Position feedback for motor control

About this document

Scope and purpose

This document describes the use of magnetic sensors in motor control to provide rotor position information.

Intended audience

The intended audiences for this document are experienced hardware and software engineers using magnetic position sensors.

Please read the sections “Important notice” and “Warnings” at the end of this document

Table of contents

1 Introduction

This application note focuses on sensors for position feedback in motor control applications. It covers feedback for brushless direct current (BLDC) motors with block commutation using Hall switches, as well as high-resolution encoder feedback for demanding servo applications. **Chapter 3** presents the working principle and different embodiments of BLDC motors, explains the various feedback technologies, and discusses possible application segments of this motor type. **Chapter 4** introduces Hall effect switches for BLDC rotor position detection and describes the working principles, switching types, and main performance characteristics.

Encoders are widely employed in applications requiring higher precision feedback, such as permanent magnet synchronous motors (PMSM) used in servo systems. Infineon's high-speed integrated giant magnetoresistive (iGMR) sensors are a good choice, and the working principle and advantages over optical encoders are described in **Chapter 5**.

It is shown that Infineon has a wide range of dedicated position sensor products for motor control applications, which not only lead from a technical point of view, but also offer considerable advantages in terms of system cost and quality.

Note: The following information is provided solely to indicate the performance of our devices and should not be considered a description or warranty of the specific function, condition, or quality of any device.

2 Brushless DC motors

This chapter discusses the working principle and advantages of brushless DC motors and explains the feedback structure and applications of BLDC motors in more detail. For more information, refer to various application notes on electronic control systems for both sensor-based and sensorless BLDC motor control systems listed in the **References** section.

2.1 Working principle

Figure 1 illustrates a typical BLDC motor. While brushed motors use a brush and a commutator to direct the current flow through the rotor windings, there is no such electrical contact between the stator and the rotor in the case of BLDC motors. In most brushed DC motors, the coil windings are fixed on the rotor part and the permanent magnets on the stator. However, in BLDC, which has a lightweight permanent magnet rotor and fixed windings on the stator, the coil windings are inverted. Both internal and external rotor motor configurations are feasible, both having a smaller rotor inertia and consequently higher efficiency of BLDC motors compared to the brushed counterparts.

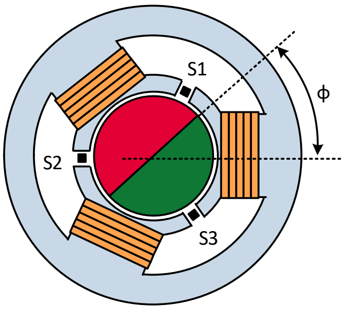

Figure 1 Internal rotor BLDC motor with three phases and one magnet pole pair. S1 to S3 are the Hall sensors

Some major disadvantages of brushed motors stem from the mechanical nature of the commutation switching. As large current pass through the brushes, sparks may form and lead to high-frequency electromagnetic emissions, which negatively affects other electronic equipment, and overload can damage these brushes. The contact brushes may wear out, leading to an increase in the failure rate and higher maintenance costs. In the case of BLDC motors, electrical contact between the stator and the rotor is avoided entirely. The advantages of BLDC motors also come at a price, which is mainly due to the higher complexity and cost of the driving electronics and the need for feedback sensors.

The motor shown in **Figure 1** uses three phases and a rotor magnet with only one pole pair, which is the simplest form of a three-phase BLDC motor. Increasing the number of magnetic pole pairs improves the smoothness of the motor, especially in external rotor BLDCs. Depending on the optimization criteria, the windings of the three phases can also be arranged differently around one circumference. On the other end of the spectrum, low-end systems, such as PC fans, can work with only one phase and are often equipped with an integrated circuit (IC) that integrates both the Hall element and the driving circuit. This application note does not focus on these applications.

2.2 Applications and trends

Due to high efficiency and reliability, BLDC motors can be found in a wealth of applications in various product segments and performance classes. Low-power motors can be found in consumer devices, such as cameras, computers, cooling fans, hard disk drives, or DVD players. The improved energy efficiency and robustness of brushless motors in automotive applications make them an ideal choice for a growing number of applications, such as HVAC blower motor. Electric bikes are yet another application in which brushless motors are used. Efficiency, safety, and reliability serve as driving forces that further strengthen the position of brushless motors, which also benefit from continuing cost reductions of control electronics. It should be noted that the commutation of the higher end motors used in electric power steering (EPS) systems and industrial automation commonly uses more sophisticated sinusoidal commutation or field-oriented control (FOC). In these cases, permanent magnet synchronous motors (PMSMs), the feedback of which is discussed in more detail in **Chapter 5**.

2.3 BLDC feedback principles

In general, any sensing principle that provides information about the rotor position can be used to electronically control the powering of the actuator coils. The three-phase Hall effect commutation, back electromotive force, and encoders are the main principles.

2.3.1 Three-phase Hall effect

The Hall effect switches are the most widely employed sensor feedback system used for BLDC commutation, as exemplified in **Figure 1**. **Figure 2** shows the typical signal pattern obtained from Hall switches S1 to S3 over one revolution of the rotor, which can be directly used for block commutation of the BLDC motor. **Chapter 4** deals with this kind of commutation in more detail.

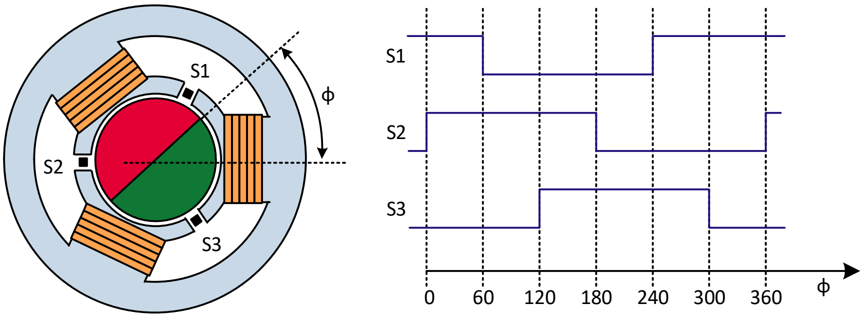

Figure 2 Switching pattern of the Hall switches S1 to S3 over one rotor evolution

2.3.2 Back electromotive force

Sensorless BLDC motors use the back electromotive force (back-EMF) induced on the non-energized coils to derive information on the rotor's position. This type of actuation has an obvious advantage that there is no need for additional sensors, which makes it a cost-effective motor assembly. On the other hand, the resulting positioning accuracy does not match the precision of sensor-based feedback principles, and additional difficulty arises at start-up since no EMF is induced at zero speed. It is necessary to take this into account for the controllers employed, which can be done using specific control algorithms running on the Infineon's microcontrollers. The interested reader will be referred to our various application notes on the topic listed at the end of this document.

3 Hall switch feedback

This chapter focuses on a dominant feedback system based on the Hall effect switches. The general working principle and sensor requirements are given and Infineon's dedicated Hall effect switches for BLDC applications are presented.

Figure 1 illustrates the easiest implementation of the Hall effect switch feedback method. The three Hall sensors are separated by 120° phase angles and triggered by the rotor magnet. A switching pattern depicted in **Figure 2** with a new digital state every 60° is produced. Therefore, the rotor position can be determined with a resolution of 60°, and if the Hall sensors are placed at the right positions, the signal transitions can be precisely matched to the ideal commutation points of coil energizing. In this envelope, constant or pulse width modulated (PWM) drive signals can be used to power the coils and drive the motor.

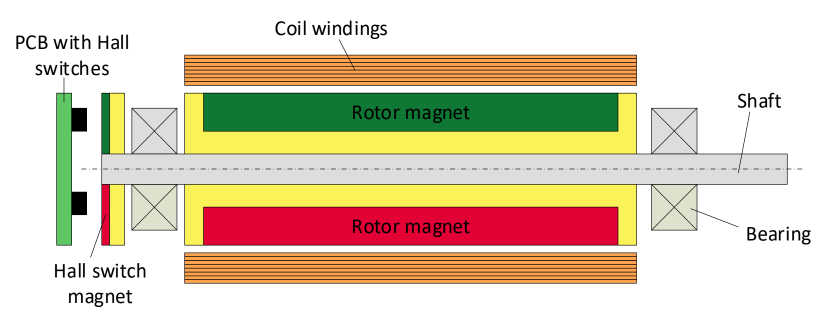

Figure 3 BLDC motor with an external Hall switch magnet

In many brushless DC motors, the Hall sensors directly sense the magnetic field of the rotor magnets, as illustrated in **Figure 1**. As a result, the sensors are placed inside the motor and are exposed to high temperatures and vibrations, without sealing, gases, and liquids can affect the components. In addition, the installation of new sensors and, in particular, the replacement of defective parts is delicate and expensive. Therefore, some motors have an additional magnet ring on the shaft, which triggers Hall switches. This makes it possible to locate the Hall switches further from the heating parts. **Figure 3** illustrates such an implementation. The benefits of such a solution are lower temperature, easier access, and added design flexibility, but at the expense of the need for an additional magnetic code wheel. Angle sensors in Hall switch mode are particularly attractive for this design type, as shown in **Chapter 4.4**.

3.1 Sensor types

The Hall effect switches switch between two logic states and exhibit some hysteresis between these two switching points. In general, there are two main types of devices: (unipolar) switches and (bipolar) latches.

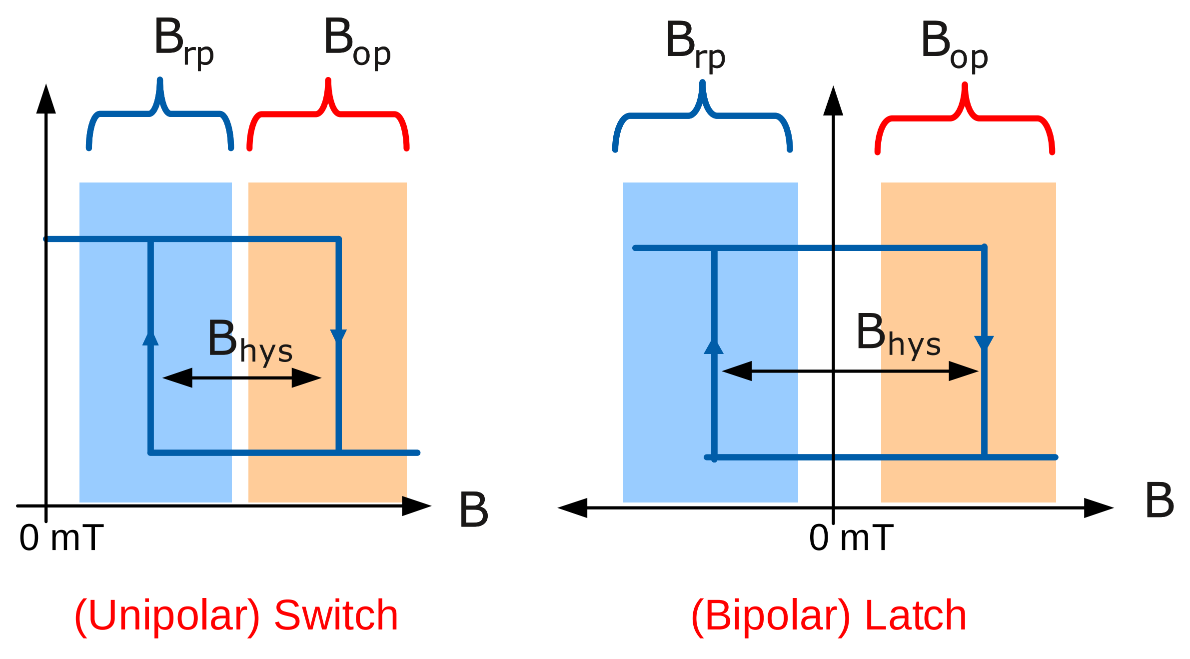

Figure 4 Unipolar switch versus bipolar latch

3.1.1 (Unipolar) Switches

Figure 4 illustrates the working principle of unipolar switches. When the applied magnetic field passes the operation point Bop, the device output switches on. When the magnetic field is released, the device switches back to the off state even before reaching the zero field at Brp. Some hysteresis, Bhys, is present to avoid transient fast-switching events between both states.

3.1.2 (Bipolar) Latches

Similar to a unipolar switch, bipolar latches also turn on after passing Bop. However, after releasing the magnetic field, the bipolar latch maintains its state even at zero. The device returns to its off state only once the inverse polarity field passes Brp, as shown in **Figure 4**. Therefore, these devices effectively latch their state, as the name implies.

3.1.3 (Bipolar) Switches

In addition, there are bipolar switches, which are a combination of unipolar switches and bipolar Latches. In principle, they work like hall latches, this means they switch on when a magnetic field is present and switch off again when there is a field of opposite polarity present. But different to hall latches these bipolar switches do not latch their current state. As a result, the current switching state between Bop and Brp is not reliably defined, so only the switching points are defined. This means that it is only possible to reliably detect the passing by of magnets of different polarities. Because of the fact that particularly low switching thresholds can be achieved with this technology, these switches are perfectly suitable for demanding motor commutations where only a low field strength is available.

3.2 Hall effect switch requirements

Next, some specific requirements of Hall effect switches used for BLDC motor commutation will be examined.

3.2.1 (Unipolar) Switch versus (bipolar) latch

The sensor detects accurately the position of the rotor. Ideally, the sensors deliver a commutation signal exactly every 60° of the rotor positions regardless of the motor speed and applied torque, and each sensor switches its output every 180°. **Figure 5** shows the behavior of a conventional switch and two different latches. It can be seen that the switch leads to an unbalanced duty cycle, whereas the latch has a duty cycle of exactly 50% when Bop and Brp have the same absolute value. A higher sensitivity will lead to less delay; therefore, switching points close to 0 mT are preferred. High-sensitivity bipolar latches are therefore the best choice for this application.

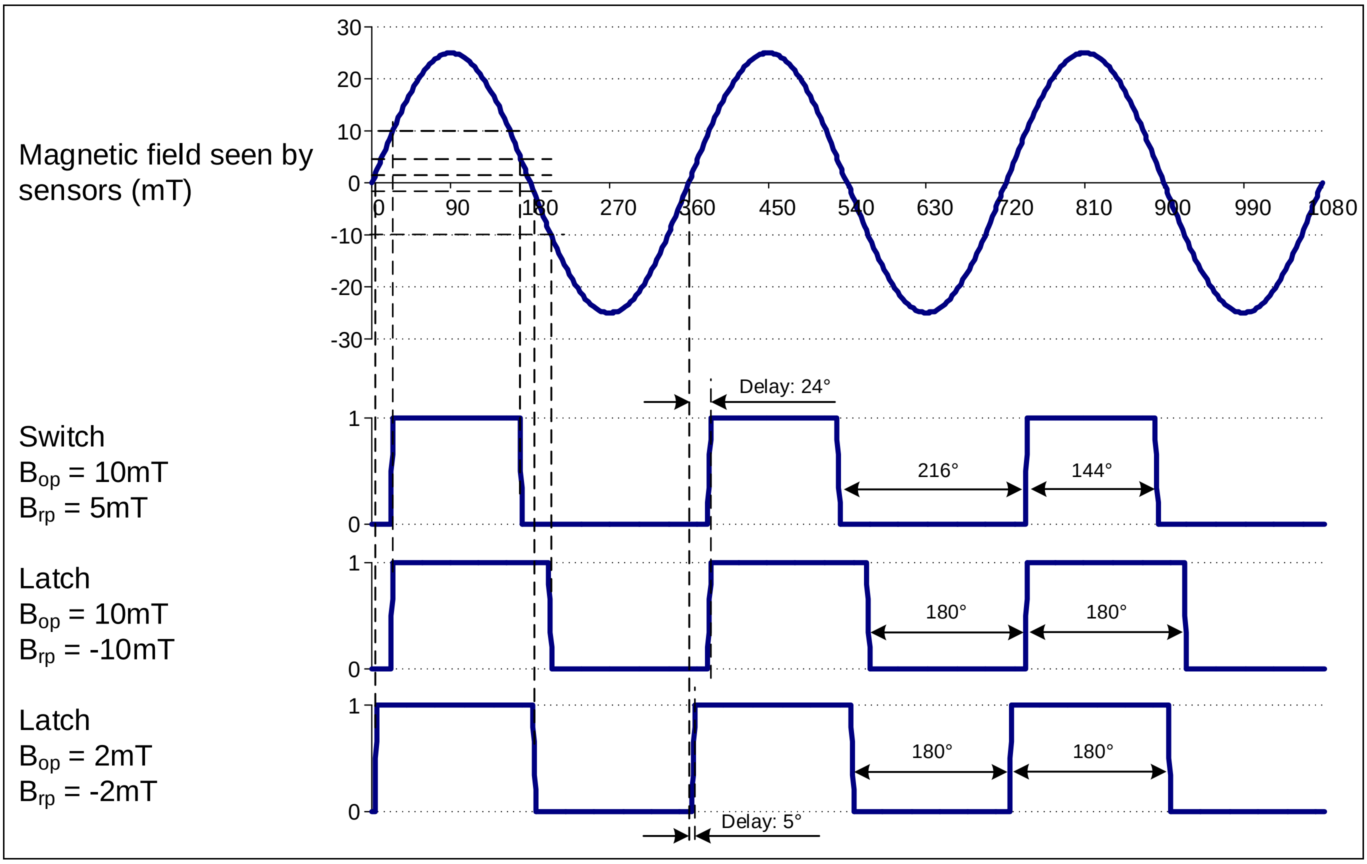

Figure 5 **Switching diagram for different Hall switches**

Note: High-sensitivity latches have the lowest delay and a balanced duty cycle.

3.2.2 Switching point accuracy

Due to the spread of processes in semiconductor manufacturing, it is unfortunately not possible to create identical sensors. Each parameter is individual, and it turns out that the magnetic switching point is one of the parameters affected by the process spread. In addition, environmental effects, such as mechanical stress due to overmolding or humidity, may lead to deviations in switching points over lifetime. Infineon's Hall effect switches of the TLx496x family employ a chopping principle, in which an ingenious method is applied to cancel out offsets of the Hall probe and input amplifier stage. This technology makes it possible to specify the switching points only in a narrow window with a small spread. The resulting high resistance against mechanical stress is another major benefit of the TLx496x family.

Figure 7 compares the two latches with different switching point spreads. In the worst-case scenario, the duty cycle can be unbalanced if Bop and Brp are at either end of the specified switching point. As shown in **Figure 7**, which employs the chopping principle, the spread of the switching points is much tighter and the effect on the duty cycle is therefore very small, leading to a balanced actuation of the motor over one full rotation.

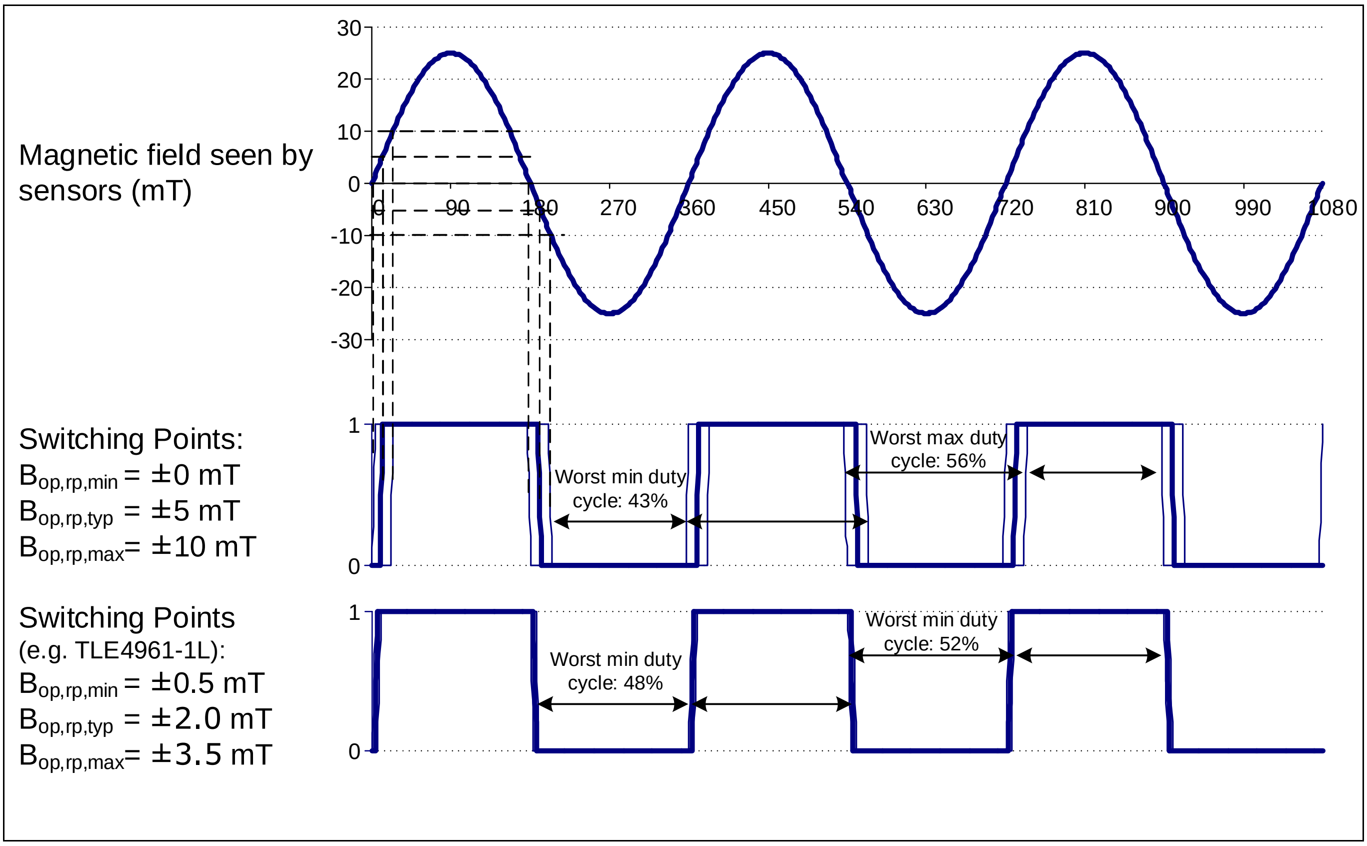

Figure 6 **Effect of switching point spread on the duty cycle**

Note: Lower spread leads to a balanced duty cycle.

3.2.3 Delay

As soon as the magnetic field crosses zero, the commutation should be instantaneous and not delayed by some internal processing of the sensor. Infineon’s Hall switches are based on a fast signal path with a small delay between the input and output.

3.2.4 Jitter

Another important criterion in motor commutation applications is the repeatability of a certain switching pattern. The jitter parameter identifies the extent to which switching points can vary during regular operation.

3.2.5 Temperature stability

The permanent magnets used in PMSM and BLDC motors lose some strength if the temperature is increased (which is also reversible). To maintain an accurate switching of the sensor at the same physical position, the temperature behavior of the magnet must be compensated. Therefore, Infineon's Hall effect switches of the TLx496x family offer well controlled state-of-the-art temperature compensation for repeatable performance over the entire operating temperature range. **Figure 7** qualitatively illustrates how temperature variations lead to different behaviors for sensors with fixed switching points, whereas temperature compensation helps to maintain the same behavior independent of temperature.

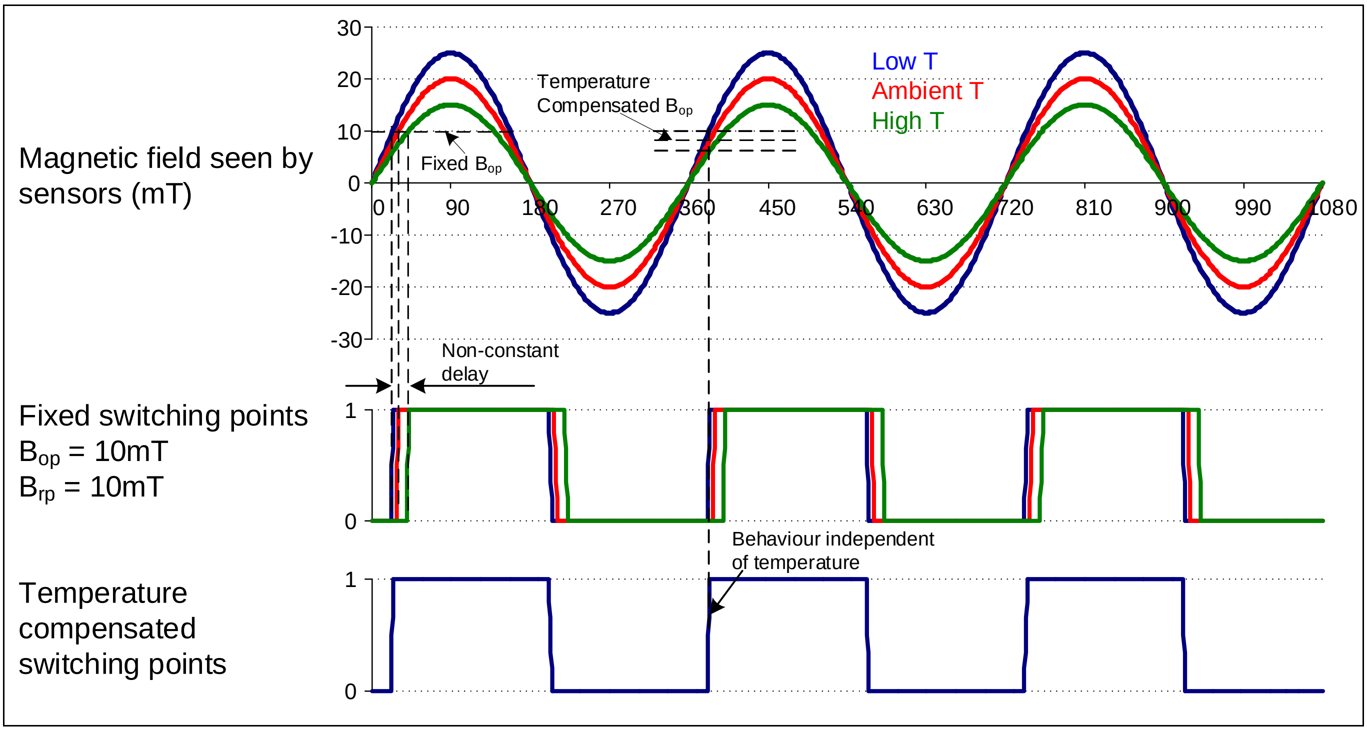

Figure 7 Fixed versus temperature compensated switching points

3.3 Infineon's Hall effect switches for motor commutation

Infineon has developed special Hall effect switches dedicated to motor control applications, available in different packages: SC59, SOT23, SSO-3; and TO92S (refer to **Figure 8**). The parts excel with:

- High sensitivity (switching points close to zero)
- Small switching point spread
- Excellent temperature compensation
- Small delay time
- Low jitter

In addition, these parts fulfill all the basic requirements for sensors working in harsh environments, including:

- Small and broad range of operating supply voltage
- High maximum supply voltage range including reverse polarity protection
- High-temperature range (operating range, maximum rating of up to 195°C for a short time)
  - -40 to 125°C (TLI496x and TLV496x)
  - -40 to 170°C (TLE496x)
- High immunity against ESD (>4 kV)
- Very low current consumption

All these features make the TLx496x family an ideal choice for motor commutation applications. Refer to the relevant datasheets for more details.

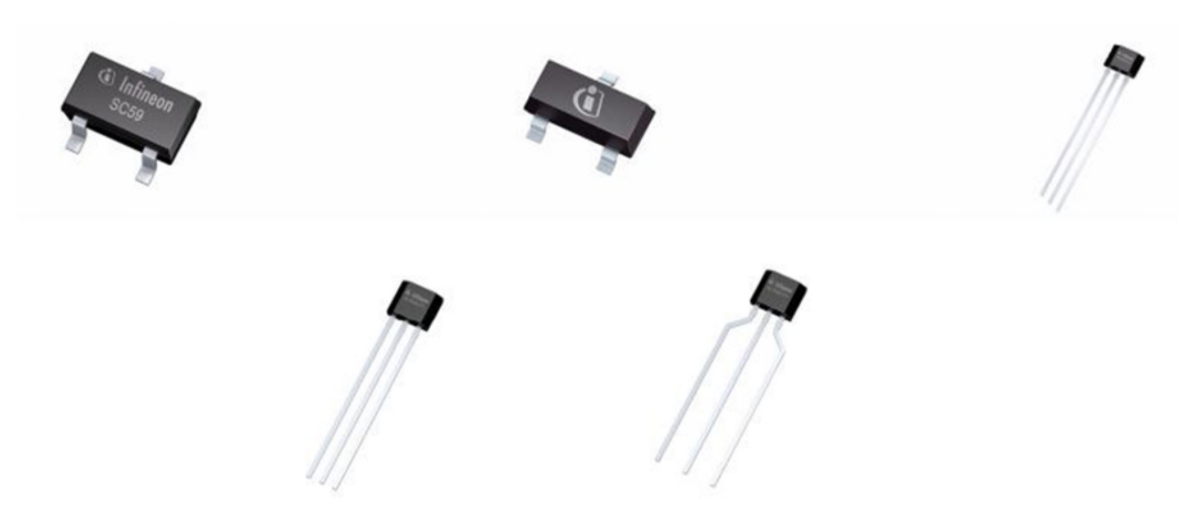

Figure 8 SC59, SOT23, SSO-3, and TO92S (A+B) packages

3.4 Infineon's angle sensors in Hall switch mode

For applications where an external magnet, as shown in **Figure 3**, is feasible, Infineon has developed an even easier solution that does not require three, but only one sensor to create the switching patterns of Hall effect switches: the TLE5012B angle sensor. This sensor is based on the giant magneto-resistive (GMR) effect, which Infineon has integrated with standard silicon processing in its successful iGMR technology. **Figure 9** shows a possible implementation of TLE5012B with a simple cylindrical magnet mounted on the shaft of the motor.

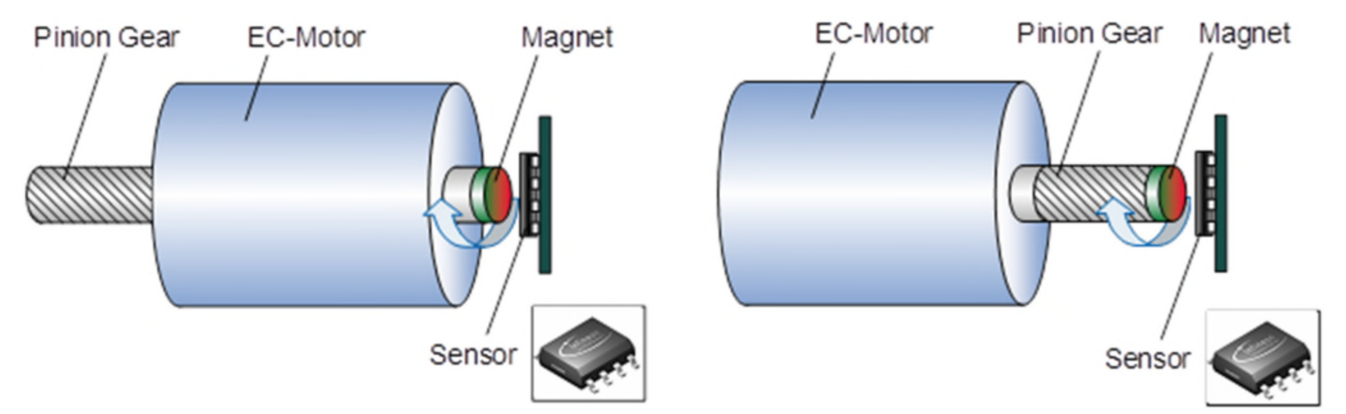

Figure 9 Mounting the TLE5012B with a diametral magnet on the shaft

TLE5012B can be used to create switching patterns required to drive rotors with 2, 3, 4, 6, 7, 8, 12 and 16 pole pairs. An autocalibration algorithm achieves an angular accuracy (mechanical) better than 1° over both temperature and lifetime. Therefore, the switching patterns of the TLE5012B are generally more accurate than those obtained even with the most precise Hall switches.

For some motors requiring high torque smoothness, block commutation, which is used in most brushless DC motors, is not sufficient. Therefore, special winding design and adapted driving algorithms are used to drive the motor in a synchronous manner. These permanent magnet synchronous motors (PMSM) typically require higher precision feedback. The TLE5012 can be used in Hall switch mode, as described above, and the encoder feedback mode outlined in **Chapter 5**.

4 Angle sensor with incremental output IIF (encoder interface)

Many motor control systems used in servo applications require a precise feedback signal to function. Many motor types can be considered for these applications, and permanent magnet synchronous motors (PMSM) are a possible choice that are often used with high-precision feedback. Encoders deliver not only two switching events over a single revolution, such as Hall switches, but also a much higher angular resolution.

Servo motors are operated with closed control loops where the output signal (that is, position, torque, speed) is sensed and processed in such a way that the best possible motor inputs are obtained. This feedback is usually achieved by resolvers or incremental encoders. Industrial equipment often uses this type of servomotors in robotic arms or production machinery, and precise motors are increasingly found in the automotive industry, for example in modern EPS systems. Typical output signals A and B produced by an incremental encoder if the motor is first turned forward and then backward are shown in **Figure 10**. The control unit is then able to adapt the internal counter register whenever an edge rises on phase B. The direction can be detected on the basis of whether phase A precedes phase B or not. An additional signal Z is often available to indicate the reference position.

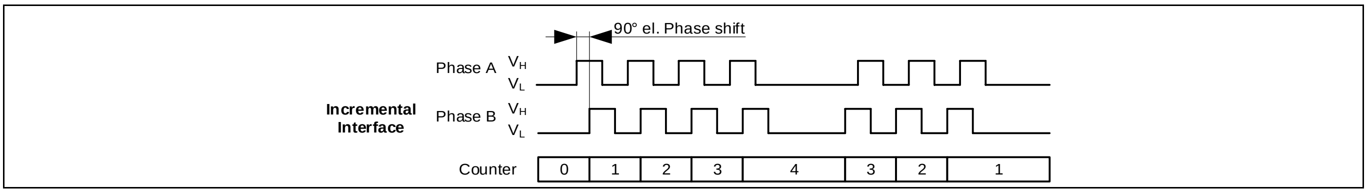

Figure 10 **Output signals A/B of an incremental interface**

4.1 Optical encoders

Optical encoders are one of the main types of encoders used today. The main advantage of being contactless is that it does not wear out. Optical encoders offer relatively high resolution and good absolute accuracy. Unfortunately, optical encoders are still relatively expensive, and the optical system is prone to dust or moisture disturbance. In addition, shrinking the optical encoders to small dimensions is difficult and expensive.

4.2 Magnetic encoders

Due to advances in the integration of magnetic sensor technology, these systems have been available for some time, making them a true alternative for angle feedback systems. The Hall effect, the anisotropic magneto-resistance effect (AMR), the GMR effect and the TMR (tunneling magnetoresistive) effect are available. Infineon uses its iGMR technology to offer a versatile state-of-the-art encoder, the TLE5012B. Magnetic systems have several advantages over optical systems:

- System cost
- Build space
- Sealing possible
- Higher temperature range

The disadvantages of magnetic encoders include reduced angular accuracy and resolution, lack of interface protocols, and lower speed. These issues can now be solved in the TLE5012B:

- High speed: The TLE5012B has a high-speed technology, allowing for an update rate of down to 43 us
- High accuracy: iGMR technology senses the direction of the magnetic field and not the strength. Therefore, the accuracy is independent of the temperature and lifetime. To further improve the accuracy, the TLE5012B uses an autocalibration algorithm that achieves an accuracy better than ±1°

- High resolution: Internally, the TLE5012B works with up to 16-bit resolution and the output has a 12-bit resolution in its incremental interface
- Interfaces: In addition to the incremental interface and Hall switch mode described above, the TLE5012B also offers a PWM interface and an SPI interface for more versatility on the customer side. With the PWM and SPI interfaces, it is possible to use the sensor as an absolute angle sensor (resolver) in which the absolute angle signal is directly available after startup, avoiding the need for referencing

These advantages make TLE5012B an excellent choice for state-of-the-art contactless position feedback systems for high performance motor control applications.

5 Angle sensors with SSC (SPI) output

The fundamental drawback of the incremental output is that the absolute angular position is only available when the rotor crosses the zero position, where the Z-pulse indicates the zero position. The absolute position can then be tracked by counting encoder pulses, and resynchronization at every zero-crossing is possible. However, the absolute position is usually not available at the start of the motor, which makes fast motor start-up difficult.

TLE5012B has a dedicated feature described in the datasheet to overcome this drawback by sending a number of encoder pulses at the start of the sensor, which correspond to the actual absolute angular position. Counting these pulses determines the absolute rotor position even at startup.

The absolute rotor position can also be determined using a sensor with an SSC (SPI) interface. This well-known communication protocol provides not only the absolute angular position with a high resolution of 15 bits, but also sensor diagnostic information that enables functional safety requirements. In order to ensure data integrity, the communication itself is protected by a CRC.

Infineon provides TLE5012B and TLE5014SP digital angle sensors that both support the SSC interface.

These sensors provide an internally calculated and compensated angle that can be directly used in the control algorithm. In addition, as described in the corresponding user manuals, these devices are flexible for a wide range of motor commutation applications.

The angle is internally calculated with a high update rate of 42 µs (TLE5012B) and 25 µs (TLE5014SP), which makes the device suitable for fast rotating motors.

6 Angle sensors with analog output

Analog angle sensors provide the raw signals sin/cos, and angle calculation is performed in the microcontroller. This ensures the highest update rate and the shortest delay time because no digital signal processing is involved inside the sensor. Advanced compensation techniques (for example, ongoing offset/amplitude correction and harmonic compensation) can also be applied to obtain the highest angle accuracy.

These types of sensors support the fastest motor speeds above 30.000 rpm. Since all the signal conditioning and calculations must be carried out in the microcontroller, the sensor itself remains small and simple. This is reflected, for example, with regards to functional safety, since the failure rate of such sensors is considerably lower than their digital counterparts.

Infineon offers a wide range of such analog sensors in various technologies:

- TLE5009: GMR-based device with a 360° measurement range; it is also available as a dual die configuration
- TLE5109: AMR-based device with the highest angle accuracy but limited to 180° measurement range; it is also available as a dual die.
- TLE5309D: A dual die consisting of one AMR and one GMR chip, combining diverse measurement technologies with the highest angle accuracy for the best functional safety support
- TLE5501: TMR-based sensor with a single die that supports ASIL-D requirements

7 Conclusion

In this application note, the principles of position feedback sensor for different motor types are described. The TLx496x family of chopped Hall effect switches has been shown to be well suited for motor commutation in BLDC applications. In particular, TLx496x Hall switches are designed to achieve the best possible performance of BLDC motors.

Many motor control systems for servo applications require precise position feedback. In the past, optical encoders have been a leading choice for this purpose. Advances in Infineon's iGMR technology now make it possible to achieve high-speed resolution and accuracy with TLE5012B, which, together with its robustness and versatility, makes it the product of choice for next generation position feedback systems.

TLE5012B and TLE5014SP are the best choice for a digital communication protocol that provides absolute angle values.

The TLE5x09 and TLE5501 sensors are recommended for those who prefer analog sin/cos interfaces to calculate the angle inside the microcontroller and optionally also apply additional advanced compensation schemes. Full control on further signal conditioning is obtained by providing the raw date sin/cos as a differential output signal.

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[9] For future Application Notes see Infineon Homepage (http://www.infineon.com)

Terminology

Table 1 Terminology

Term	Definition
AMR	Anisotropic magneto resistance
back-EMF	Back electromotive force
BLDC motor	Brushless direct current motor
Bop	Operating point of a Hall effect switch
Brp	Release point of a Hall effect switch
DC	Direct current
EC motor	Electronically commutated motor
EPS	Electric power steering
IIF	Incremental interface
GMR	Giant magneto resistance
HVAC	Heating venting air conditioning system
PMSM	Permanent magnet synchronous motor
PWM	Pulse width modulation
SSC	Synchronous serial interface
SPI	Serial peripheral interface
TMR	Tunneling magneto resistance

Revision history

Document revision	Date	Description of changes
1.3	2022-07-12	• Template update • Rework of application note
1.4	2024-03-22	• Template update • Rework of application note

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