Position Feedback for Motor Control Using Magnetic Sensors

Application Note

Rev. 1.1, 2010-05-26

Sense & Control

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Revision History: 2010-05-26, Rev. 1.1

Previous Revision: Rev. 0.1

Page	Subjects (major changes since last revision)
12	Chapter 3.4 added
13	Chapter 4 added
14	Chapter 5 updated
general	Correction of typing errors

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Table of Contents

1 Introduction

This application note is dedicated to sensors for position feedback in motor control. Feedback for brushless direct current (BLDC) motors with block commutation by using Hall switches as well as high resolution encoder feedback for demanding servo applications are covered. In **Chapter 2**, the working principle and different embodiments of BLDC motors are presented, the various feedback technologies are explained and possible application segments of this motor type are given. In **Chapter 3**, Hall effect switches for BLDC rotor position detection are introduced and their working principle, switching type and main performance characteristics are given.

In applications requiring higher precision feedback such as permanent magnet synchronous motors (PMSM) used in servo systems, encoders are widely employed. Infineon's high speed integrated giant magnetoresistive (iGMR) sensors are a good choice and their working principle as well as their advantages over optical encoders is detailed in **Chapter 4**.

It is shown that Infineon has a broad portfolio of dedicated position sensor products for motor control applications, which are not only leading from a technical point of view, but which offer considerable advantages on the system cost and quality side as is shown in this application note.

2 Brushless DC Motors

This chapter talks about the working principle and advantages of brushless DC motor types and then explains in more detail the feedback structure and the applications of BLDC motors. Please also consider our various application notes on electronic control systems for both sensor-based and sensorless BLDC motor control systems listed in the References on **Page 15**.

2.1 Working Principle

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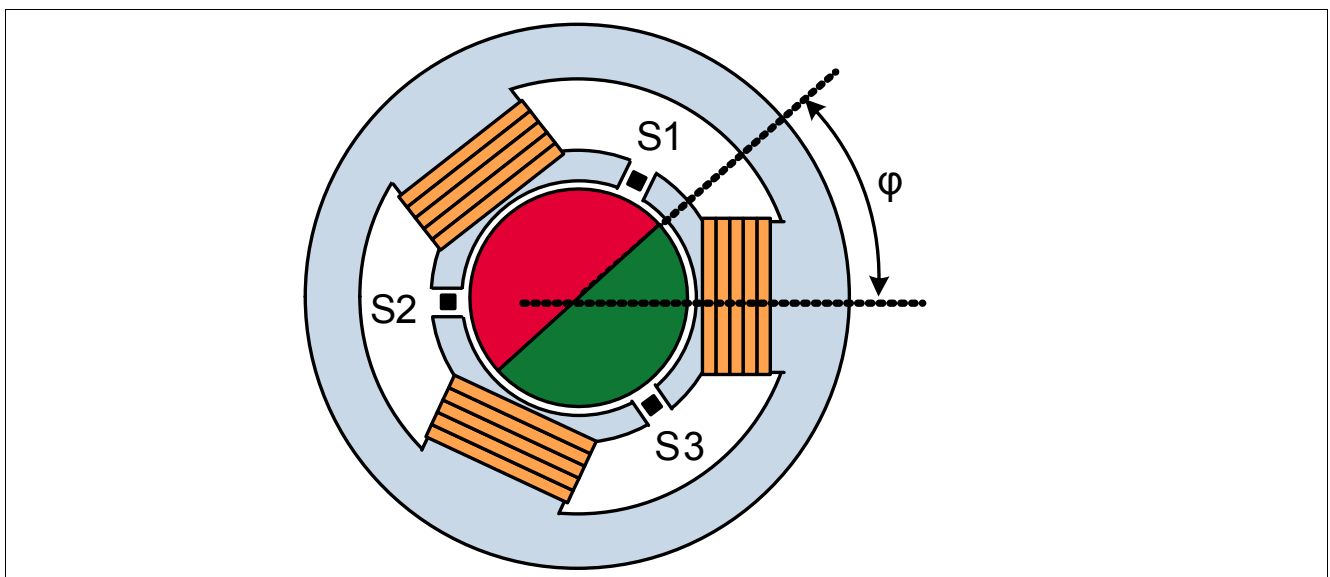

Figure 1 **Internal rotor BLDC motor with 3 phases and 1 magnet pole pair. S1 to S3 are the Hall sensors.**

Some major disadvantages in brushed motors stem from the mechanical nature of the commutation switching. Since a considerable current is being driven through the brushes, sparks can form and lead to high-frequency electromagnetic emissions, affecting other electronic equipment negatively, and overload can deteriorate these brushes. The contact brushes can wear out, leading to increased failure rates and higher maintenance cost. This is avoided in BLDC motors entirely by avoiding electrical contacts between stator and rotor. The advantages of BLDC motors also come at a price, which is mainly the higher complexity and cost in driving electronics and the need for feedback sensors.

The motor in **Figure 1** uses three phases and a rotor magnet with only one pole pair, which is the simplest possible form of a three phase BLDC motor. Increasing the amount of magnetic pole pairs helps to improve the smoothness of the motor, which is especially found in external rotor BLDCs. The windings of the three phases can also be arranged differently around one circumference, depending on the optimization criteria. On the other end of the spectrum, low end systems as used for PC fans can work with only one phase and are often equipped with an IC that integrates both Hall element and driving circuitry. We will not focus on those applications in this application note.

2.2 Applications and Trends

Due to their high efficiency and reliability, BLDC motors can be found in a wealth of applications in all kinds of product segments and performance classes. Low power motors can be found in consumer devices such as cameras or computers, powering cooling fans, hard disk drives or DVD players. In automotive applications, the improved energy efficiency and robustness of brushless motors make them an ideal choice for a growing number of applications as for example HVAC blower motors. Electric bikes are yet another application where brushless motors are found. Efficiency, safety & reliability serve as driving forces further strengthening the position of brushless motors, which also benefit from continuing cost reductions of the control electronics. Please note that the commutation of the higher end motors as used in electric power steering (EPS) systems and industrial automation commonly uses more sophisticated sinusoidal commutation. In these cases, one speaks of permanent magnet synchronous motors (PMSM), the feedback of which is covered in more detail in **Chapter 4**.

2.3 BLDC Feedback Principles

Basically, any sensing principle that delivers information about the rotor position can be employed to electronically control the powering of the actuator coils. The main principles are 3-phase Hall effect commutation, back electromotive force and encoders.

3-Phase Hall Effect

The most widely employed sensor feedback system used for BLDC commutation are Hall effect switches as exemplified in **Figure 1**. The typical signal pattern obtained from the Hall switches S1 to S3 over one revolution of the rotor can be seen in **Figure 2**, which can directly be used for block commutation of the BLDC motor. **Chapter 3** will deal with this kind of commutation in more detail
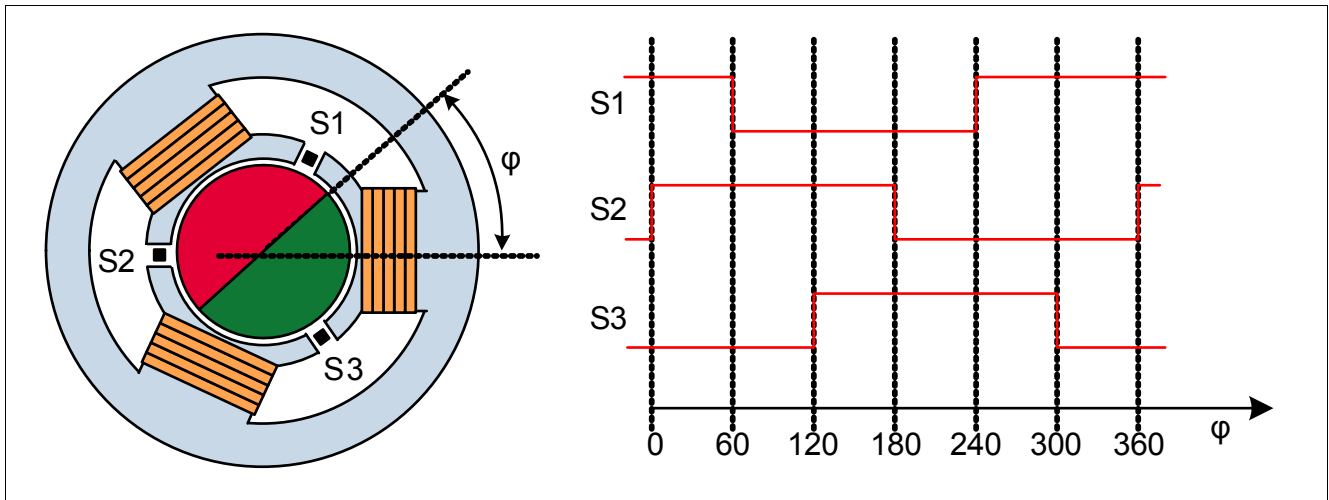
Figure 2   Switching pattern of the Hall switches S1 to S3 over one rotor revolution.

Back Electromotive Force

One type of BLDC motors known as sensorless uses the back electromotive force (back-EMF) induced on the non-energized coils in order to derive information on the rotor's position. This type of actuation has the obvious advantage that it doesn't need any additional sensors and therefore makes for a cost effective motor assembly. On the other hand, the resulting positioning accuracy doesn't match the precision of sensor-based feedback principles and additional difficulty arises at start-up since no EMF is induced at zero speed. The employed controllers need to take this into account, which can be done with dedicated control algorithms running on Infineon's microcontrollers. The interested reader is referred to our various application notes on the topic listed at the end of this document.

3   Hall Switch Feedback

This chapter focuses on the dominant feedback system based on 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 shows the easiest implementation type of Hall effect switch feedback. The three Hall sensors are separated by 120° phase angles and triggered by the rotor magnet. They produce a switching pattern depicted in **Figure 2** with a new digital state every 60°. It is therefore possible to know the rotor position with a resolution of 60°, and if the Hall sensors are placed at the right positions, the signal transitions can be matched exactly to the ideal commutation points of coil energizing. Within this envelope, either constant or pulse width modulated (PWM) drive signals can be used to power the coils and drive the motor.
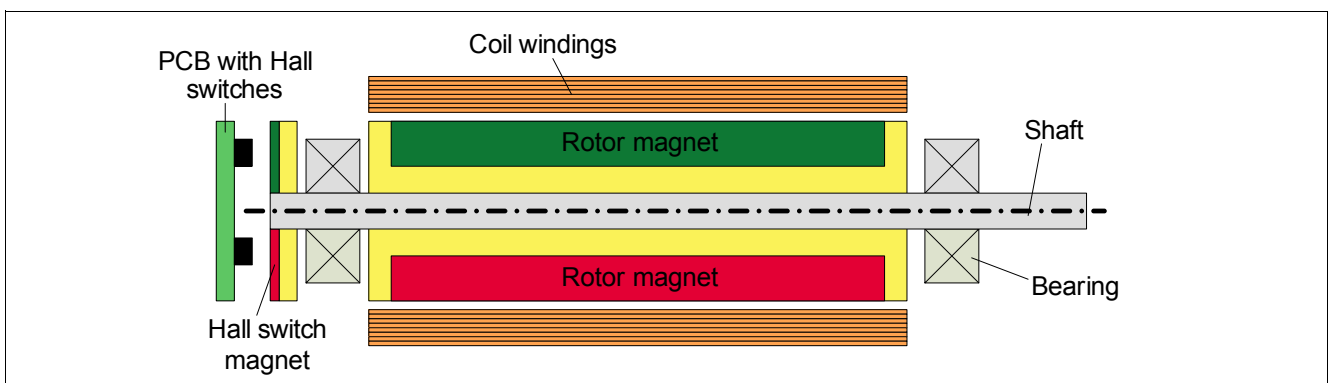

Figure 3   BLDC motor with external Hall switch magnet

In many brushless DC motors, the Hall sensors are directly sensing the magnetic field of the rotor magnets as the example of **Figure 1**. As a consequence, the sensors are mounted inside the motor and are exposed to high temperatures and vibrations and lacking a sealing, gases and liquids can affect the parts. Additionally, mounting new sensors and especially replacing failed parts is delicate and expensive. Some motors therefore have an additional magnet ring mounted on the shaft, the Hall switches being triggered by this magnet ring. This allows the Hall switches to be located further away from the heating parts. **Figure 3** shows such an implementation. Lower temperature, easier access and added design flexibility are the benefits of such a solution, which comes at the expense of requiring an additional magnetic code wheel. For this design type, angle sensors in Hall switch mode are especially attractive as shown in **Chapter 3.4**.

3.1 Sensor Types

Hall effect switches switch between two logic states and exhibit some hysteresis between these two switching points. One generally distinguishes between two main types of devices: unipolar switches and bipolar latches. Omnipolar switches and bipolar switches are not considered here.
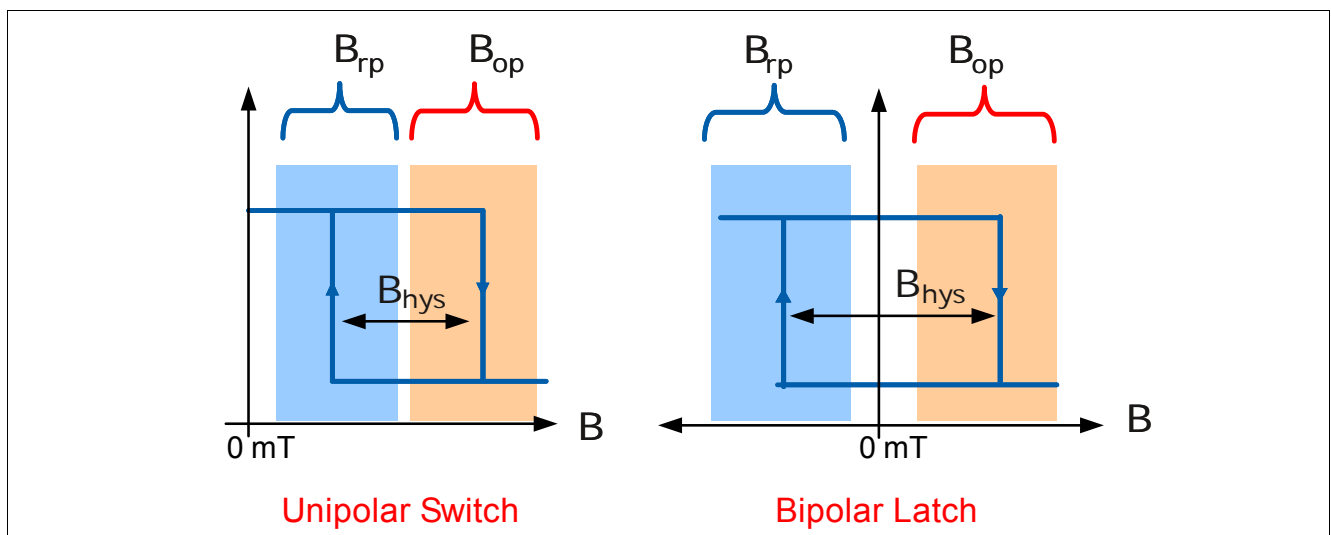

Figure 4 Unipolar Switch vs. Bipolar Latch

Unipolar Switches

Figure 4 shows the working principle of unipolar switches. The device output switches on when an applied magnetic field passes the operate point Bop. If the magnetic field is released, the device switches back to an off state still before reaching zero field at Brp. Some hysteresis Bhys is present to avoid transient fast switching events between both states.

Bipolar Latches

Similar as the unipolar switch, bipolar latches also turn on after passing Bop. However, after releasing the magnetic field, the bipolar latch keeps its state even at zero field. It is only once the inverse polarity field is passing Brp that the device returns to its off state as shown in **Figure 4**. These devices therefore effectively latch their state as their name implies.

3.2 Hall Effect Switch Requirements

We will next look into some specific requirements of Hall effect switches used for BLDC motor commutation

Unipolar vs. Bipolar

The task of the sensor is to detect the position of the rotor accurately. Ideally, the sensors deliver a commutation signal exactly every 60° of rotor position regardless of motor speed and applied torque and each individual sensor switches its output every 180°. **Figure 5** shows how a conventional unipolar switch and two different bipolar latches would behave. It can be seen that the unipolar switch would lead to an unbalanced duty cycle, while the bipolar 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, that's why switching points close to 0mT are preferred. High sensitivity bipolar latches are therefore the best choice for this application.
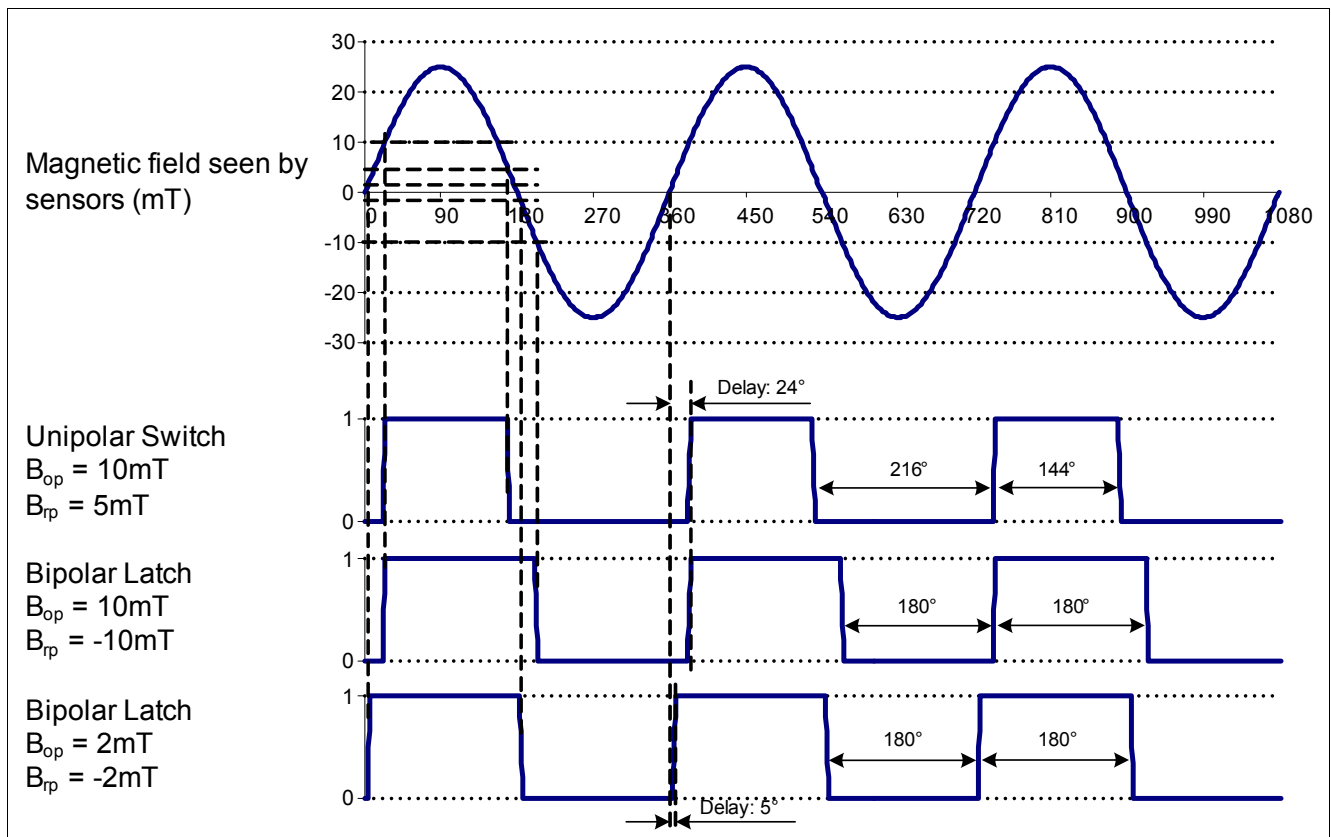

Figure 5   Switching diagram for different Hall switches. High sensitivity bipolar latches have lowest delay and a balanced duty cycle

Switching Point Accuracy

Due to process spreads in the semiconductor manufacturing, it is unfortunately not possible to create identical sensors. Each one is individual, and it turns out that the magnetic switching point is one of the parameters that is affected considerably by process spread. Additionally, environmental effects such as mechanical stress arising due to overmolding or humidity can lead to deviations in switching points over lifetime. To minimize these effects, Infineon's Hall effect switches of the TLE49x6 family employ a chopping principle, in which an ingenious method is applied to chancel out offsets of the Hall probe and input amplifier stage. This technology allows to specify the switching points in a narrow window with a small spread only. A resulting high resistance against mechanical stress is another big benefit of the TLE49x6 family.

Figure 7 shows how two bipolar latches with different switching point spreads would compare. It can be seen that in the worst case, the duty cycle can be very unbalanced if Bop and Brp happen to be on either end of the specified switching point range. In the case of the TLE4946-2K and TLE4946-2L, which employ said chopping principle, the spread of the switching points is much tighter and the effect on the duty cycle is accordingly very small, leading to a balanced actuation of the motor over one full rotation.
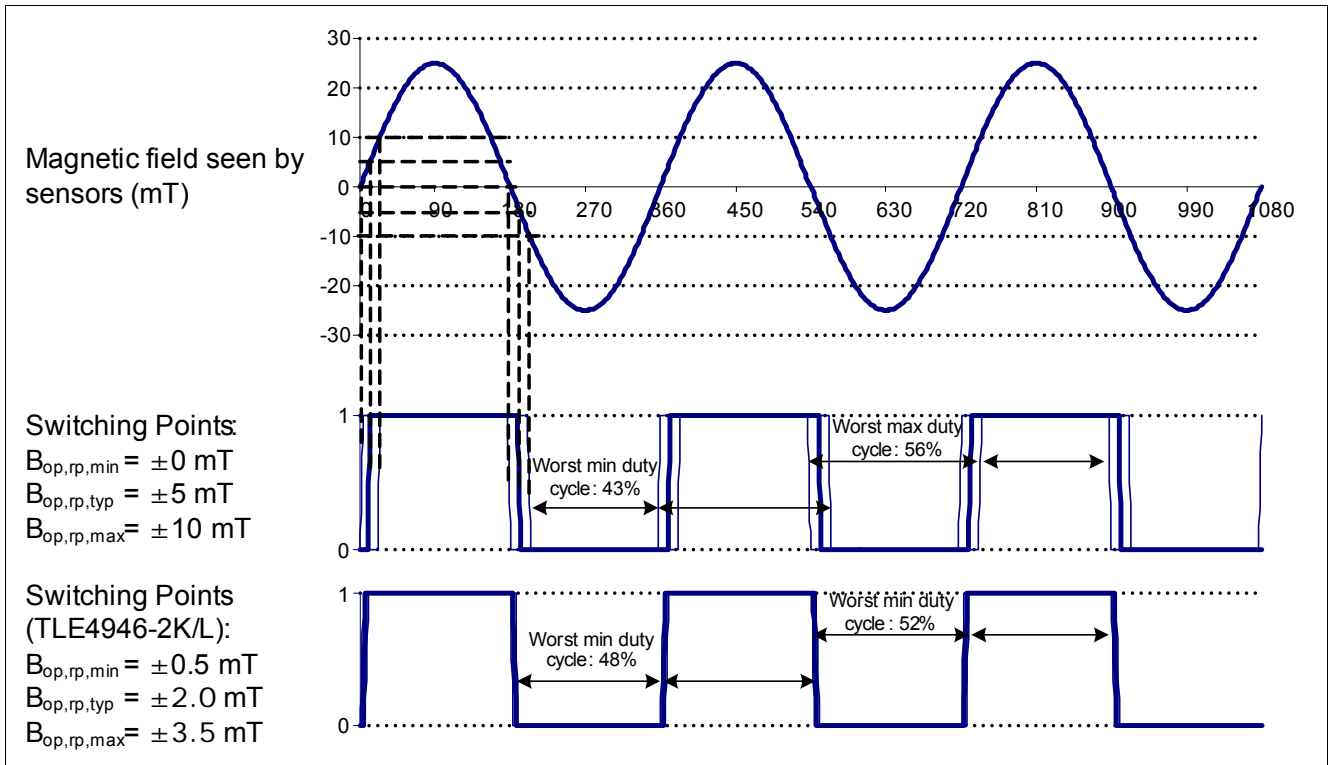
Figure 6   Effect of switching point spread on duty cycle. Lower spread leads to a balanced duty cycle

Delay

Once there is a zero crossing of the magnetic field, the commutation should be immediate and not delayed by some internal processing in the sensor. Infineon's Hall switches are based on a fast signal path which only generates a tiny delay between input and output.

Jitter

The repeatability of a certain switching pattern is another important criterion in motor commutation applications. The jitter parameter identifies by how much the switching points can vary during regular operation.

Temperature stability

The permanent magnets used in PMSM and BLDC motors unfortunately lose some of their strength if temperature is increased (which is also reversible). In order to maintain an accurate switching of the sensor at the same physical position, the sensor has to follow the temperature behaviour of the magnet to compensate this effect. Therefore, sensing the ambient temperature, Infineon's Hall effect switches of the TLE49x6 family offer well controlled state of the art temperature compensation for repeatable performance over the whole operating temperature range. **Figure 7** qualitatively shows how temperature variations lead to different behaviour for sensors with fixed switching points while temperature compensation helps to maintain the same behaviour independent of temperature.
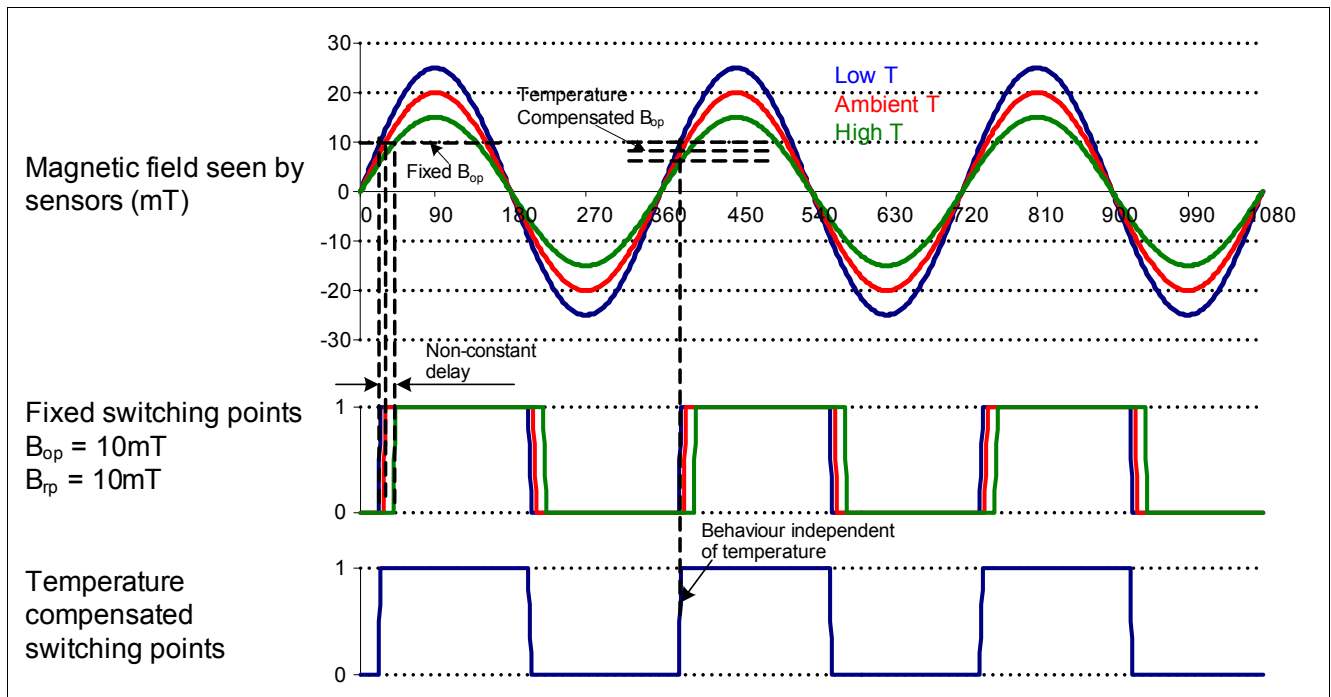
Figure 7   Fixed vs. temperature compensated switching points

3.3   Infineon's Hall Effect Switches for Motor Commutation

Based on the performance indicators outlined above, Infineon has developed a Hall effect switch dedicated to motor control applications, available in two packages: The TLE4946-2K in an SC59 SMD package as well as the TLE4946-2L in a leaded PG-SSO-3-2 package (c.f. **Figure 8**). The parts excel with

- High sensitivity (switching points close to zero, Bop 2mT and Brp -2mT typical)
- Small switching point spread (Bop between 0.5 and 3.5mT, Brp between -3.5 and -0.5mT)
- Excellent Temperature compensation (set to -350ppm/°C typical)
- Small delay time (typically 13us)
- Low jitter (typically 1us)

Additionally, all the basic requirements for sensors working in harsh environments are fulfilled by this part, including

- Broad operating supply voltage range (2.7 V to 18 V)
- High maximum supply voltage range including reverse polarity protection (-18 V to 26 V)
- High temperature range (-40 to 150 °C operating range, max rating up to 195 °C for short time)
- High immunity against ESD (> 4 kV)

All those features make the TLE4946-2L and the TLE4946-2K ideal choices for motor commutation applications. For details about this part, please refer to the corresponding datasheets.

Figure 8 **Infineon's Hall effect switches for motor commutation are available in the leaded PG-SSO-3-2 package (-L types) as well as in the small SC59 SMD package (-H, -K types).**

3.4 Infineon's Angle Sensors in Hall Switch Mode

For applications where an external Hall magnet as in **Figure 3** is feasible, Infineon has now developed an even easier solution that does not require three, but only one sensor to create the switching patterns of Hall effect switches: The TLE5012 angle sensor. This sensor is based on the Nobel Prize winning 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 the TLE5012 with a simple cylindrical magnet mounted on the shaft of the motor.
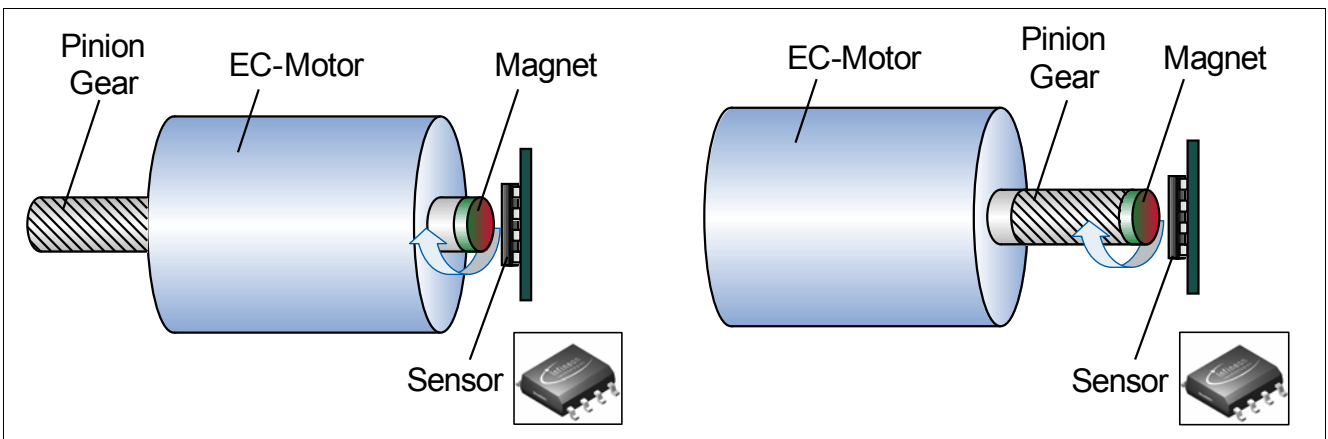

Figure 9 **Mounting the TLE5012 with a diametral magnet on the shaft.**

The TLE5012 can be used to create switching patterns required to drive rotors with 2, 3, 4, 6, 7, 8, 12 and 16 polepairs. Due to an autocalibration algorithm, it achieves an angular accuracy (mechanical) better than 1° over both temperature and lifetime. This means that the switching patterns of the TLE5012 are typically more accurate than the ones one can obtain even with the most precise Hall switches.

For some motors requiring yet higher torque smoothness, block commutation as employed in most brushless DC motors is not sufficient and special windings design as well as adapted driving algorithms are used to drive the motor in a synchronous way. These permanent magnet synchronous motors (PMSM) typically require higher precision feedback. One possibility is to use the TLE5012 in Hall switch mode as described above, another is to use the encoder feedback mode outlined in the next chapter.

4 Encoder Feedback

Many motor control systems for servo applications require a precise feedback signal to work. Many motor types can be considered for these applications and the permanent magnet synchronous motors (PMSM) are one possible choice often used with high precision feedback. Encoders deliver not just two switching events over one revolution like the Hall switches, but can have a much higher angular resolution.

Servo motors are operated with closed control loops, the output signal (i.e. position, torque, speed) being sensed and processed to derive the best possible motor inputs. The feedback is usually achieved by employing resolvers or incremental encoders. Industrial equipment often uses this kind of servomotors in robotic arms or production machinery, and precise motors are more and more found in the automotive industry, too, for example in modern EPS systems. **Figure 10** shows a typical output signals A and B produced by an incremental encoder if the motor is first turned forward, then backwards. The control unit can then adapt an internal counter register each time a rising edge happens on phase B. The direction can be detected based on whether or not phase A precedes B. An additional signal Z is often available to indicate the reference position.
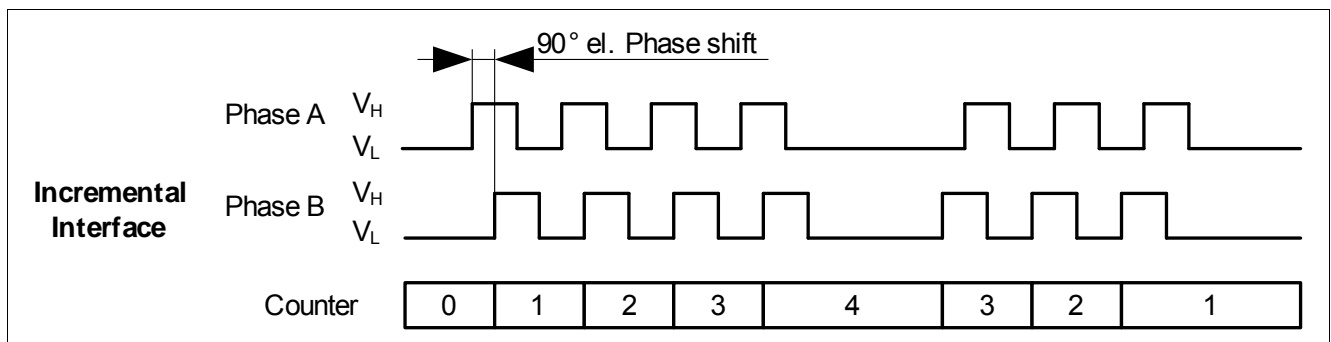

Figure 10   Output signals A/B of an incremental interface

4.1 Optical Encoders

Optical encoders are one main type of encoder in use today. Its main advantage of being contactless allows it not to wear out. Optical encoders are available with relatively high resolution and offer good absolute accuracy. Unfortunately, optical encoders are still relatively expensive, and the optical system is prone to be disturbed by dust or moisture. Additionally, it is difficult and expensive to shrink optical encoders to small dimensions.

4.2 Magnetic Encoders

These systems are available for some time due to advances in the integration of magnetic sensor technology, making them a true alternative for angle feedback systems. There are systems available using the Hall effect, the Anisotropic Magneto-Resistance effect (AMR) or the GMR effect. Infineon is using its iGMR technology to offer a versatile state of the art encoder, the TLE5012. The magnetic system has many advantages over an optical system

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

Some of the disadvantages of magnetic encoders so far included the reduced angular accuracy and resolution, lack of interface protocols as well as their lower speed. These issues could now be solved in the TLE5012:

- High speed: The TLE5012 is built in a high speed technology, allowing for an update rate of down to 43 us
- High accuracy: The iGMR technology senses the direction of the magnetic field, not the strength. This means that the accuracy is independent of temperature and lifetime. To even further improve the accuracy, the TLE5012 uses an autocalibration algorithm to achieve accuracy better than +/- 1°

- High resolution: The TLE5012 works with up to 16 bit resolution internally and the output has a 12bit resolution in its incremental interface
- Interfaces: Additionally to the incremental interface and the Hall switch mode described previously, the TLE5012 also offers a PWM interface as well as 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 available directly after startup, avoiding the need for referencing

These advantages make the TLE5012 an excellent choice for state of the art contactless position feedback systems for high performance motor control applications.

5 Conclusion

In this application note, position feedback sensor principles for different motor types were described. It has been shown that the TLE49x6 family of chopped Hall effect switches is well suited to be used for motor commutation in BLDC applications. Especially the TLE4946-2K and the TLE4946-2L are designed to achieve the best possible performance out of BLDC motors.

Many motors control systems need precise position feedback for servo applications. In the past, optical encoders were a leading choice for this purpose. Advances in Infineon's iGMR technology now make it possible to achieve high speed, resolution and accuracy with the TLE5012, which together with its robustness and versatility make it the product of choice for next generation position feedback systems.

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Terminology

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
HVAC	Heating Venting Air Conditioning System
PMSM	Permanent magnet synchronous motor
PWM	Pulse Width Modulation
SPI	Serial Peripheral Interface