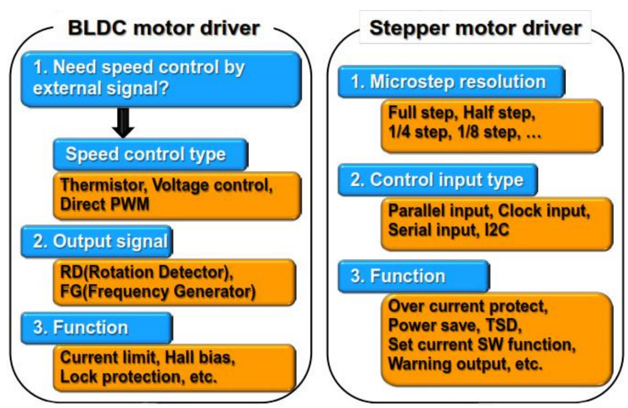

Figure 14. Selecting a BLDC or Stepper Motor Driver

To select a stepper motor driver you need to know:

1. What is the micro-step resolution – 1/2 step, 1/4 step, 1/8 step, etc.?
2. What is the control input type – parallel, clock, serial, I^2C, etc.?
3. What other functionality is requested – over-current protection, power saving, TSD, set current software function, warning output, etc.?

Once you've clarified your needs and outlined your parameters, you can do a parametric search for motor drivers on ON Semiconductor's website at www.onsemi.com, which features hundreds of motor drivers, at least one of which is likely to suit any given application.

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