**Freescale Semiconductor**
Application Note

AN1916
Rev. 2.0, 11/2005

# 3-Phase BLDC Motor Control with Hall Sensors Using 56800/E Digital Signal Controllers

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## Contents

## 1. Application Benefits

This document describes the design of a 3-phase BLDC (Brushless DC) motor drive based on Freescale's 56800/E dedicated motor control devices.

BLDC motors are very popular in a wide variety of applications. Compared with a DC motor, the BLDC motor uses an electric commutator rather than a mechanical commutator, so it is more reliable than the DC motor. In a BLDC motor, rotor magnets generate the rotor's magnetic flux, so BLDC motors achieve higher efficiency. Therefore, BLDC motors may be used in high-end white goods (refrigerators, washing machines, dishwashers, etc.), high-end pumps, fans and in other appliances which require high reliability and efficiency.

## 2. Target Motor Theory

A brushless DC (BLDC) motor is a rotating electric machine, where the stator is a classic 3-phase stator like that of an induction motor, and the rotor has surface-mounted permanent magnets; see **Figure 2-1**.

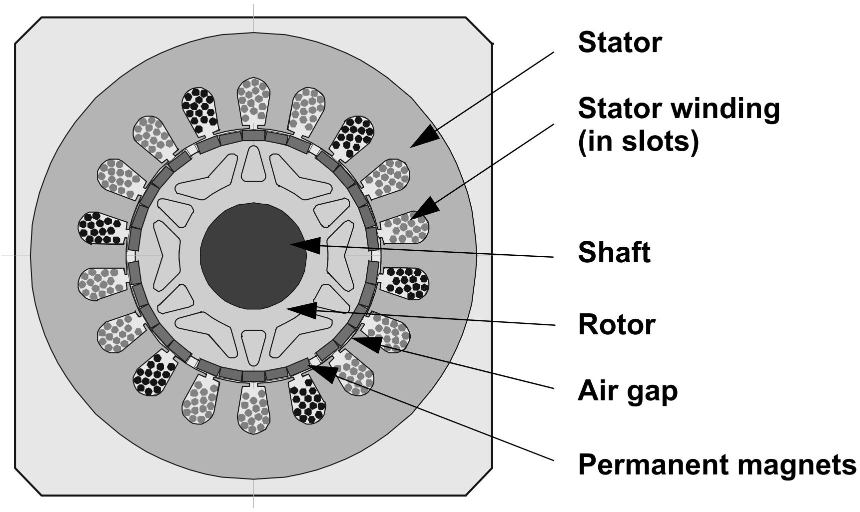

Figure 2-1. BLDC Motor - Cross Section

In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which the magnet rotates while the conductors remain stationary. In the DC commutator motor, the current polarity is altered by the commutator and brushes. However, in the brushless DC motor, polarity reversal is performed by power transistors switching in synchronization with the rotor position. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor position, or the position can be detected without sensors.

## 2.1 Digital Control of a BLDC Motor

The BLDC motor is driven by rectangular voltage strokes coupled with the given rotor position; see **Figure 2-2**. The generated stator flux interacts with the rotor flux, which is generated by a rotor magnet, defines the torque and thus the speed of the motor. The voltage strokes must be properly applied to the two phases of the 3-phase winding system so that the angle between the stator flux and the rotor flux is kept close to 90° for the maximum generated torque. This means the motor requires electronic control for proper operation.

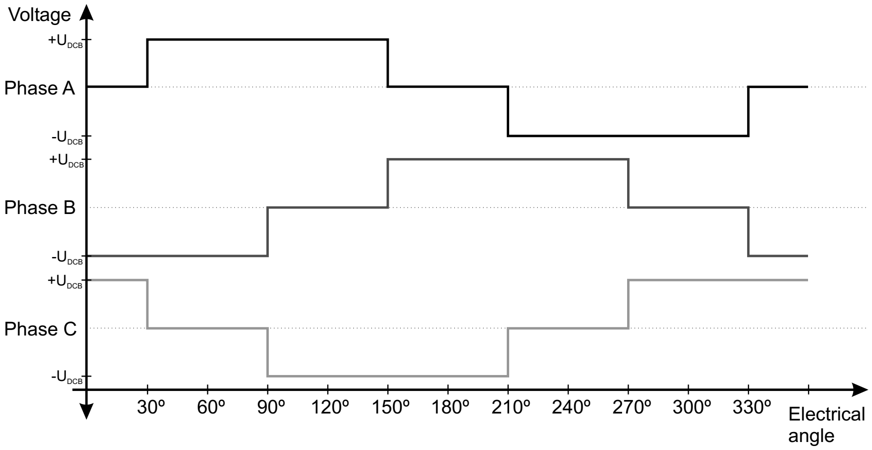

Figure 2-2. Voltage Strokes Applied To the 3-ph BLDC Motor

A standard 3-phase power stage is used for the common 3-phase BLDC motor, as illustrated in **Figure 2-3**. The power stage utilizes six power transistors with switching in either the independent mode or complementary mode.

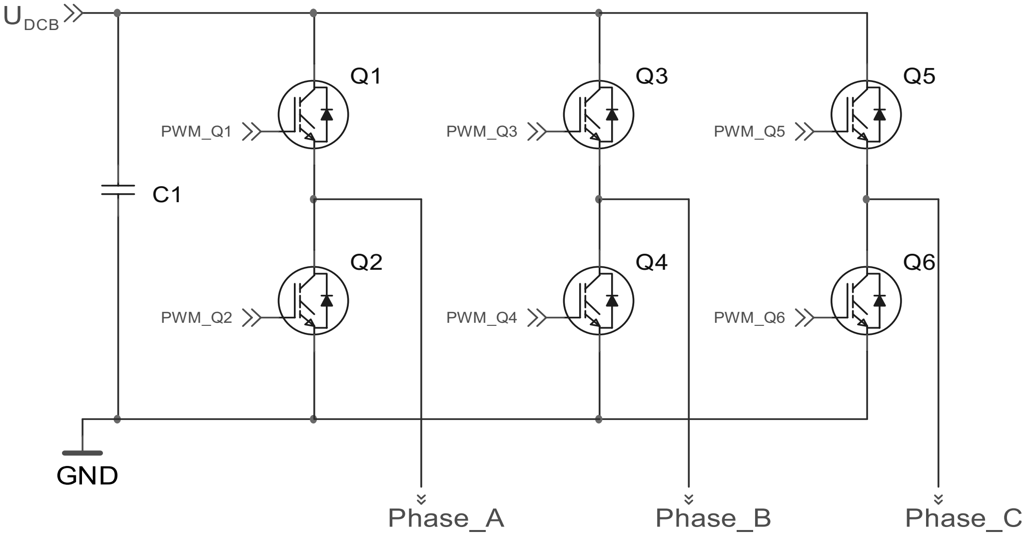

**Figure 2-3. 3-Phase BLDC Power Stage**

In both mode, the 3-phase power stage energizes two motor phases concurrently. The third phase is unpowered; see **Figure 2-2**. Thus, six possible voltage vectors are applied to the BLDC motor using a PWM technique; see **Figure 2-4** and **Figure 2-5**. There are two basic types of power transistor switching, independent switching and complementary switching, which are discussed in the following sections.

### 2.1.1 Independent Switching of Power Transistors

During independent switching, only two transistors are switched on when current is conducted from the power supply to the phase of the BLDC motor. In one phase, the top transistor is switched on; in the second phase, the bottom transistor is switched on and the third phase is not powered. During freewheeling, all transistors are switched off ; see **Figure 2-4**.

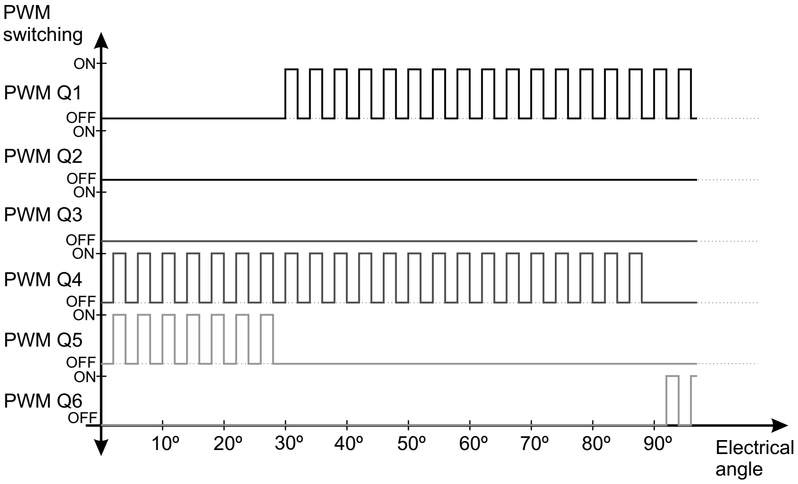

**Figure 2-4. Independent Switching of Power Transistors**

### 2.1.2 Complementary Switching of Power Transistors

During complementary switching, two transistors are switched on when the phase of the BLDC motor is connected to the power supply. One primary difference occurs during freewheeling. During independent switching, all transistors are switched off. The current continues to flow in the same direction through freewheeling diodes until it falls to zero. In complementary switching, the complementary transistors are switched on during freewheeling, so the current may be able to flow in the opposite direction. **Figure 2-5** depicts complementary switching.

**Notes:** Both the independent and complementary switching modes can work in bipolar or unipolar mode. **Figure 2-4** and **Figure 2-5** illustrate the bipolar switching mode. This application utilizes the complementary unipolar PWM mode.

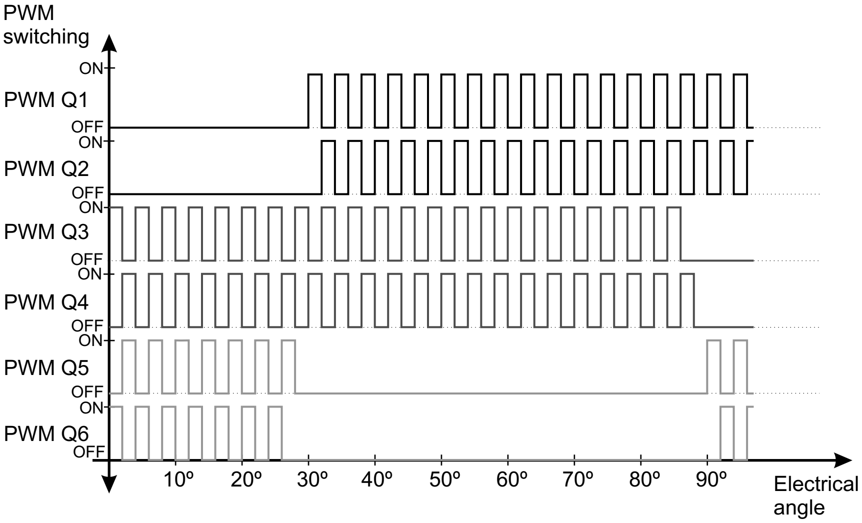

**Figure 2-5. Complementary Switching of Power Transistors**

### 2.1.3 Commutation

Commutation provides the creation of a rotation field. As previously explained, it is necessary to keep the angle between stator and rotor flux close to 90° for a BLDC motor to operate properly. Six-step control creates a total of six possible stator flux vectors. The stator flux vector must be changed at a certain rotor position. The rotor position is usually sensed by Hall sensors. The Hall sensors generate three signals that also comprise six states. Each of Hall sensors' states corresponds to a certain stator flux vector. All Hall sensor states with corresponding stator flux vectors are illustrated in **Figure 2-6**. The same information is detailed in **Table 2-1** and **Table 2-2**.

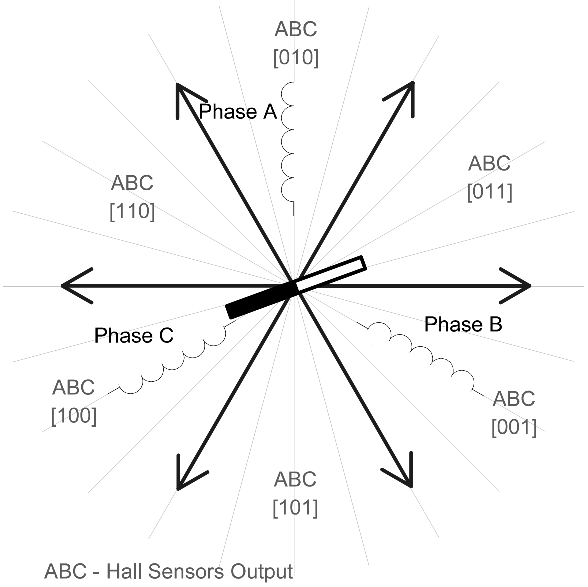

**Figure 2-6. Stator Flux Vectors at Six-Step Control**

The following two figures depict the commutation process. The actual rotor position in **Figure 2-7** corresponds to the Hall sensors' state ABC[110]; see **Figure 2-6**. The actual voltage pattern can be derived from **Table 2-1**. Phase A is connected to the positive DCBus voltage by the transistor Q1; Phase C is connected to the ground by transistor Q6; Phase B is unpowered.

As soon as the rotor reaches a certain position (see **Figure 2-7**), the Hall sensors' state changes its value from ABC[110] to ABC[100]. A new voltage pattern is selected from **Table 2-1** and applied to the BLDC motor.

As shown, when using a six-step control technique, it's impossible to keep the angle between the rotor flux and the stator flux precisely at 90°. The actual angle varies from 60° to 120°.

Commutation is repeated every 60° electrical. The commutation event is critical for its angular (time) accuracy. Any deviation causes torque ripples, leading to a variation in speed.

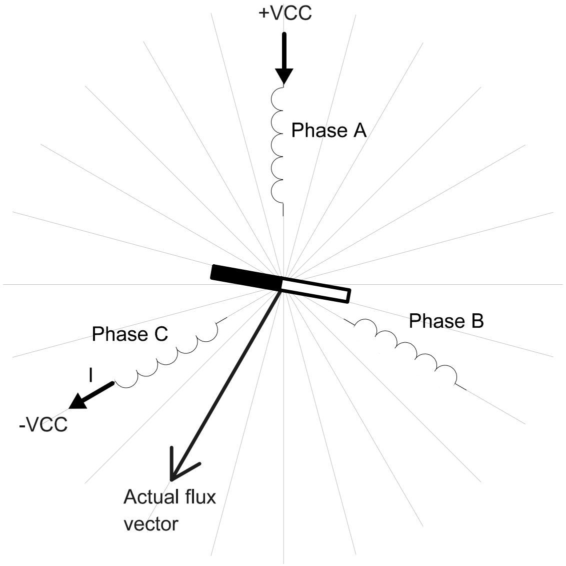

Figure 2-7. Situation Right Before Commutation

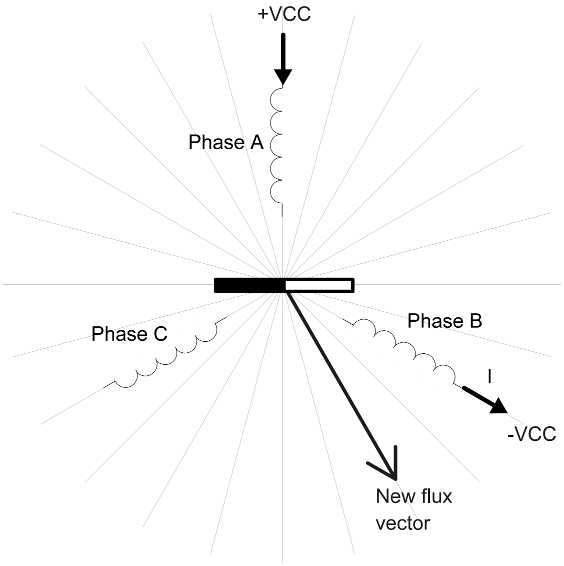

Figure 2-8. Situation Right After Commutation

### Table 2-1. Commutation Sequence for Clockwise Rotation

| Hall Sensor A | Hall Sensor B | Hall Sensor C | Phase A | Phase B | Phase C |
|---|---|---|---|---|---|
| 1 | 0 | 0 | $-V_{DCB}$ | $+V_{DCB}$ | NC |
| 1 | 0 | 1 | NC | $+V_{DCB}$ | $-V_{DCB}$ |
| 0 | 0 | 1 | $+V_{DCB}$ | NC | $-V_{DCB}$ |
| 0 | 1 | 1 | $+V_{DCB}$ | $-V_{DCB}$ | NC |
| 0 | 1 | 0 | NC | $-V_{DCB}$ | $+V_{DCB}$ |
| 1 | 1 | 0 | $-V_{DCB}$ | NC | $+V_{DCB}$ |

### Table 2-2. Commutation Sequence for Counterclockwise Rotation

| Hall Sensor A | Hall Sensor B | Hall Sensor C | Phase A | Phase B | Phase C |
|---|---|---|---|---|---|
| 1 | 0 | 0 | $+V_{DCB}$ | $-V_{DCB}$ | NC |
| 1 | 1 | 0 | $+V_{DCB}$ | NC | $-V_{DCB}$ |
| 0 | 1 | 0 | NC | $+V_{DCB}$ | $-V_{DCB}$ |
| 0 | 1 | 1 | $-V_{DCB}$ | $+V_{DCB}$ | NC |
| 0 | 0 | 1 | $-V_{DCB}$ | NC | $+V_{DCB}$ |
| 1 | 0 | 1 | NC | $-V_{DCB}$ | $+V_{DCB}$ |

### 2.1.4 Speed Control

Commutation ensures proper rotor rotation of the BLDC motor, while the motor speed depends only on the amplitude of the applied voltage. The amplitude of the applied voltage is adjusted by using the PWM technique. The required speed is controlled by a speed controller. The speed controller is implemented as a conventional PI controller. The difference between the actual and required speed is input to the PI controller and, based on this difference, the PI controller controls the duty cycle of PWM pulses, which corresponds to the voltage amplitude required to keep the required speed.

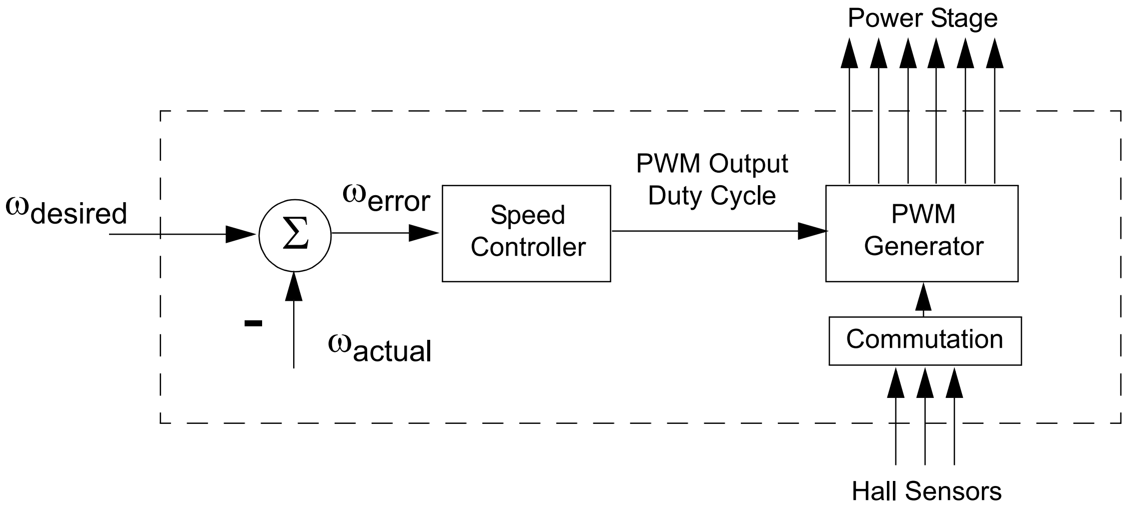

**Figure 2-9. Speed Controller**

The speed controller calculates a Proportional-Integral (PI) algorithm according to the following equations:

$$u(t) = K_c\left[e(t) + \frac{1}{T_I}\int_0^t e(\tau)d\tau\right] \qquad \text{(EQ 2-1.)}$$

Transformation to a discrete time domain using an integral approximation by a Backward Euler method yields the following equations for the numerical PI controller calculation:

$$u(k) = u_P(k) + u_I(k) \qquad \text{(EQ 2-2.)}$$

$$u_P(k) = K_c \cdot e(k) \qquad \text{(EQ 2-3.)}$$

$$u_I(k) = u_I(k-1) + K_c\frac{T}{T_I} \cdot e(k) \qquad \text{(EQ 2-4.)}$$

where:

$e(k)$ = Input error in step $k$

$w(k)$ = Desired value in step $k$

$m(k)$ = Measured value in step $k$

$u(k)$ = Controller output in step $k$

$u_p(k)$ = Proportional output portion in step $k$

$u_I(k)$ = Integral output portion in step $k$

$u_I(k-1)$ = Integral output portion in step $k-1$

$T_I$ = Integral time constant

$T$ = Sampling time

$K_c$ = Controller gain

### 2.1.5 Torque Control

For applications requiring the motor to operate with a specified torque regardless of speed (e.g., in-line tensioning), a current controller can be used, since torque is directly proportional to current. In this mode, the speed will be held at the value set by the speed reference signal for all loads up to the point where the full armature current is needed. If the load torque increases further, the speed will drop because the current-loop will not allow more armature current to flow. Conversely, if the load attempted to force the speed above the set value, the motor current will be reversed automaticaly, so that the motor acts as a brake and regenerates power to the mains. The current controller is implemented as a conventional Proportional-Integral (PI) controller. The output from the speed controller will be input into the current controller, along with measured DCBus current. The output of the current controller will control the duty cycle of the PWM pulses. The combination of both speed and torue controllers is shown in **Figure 2-10**.

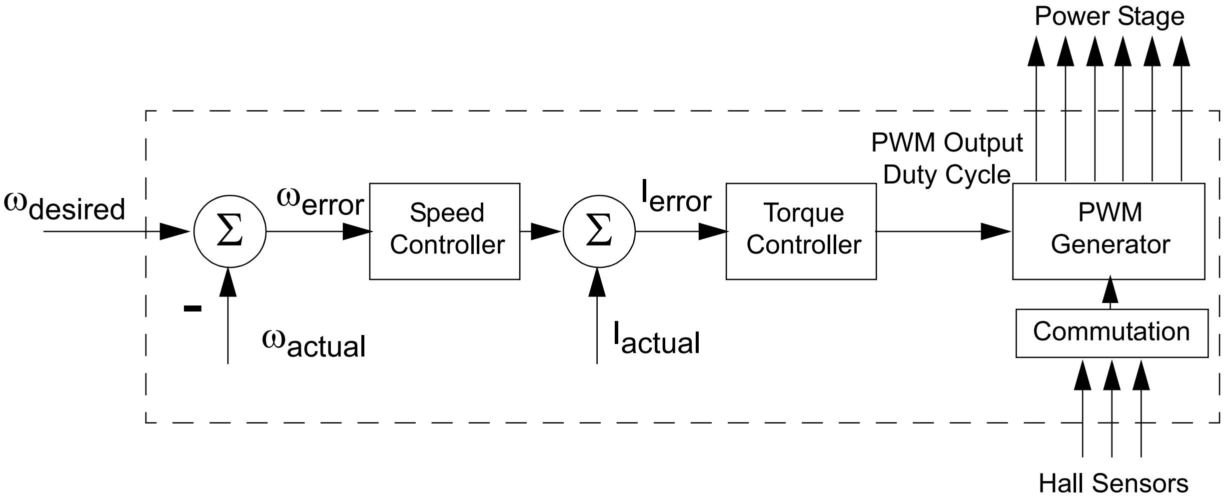

**Figure 2-10. Combination of Speed and Torque Controllers**

## 3. Targeting 56800/E Digital Signal Controllers

Freescale's 56800/E Controllers are well suited for BLDC motor control applications. They combine on a single chip the DSP's calculation capability with the MCU's controller features. These devices offer many peripherals dedicated to motor control, such as Pulse Width Modulation (PWM) modules, Analog-to-Digital Converter (ADC), Timers, communication peripherals (SCI, SPI, etc.), on-board Flash and RAM.

Implementation of the BLDC application with Hall Sensors will vary sligtly from one 56800/E device to another, and it will also depend on type of motor hardware used. See application-specific targeting manuals for more information.

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