Application note

Sensors for motor control feedback loops

Melexis
INSPIRED ENGINEERING

1. Scope

This document provides an overview of Melexis magnetic position sensors for motor commutation and/or positioning. Discover three types of magnetic position sensor IC and their general concepts: latch/switch, linear Hall or resolver.

2. Contents

3. Why use a position sensor with a motor driver?

Electrical motor drive is a complex domain with as many use cases as we have applications. In this area there are Motor drivers that can perfectly operate without a position sensor (sensor less). So why add extra component(s)? Let's first distinguish the two possible roles that can play a position sensor here.

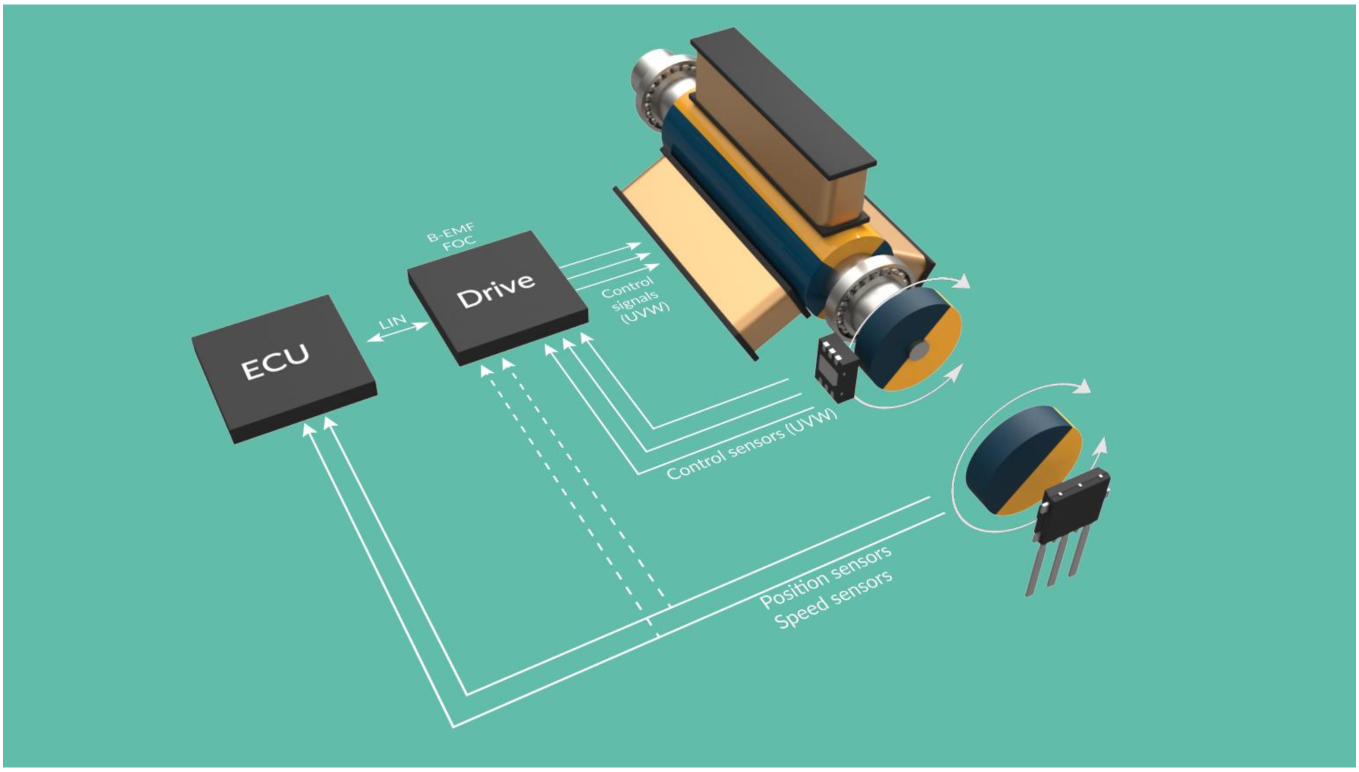


Figure 1: General Building Blocks and paths to enable motor commutation and application positioning

Motor control can have multiple feedback loops: one for the motor commutation and one for the positioning. These control loops do not necessarily use the same position sensor since different characteristics are needed to optimize the system and BOM. Position sensors improve the control on the system: position, torque and speed.

Position Control

- Enables a known (safe) position at startup and throughout motion
- No missed steps when using stepper motor

Torque Control

- Enables low speed and low noise generation especially for larger motors like pumps

Speed Control

- Enables Reliable startup
- Low speed drive
- Capability to handle highly dynamic loads

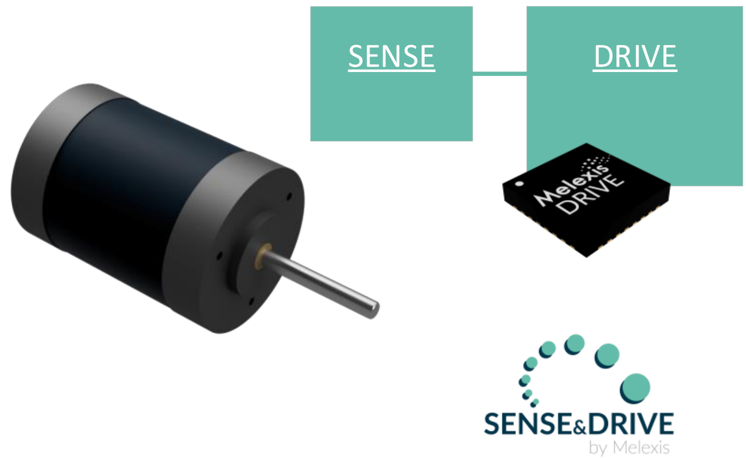


Figure 2: Benefits of a position sensor in motor drive application

3.1. Motor commutation

Position sensors can be an integral part of the **motor commutation** control loops for several types of electrical motors.

The motor control algorithm determines the currents through the coils and the timing of those currents. The angle of applied field has to be in quadrature to the rotor's field direction for maximum efficiency.

Concepts will be detailed in a later chapter but note that the type of motor control algorithm is linked with the motor design and the sensor type. For example, brushless motors can work with trapezoid control, sinusoidal control and field-oriented control:

- Trapezoid control, the basic, can use latch/switch readout for the position of the rotor. It is sufficient for a Brushless DC motor (BLDC). This concept supports high speed but torque ripple might be present and unwanted. Imagine an accelerating electrical car where the acceleration is not smooth.
- Sinusoidal control or Field Oriented Control will behave better however they require an accurate angle position of the rotor (an angle with much higher resolution). The more accurate, the higher the efficiency will be and, in some cases, even better safety. These control algorithms can also be used for a Permanent Magnet Synchronous Motor (PMSM).

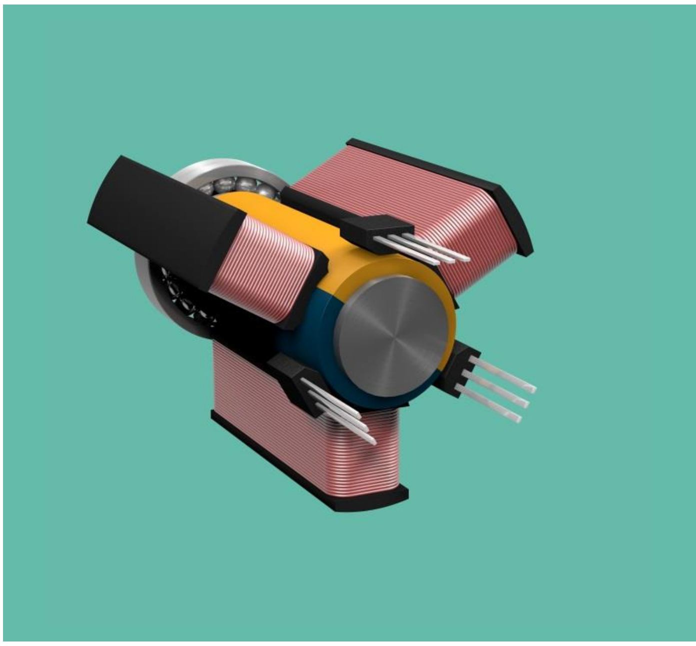


Figure 3: latch and linear principle

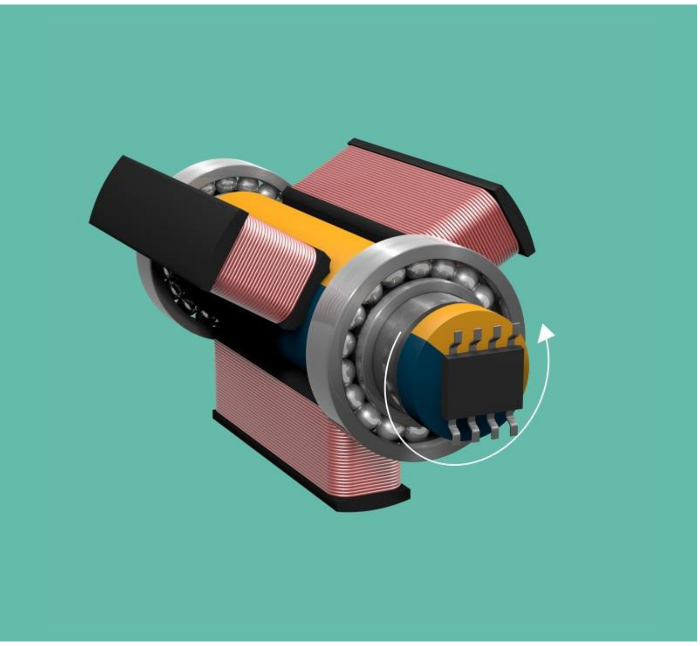


Figure 4: resolver principle

3.2. Application positioning

Position sensors can be required for the **application positioning**. Take for example a critical smart valve. The position sensor ensures a correct position of the valve independently from its motor position. Another example is a robot arm where the servo motor accurately positions a joint.

Here, the sensors needed for motor positioning might be the one(s) used for motor commutation. This is especially true if the rotor shaft's position and the motor's output shaft are 100% correlated. This is not always the case however. In some cases, an internal gear box converts a high speed/low torque rotor to a lower speed/higher torque output shaft. It then might be necessary to put an additional – lower speed-sensor on the output sensor.

4. Melexis Products

4.1. Sensor ICs for motor commutation

This chapter gives a high-level overview of 3 different hall-based product categories for motor commutation: latch/switch, linear hall and resolver.

Motor Commutation (High speed)	Low resolution	High resolution
Multiple IC	Latch/Switch	Linear Hall
Single IC (or dual IC for redundancy)		Resolver

4.1.1. Motor commutation with Latch/Switch

Latch/Switch products are placed in the stator in a multi-IC configuration. They are interesting for trapezoid control of BLDC motors: 3 ICs are used, 1 for each phase.

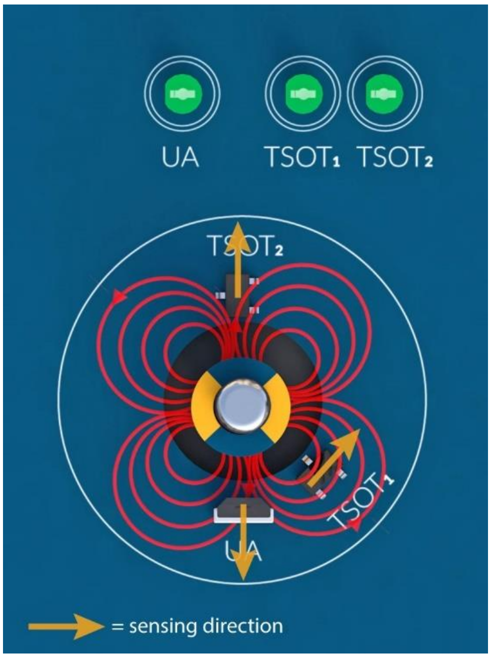


Figure 5:
lateral or perpendicular sensing

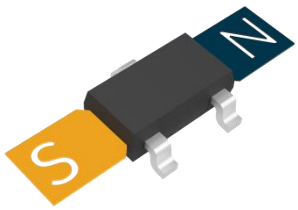


Figure 6:
lateral / X-axis

Figure 7:
Perpendicular / Z-axis

Melexis provides a whole range of Hall Effect latches with fixed, pre-programmed or programmable parameters. Next to the traditional sensors which are sensitive to the magnetic flux density that is applied perpendicular to the die surface, Melexis offers latches that sense a lateral magnetic flux density. This feature brings a large flexibility in the positioning of the sensor versus the magnet (rotor or sensing magnet). The sensors are available in a single die TSOT-3L or TO92-3L. Melexis also offer the first ASIL-B capable latch/switch on the market.

Discover more

- Latch/Switch with IMC technology, for motor commutation
- Latch/Switch selection guide

4.1.2. Motor commutation with Linear Hall

A linear Hall Effect sensor can be used to replace the hall Latch sensors. Using multiple sensors in quadrature gives the absolute angle of the rotor with high angle resolution. Their analog output makes it possible to calculate, with a dedicated algorithm, a much more accurate rotor position. This makes them not only suitable for detecting the motor commutation point but also for an accurate position control.

Two linear hall sensors placed at a 90° magnetic phase shift can also be used as a sine cosine angle sensor. The angle α is calculated from the arctangent of SIN over COS.

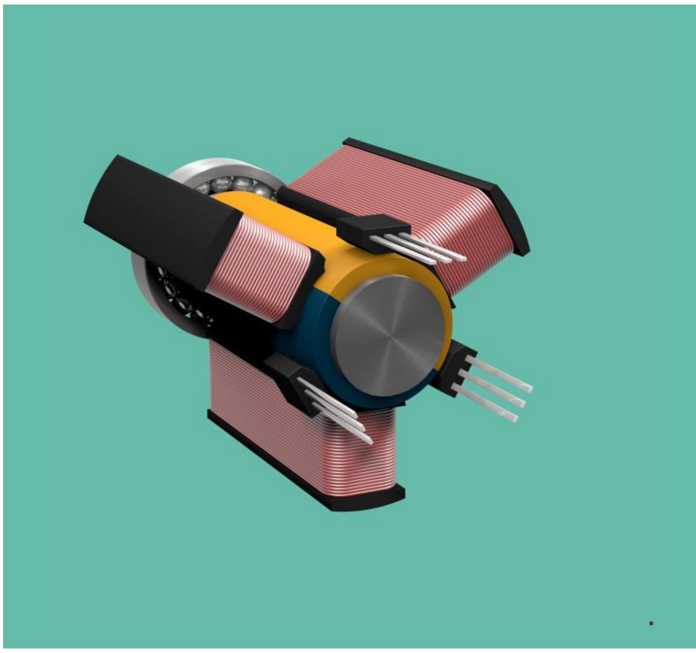


Figure 8: setup with 3 sensors

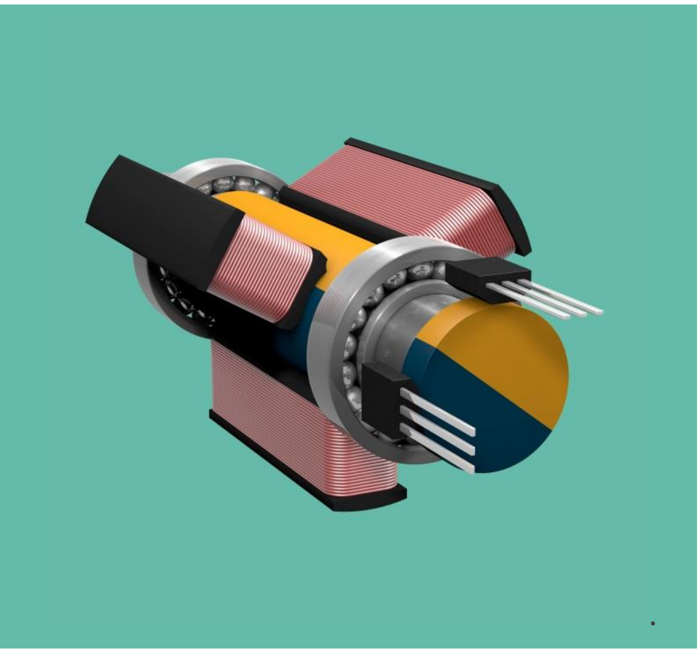


Figure 9: setup with 2 sensors

Discover more

- MLX90290, High Speed Pre-Programmed Linear Hall IC, analog ratiometric output
- All Melexis Linear Hall ICs

4.1.3. Motor commutation with Magnetic Resolver

Magnetic Resolvers, also known as resolvers or motor resolvers, are fast IC solutions which provides ratiometric analog sine-cosine outputs. These outputs are representative of the rotor magnetic flux and thus can be used to detect the motor position. The latest generation can be placed either on-axis (End of Shaft) or off-axis (Though Shaft).

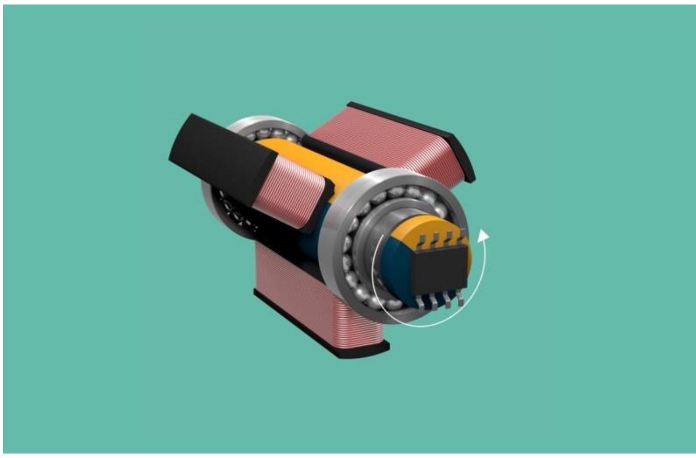


Figure 10: End of Shaft

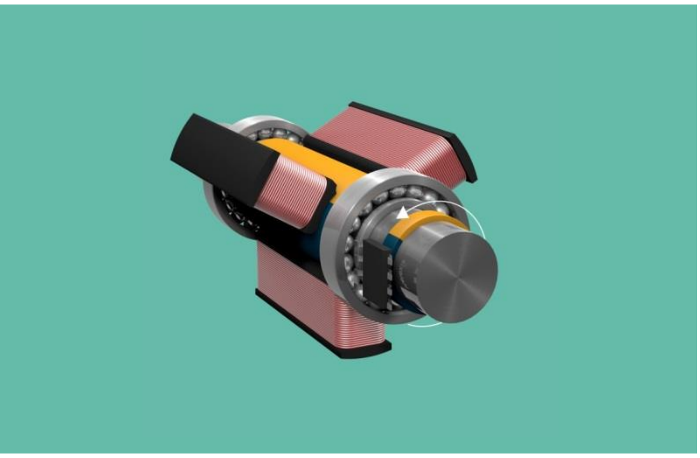
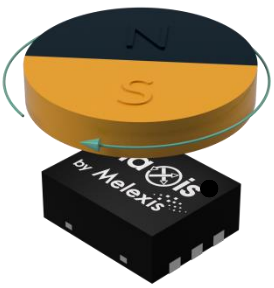
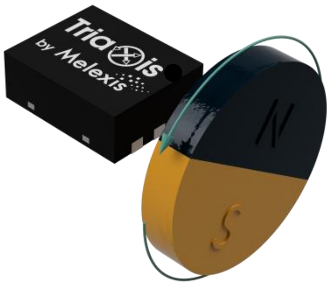


Figure 11: Through Shaft

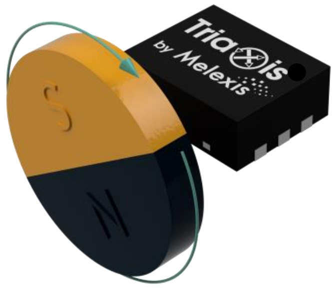
Triaxis® Resolvers have an X-Y-Z magnetic axis configuration. This feature brings a large flexibility in the positioning of the sensor versus the magnet (rotor or sensing magnet).



X/Y Magnetic Axis



X/Z Magnetic Axis



Y/Z Magnetic Axis

OUT1 and OUT2 (Sine and Cosine signal) of the sensor can be configured in X/Y magnetic axis, X/Z magnetic axis or Z/Y magnetic axis for End of Shaft or Through Shaft sensing.

Discover more

- MLX90380, Triaxis® Resolver, 360 Degree, two ratiometric analog outputs, high speed
- MLX90381, Triaxis® Pico-Resolver, 360 Degree, two ratiometric analog outputs, high speed
- Magnetic position sensors selection guide

4.2. Sensor ICs for positioning

Some motor applications have an extra control loop for positioning. Think for example a valve for which the actuator run at lower speed. Or when application uses an internal gearbox to convert a high speed/low torque rotation to a low speed/high torque rotation. Due to wear in the gearbox, the 1-1 relation between rotor position and motor output shaft is lost. As such, some designs put an extra position sensor on the output shaft.

Application Positioning (Lower speed)	Raw information (Embedded)	Computed angle (Standalone)
Combined with the motor commutation	Latch/Switch	
	Resolver	
	Linear Hall	
Specific performances	Triaxis Value Optimized (Magnetometer)	Triaxis Mainstream (MLX9042x)
High performances		Triaxis Performance (MLX9037x)

The products mentioned for the motor commutation are very focused on high speed. Their update rate is expressed in few µs, and they generally output a raw information. This information is then treated by the related MCU. For the application positioning, the fast response is no longer the main focus. Therefore, we can use “smarter” sensor that output an already computed angle information. Such a sensor benefits from a DSP and therefore offers more functionalities (signal compensation, programmable diagnostics…) which can further simplify the system design. Melexis offers a wide range of angular position sensors at lower speeds. Here, low speed means an update rate from 200µs.

Discover more

- MLX90392/3/5/7 (Value optimized), Magnetometers requiring post processing. For consumer or automotive applications.
- MLX9042x (Mainstream), Magnetic Position Sensor for cost conscious but demanding applications.
- MLX9037x (Performance), Magnetic Position Sensor with the highest performance, safety and feature set requirements.
- Selection guide Magnetic position sensors - Triaxis® for Automotive and Industrial
- Selection guide Magnetic position sensors - Triaxis® for E-mobility, Smart appliance, Home, Industrial & Medical

4.3. Driver ICs for actuator

Melexis' all-in-one LIN motor driver and pre-driver reduces BoM and simplifies design of automotive mechatronic applications: motor-controlled flaps, valves, fans and pumps. The devices are also used in robotic systems and e-bikes/e-scooters.

They support 2-wire DC motor, 3-wire BLDC motor or 4-wire bipolar stepper motor, using either **sensored** or **sensor less** field-oriented control (FOC) algorithms.

For sensored applications, Melexis is your one-stop-shop with Sense & Drive solutions.
Absolute angle position sensors can be used with Melexis' driver ICs, to drive and sense the position of a smart valve for efficient cooling of the battery or engine. It is also compatible with Melexis' pre-driver ICs to track the rotor position in smart pumps, to control the pump efficiently and dynamically with the right torque.

Our complete third generation of embedded drivers includes
- the LIN drivers MLX81330 and MLX81332 for 1...10 W applications
- the LIN pre-drivers MLX81340, MLX81344 and MLX81346 for 10...2000 W applications,
Note that with the MLX81346, Melexis is the first company to bring a fully integrated 48 V pre-driver System-on-Chip (SoC) to the market.

Discover more

- LIN motor driver (current < 1 A)
- LIN motor pre-driver (current > 1 A)
- Selection guide Smart LIN motor drivers

5. General concepts

5.1. Latch and Switch

5.1.1. Switch point

Magnetic Latch/Switch are digital semiconductor device that are activated in the presence of a magnetic field. The output of a latch changes state when a magnetic field, of sufficient strength and appropriate polarity is applied, crosses the operating point threshold (Bop). The device will "latch" its state when the applied magnetic field is removed (0mT). The state will be releases when a magnetic field of sufficient strength of the OPPOSITE polarity is applied that crosses the release point threshold (Brp).

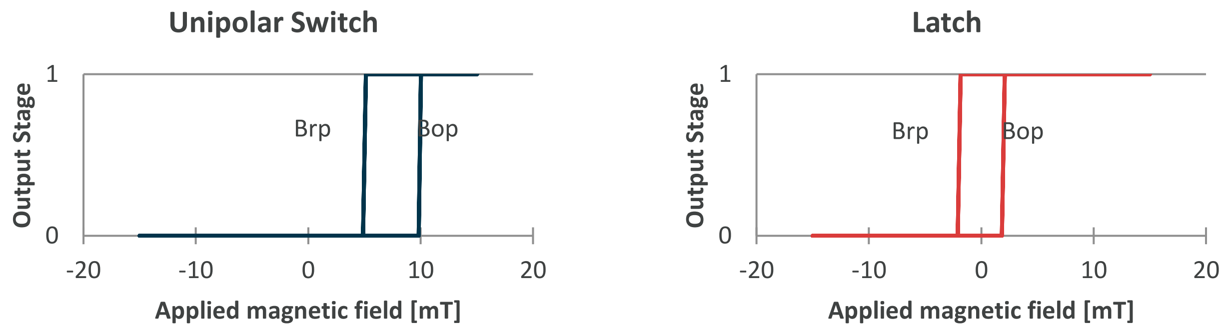


Figure 12: switching point latch and switch

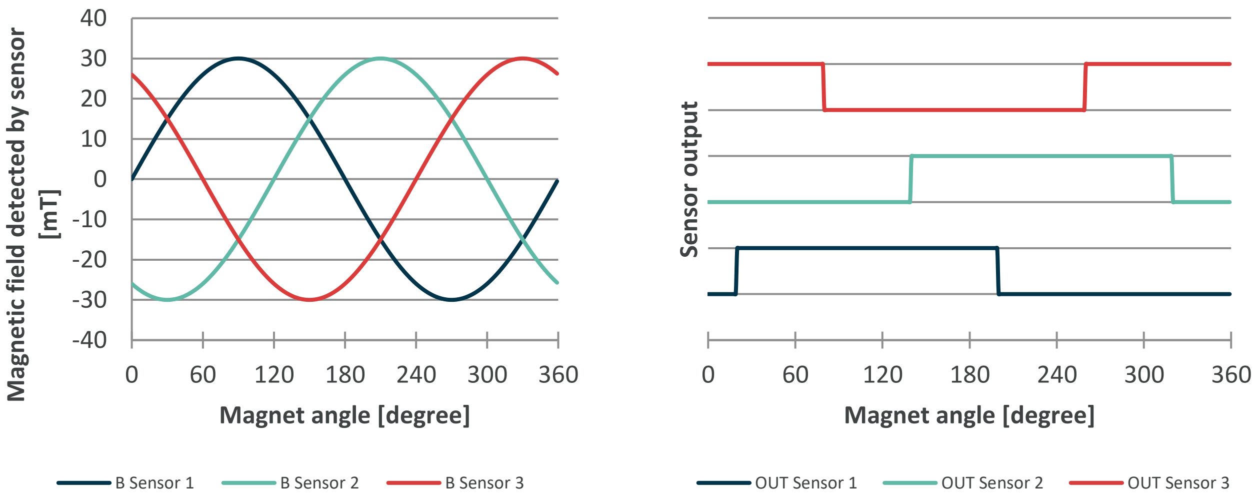
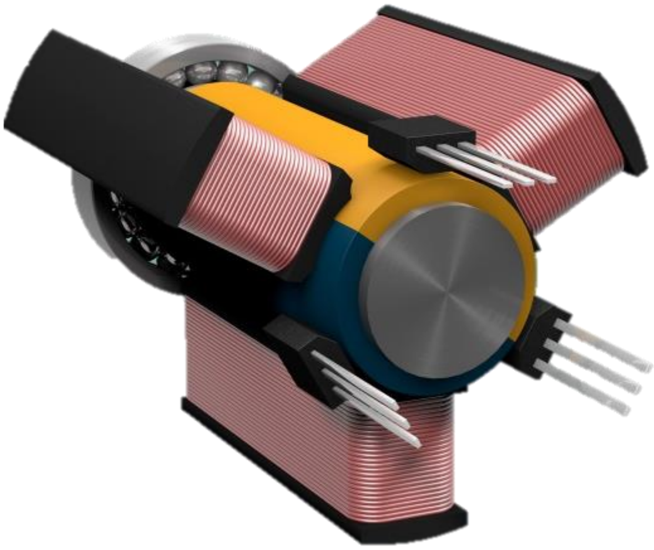


Figure 13: latch and switch sensor signals

The sensors in a motor commutation are used to detect the rotor position while the rotor turns. For a standard 3 phase system the sensors will generate three square wave signals with a duty cycle of 180° each shifted with 120°. It results in a switching pattern of three digital signals which generate a unique code every 60°. In other words, the three sensor signals can give a rotor position with a resolution of 60°. When the sensors are mechanically aligned correctly, the signals can be used for the communi cation point of the motor.

The Figure 13 shows the sensors output signals.



The next chapters give an overview of the typical characteristics that latch and switch sensors face in the motor commutation application.

5.1.2. Signal Delay

The Bop and Brp points of a switch or latch have a direct impact on the accuracy of the signal duty cycle and the magnetic angle of the switching point. The Bop level creates a trigger delay form the 0mT crossing. The relation of Brp vs. Bop determines the duty cycle of signal.

Figure 14 shows the output signals of a unipolar switch with a Bop at 10mT and a Brp at 5mT. The Bop creates a signal delay of 20°. The Brp vs. the Bop sets set the duty cycle at 150° over 360° = 41.7%.

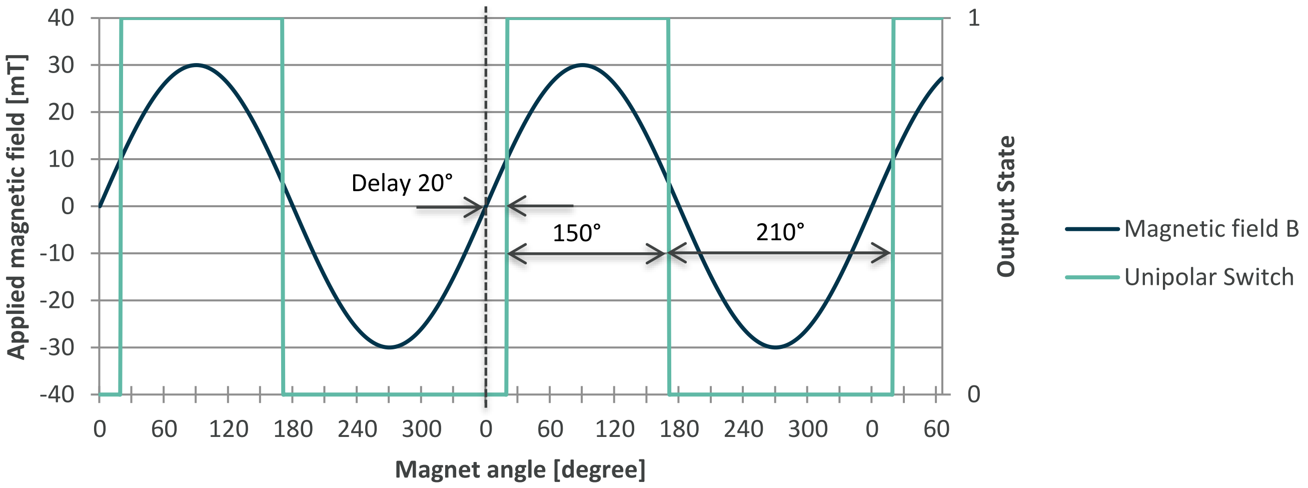


Figure 14: switch point unipolar switch

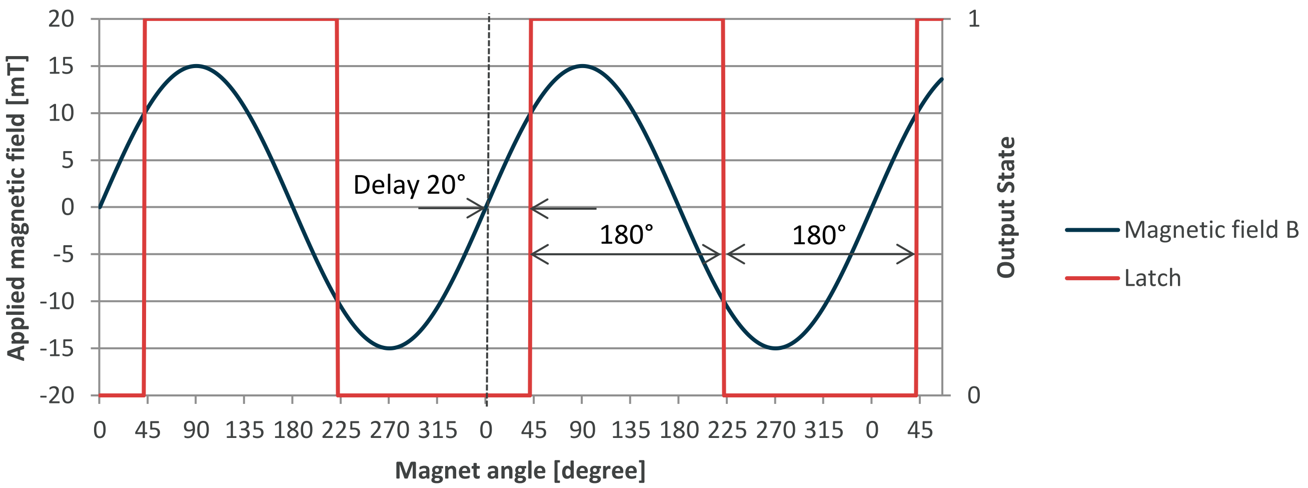


Figure 15: switch point latch

Figure 15 shows the output signals of a latch with a Bop at 10mT and a Brp at -10mT. The Bop creates a signal delay of 20°. The Brp vs. the BOP sets the duty cycle at 180° over 360° = 50%.

The new generation latches are equipped with a non-volatile memory that is used to accurately trim the switching thresholds and define the needed output magnetic characteristics (TC, Bop, Brp, Output pole functionality). In Figure 16 Bop is set to 0.5mT and Brp to -0.5mT. In this setup the signal delay is reduced to 2° with DC = 50%.

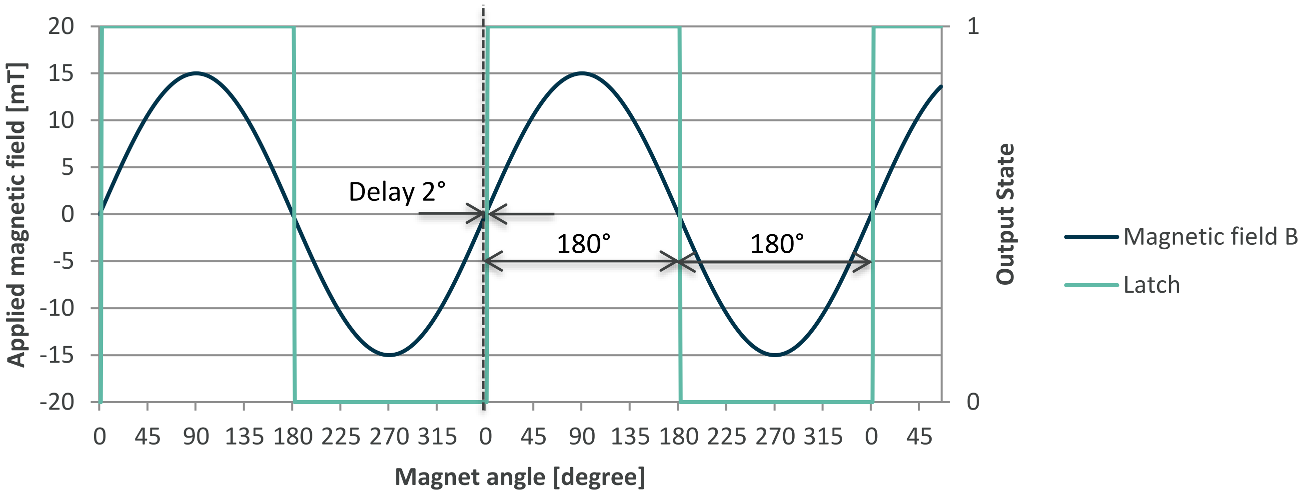


Figure 16: switch point latch

Also, the sensors Refresh Period and the Output Rise/Fall Time can have an influence on the signal delay. Their significance or impact on the signal delay depends on the speed/RPM's at which the motor operates. The Output Rise/Fall Time depends on the load capacitor and pull-up resistor placed on the output of the sensor.

5.1.3. Bop – Brp Accuracy

The accuracy of the sensors magnetic switching points, Bop and Brp, are affected by the semiconductor manufacturing process spread. The process spread creates a part to part variation on the (3) sensors parameters. Important highlights are the programmability of Melexis Latch/Switch and Melexis final test which is done on 100% of the parts to absorb the part to part process variations.

Figure 17 shows the effect that the Bop and Brp tolerances have on the duty cycle of the sensor signal. For example: a typical switching point of Bop = 2mT and Brp = -2mT the duty cycle is 50%. For the minimum switching point where Bop = 0.6mT and Brp = -3.8mT, the duty cycle is ~51%. For the maximum switching point where Bop = 3.8mT and Brp = -0.6mT, the duty cycle is ~48%.

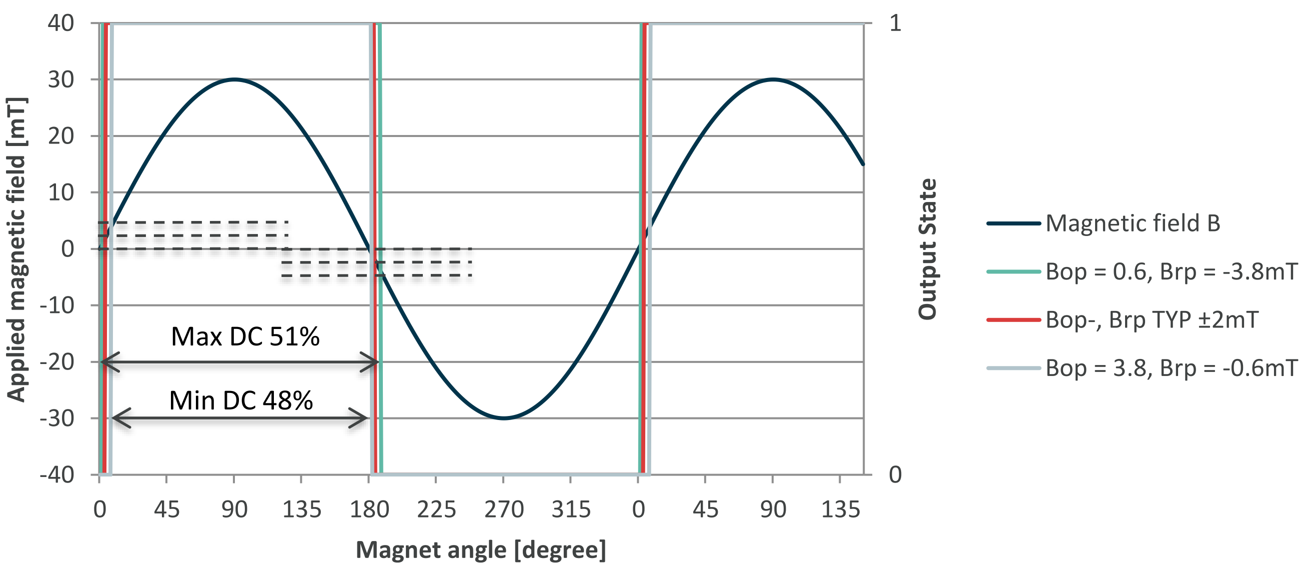


Figure 17: Bop and Brp specification

5.1.4. Jitter

Next to the tolerances on the Bop and Brp, there is also the jitter on the Bop and Brp points of the sensor. The jitter of the sensor is linked to the response time of the sensor. This will determine the repeatability of the switching point over time and over speed.

5.1.5. Temperature behavior

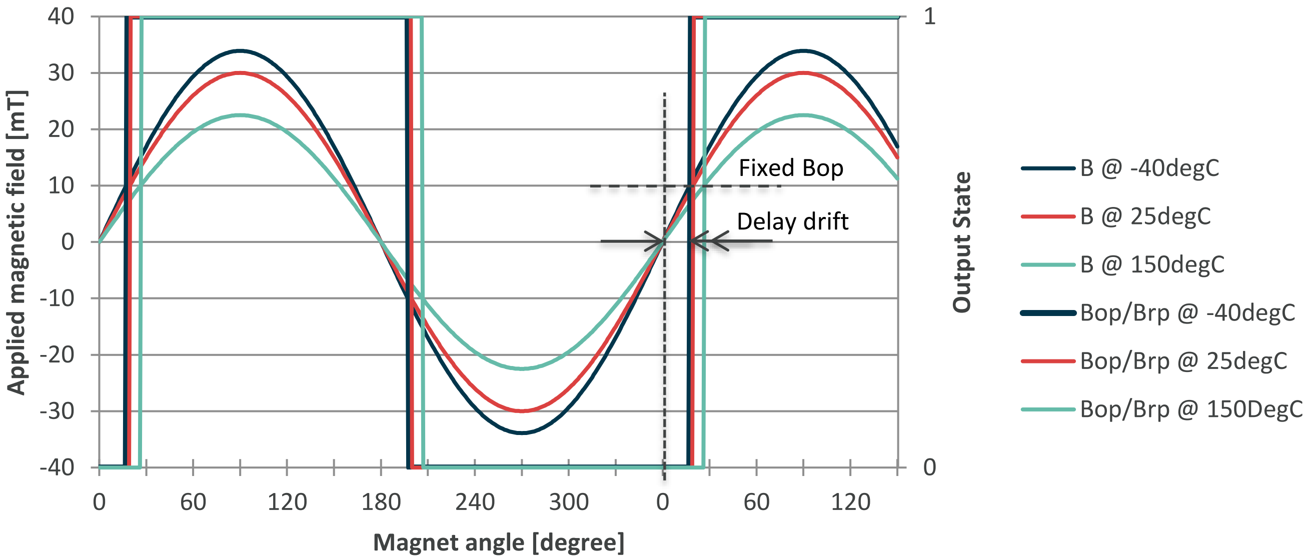


Figure 18: temperature behavior of a fixed Bop and Brp.

Melexis latch and switch sensors can compensate for thermal drift properties of the magnet (the so-called TC).

Permanent magnets lose some of their strength over temperature and over time. The temperature effect is reproducible. Increasing temperature gives lower field, decreasing temperatures gives higher field for the same position. Because of this the amplitude of the flux density B seen by the sensor varies over time by thermal and aging effects.

Figure 18 shows the effect of temperature variations on the switching point with a fixed Bop and Brp level. As the switching point is fixed to a specific flux density, the magnetic angle at which the Bop/Brp switches will drift over temperature.

To fix this switching angle over temperature, Melexis latch and switch sensors are foreseen with a programmable Built-in Negative TC coefficient. As such, these sensors counteract the magnet's thermal drift as illustrated in Figure 19. The red curve w/TC Bop-Brp is temperature **independent.**

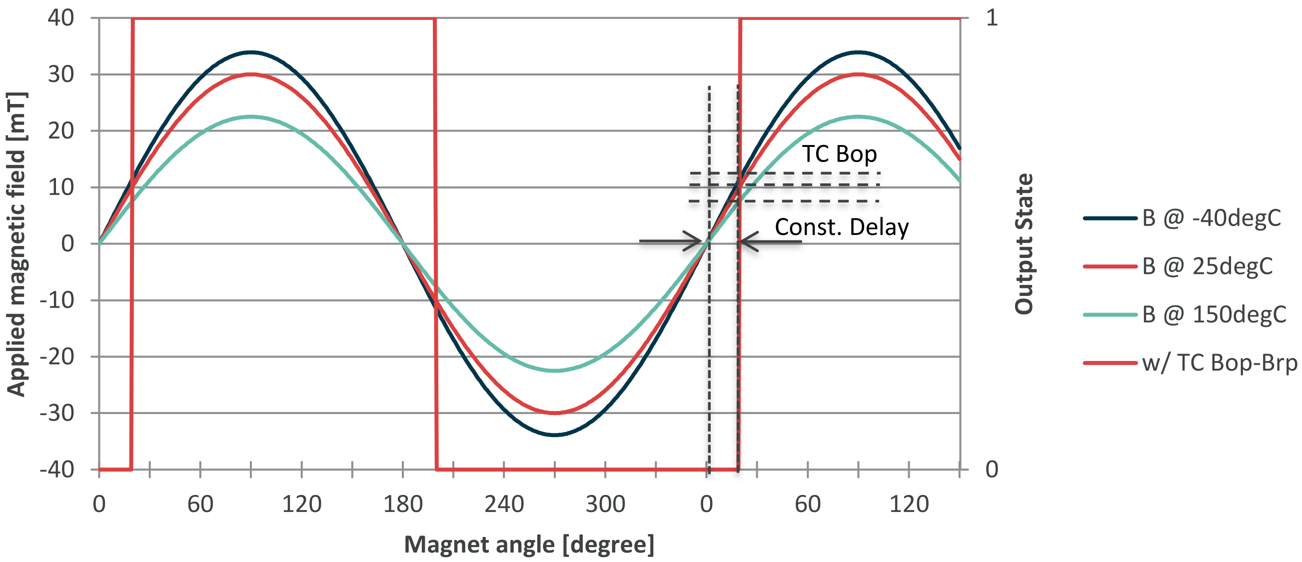


Figure 19: temperature behavior of a Bop and Brp with temperature compensation.

5.2. Linear Hall

The Melexis high speed pre-programmed linear Hall-effect sensor is designed in mixed signal CMOS technology. It is an analog sensor with an output voltage proportional to the applied magnetic field and to the chip supply voltage (ratiometric). The Output Offset Level (Quiescent Level) at zero magnetic field is equal to 50% of the chip supply voltage.

A linear Hall Effect sensor can be used to replace the hall Latch sensors to detect the position of the rotor. Their analog output also makes it possible to calculate, with a dedicated algorithm, a much more accurate rotor position. This makes them not only suitable for detecting the motor commutation point but also for an accurate position control of the motor.

Two linear hall sensors placed at a 90° magnetic phase shift can also be used as a sine cosine angle sensor. The angle α is calculated from the arctangent of SIN over COS.

For the accuracy
- The resolver sensor uses similar tips/tricks as this multi linear Hall Effect sensor configuration. Here, both benefit from an algorithm to absorb sensitivity and offset variations. The typical min/max algorithm can be used here. More details are mentioned in the next section.
- As the linear Hall Effect sensors are used in a multi-sensor configuration, the positioning of the individual sensors is more important than on a single resolver sensor configuration. Also, the part to part variations caused by the semiconductor process spread will play a role in the module performance. Although, Melexis final test on 100% of the parts will absorb most products variations.

For the behavior over temperature
Also, note that the MLX90290 (Linear Hall sensor IC) can compensate the magnet thermal drift.

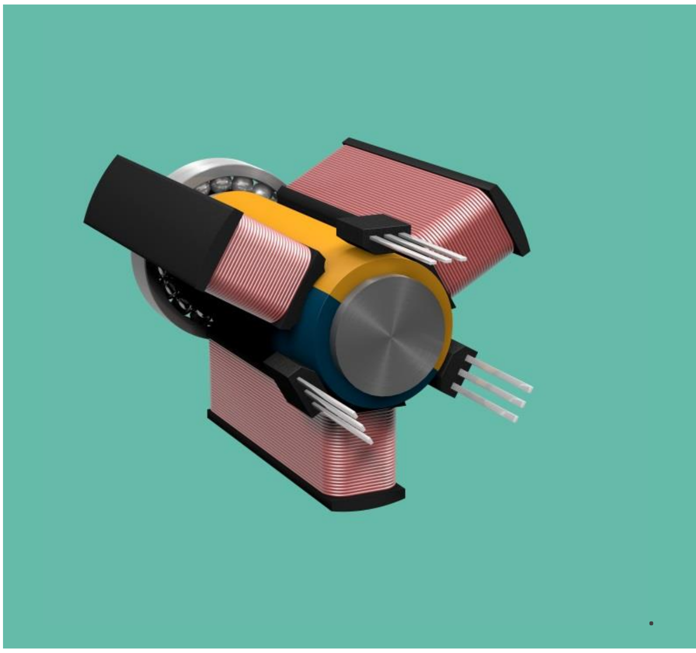


Figure 20: setup with 3 sensors

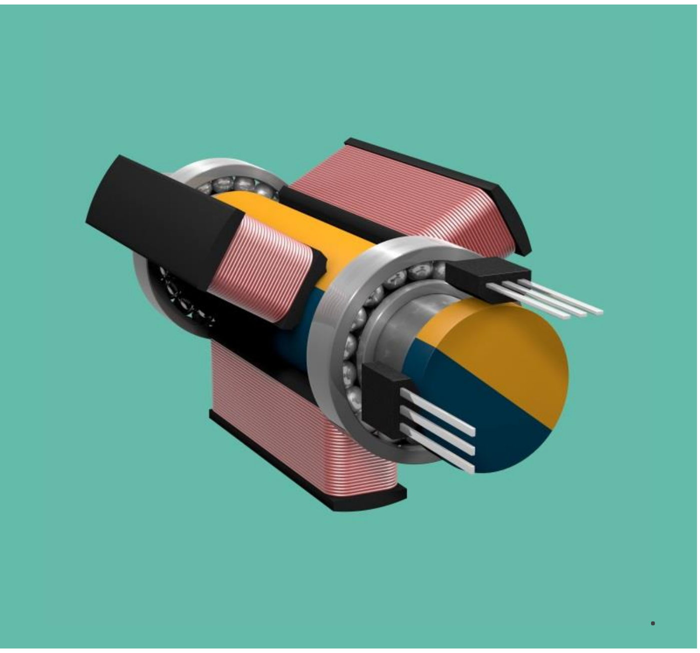


Figure 21: setup with 2 sensors

5.3. Magnetic Resolver

The magnetic resolver sensor is a monolithic sensor IC sensitive to the flux density applied orthogonally and parallel to the IC surface. High-speed dual analog outputs allow the resolver to deliver accurate, contact-less, true 360° sine/cosine signals when used with a rotating permanent magnet.

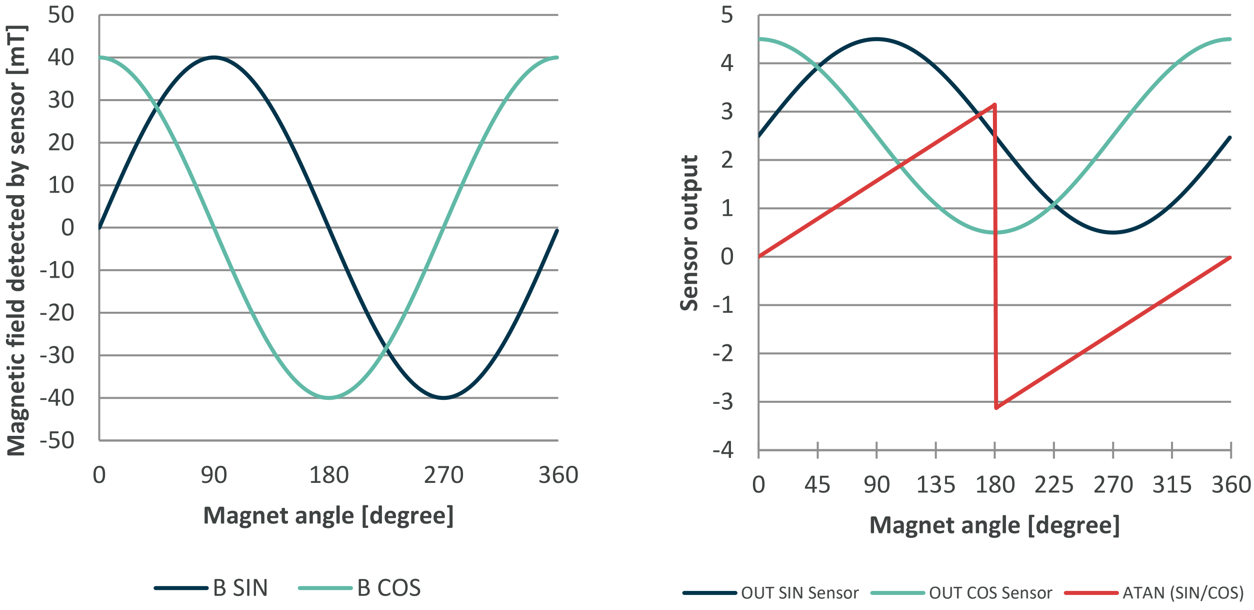


Figure 22: resolver sensor signals

In motor commutation the resolver sensors are used to detect the rotor position while the rotor turns. The sensor(s) will give one full sine and cosine signal for one full 360° magnetic rotation. With the arctangent, one can calculate the angle from the sine/cosine signals.

Resolver sensors give a higher angle accuracy making them suitable for absolute motor position control. The next chapters give an overview of the typical characteristics of resolvers for motor commutation applications.

5.3.1. End of shaft vs. through shaft applications

Next to the temperature and aging effects of the magnet there is some non-ideal behavior of the sine and cosine signals induced by the application, magnetic construction of the application and the magnetization of the magnet. Those non-ideal behaviors can be split in four main categories:

- Offset Mismatch of B_{SIN} and B_{COS};
- Sensitivity Mismatch or amplitude mismatch of B_{SIN} and B_{COS};
- Orthogonality Error or phase shift between B_{SIN} and B_{COS};
- Signal Non-Linearity of the B_{SIN} and B_{COS}.

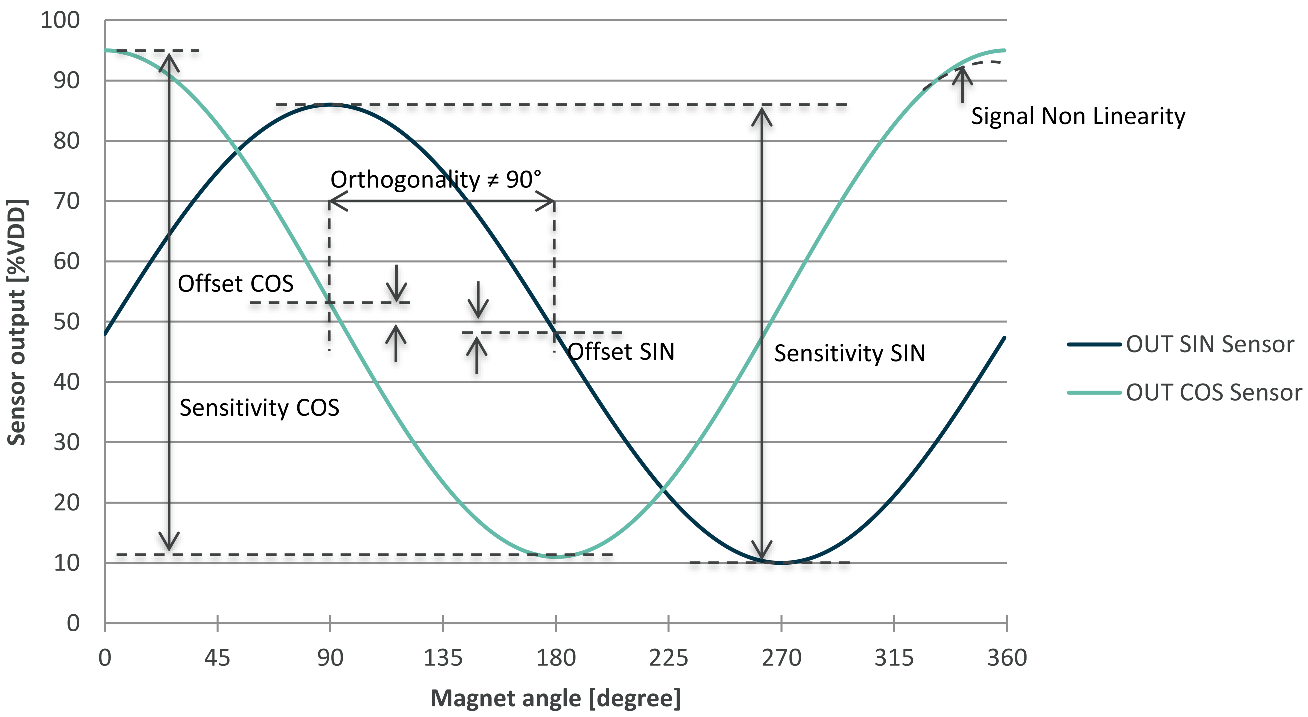


Figure 23 Non-ideal behavior of the Sine & Cosine

Figure 23 gives an overview of the four non-idealities: offset drift, sensitivity drift, orthogonality drift and signal non-linearity. A dynamic min-max algorithm can cancel out offset drift & sensitivity drift.

Important: note that most of the mentioned characteristics can be compensated by a 'clever motor control algorithm'. For example, the signal delay is predictable. The motor control algorithm as such can compensate. A min-max algorithm can absorb sensitivity and offset thermal drift variations. Such min-max method adjusts offset and sensitivity of the two individual components. More detailed information on magnetic resolver IC can be found in MLX90381-End-of-line-calibration-application-note.pdf

For end of shaft applications, the non-ideal behaviors are relatively small as the flux density and the curve of the field lines remain fairly stable at the sensing point of the magnetic field angle while the magnet turns. “The sensor always measures the angle of the same field lines”.

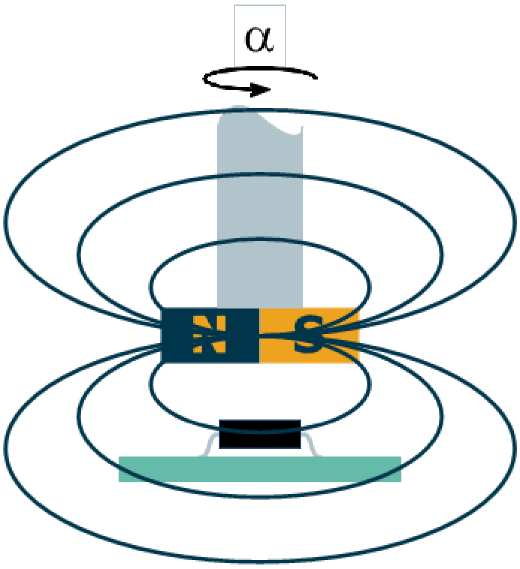


Figure 24 gives an end of shaft application.

For through shaft applications the non-ideal behaviors are larger as the variation in flux density and the curve of the field lines are larger at the sensing point of the magnetic field angle while the magnet turns. “The sensor crosses different field lines”.

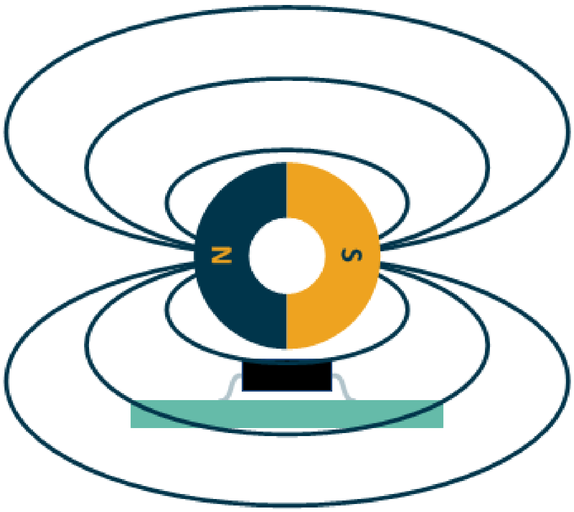


Figure 25 gives an off-axis solution

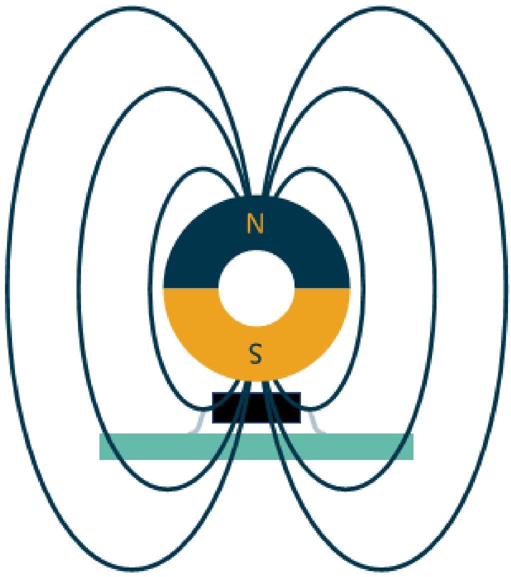


Figure 26 is the same application as Figure 26, but 90° rotation of the magnet.

For a multi-pole magnet, the sensor will report for each pole pair a full magnetic rotation. The magnetization and symmetry of the magnet poles have a large influence on the symmetry of the sine and cosine signal of each magnetic rotation and therefore also on the achievable system accuracy.

5.3.2. Angle non-linearity correction

There are various techniques to correct the angle error of the application. For the front-end calibration, the sensitivity mismatch and offset mismatch, there is the MIN-MAX method where the sensitivity and offset of the SIN and COS are normalize based on the measured amplitude of the two signals. As a back-end calibration one can apply a piece wise linearization on the calculated angle by the arctangent.

For more information on the topic, please refer to the application note MLX90381-End-of-line-calibration-application-note.pdf

5.3.3. Signal Delay (example with the MLX90380)

The Signal Phase Shift error or PHI is a between the $B_{COS} - B_{SIN}$ components of the magnetic field and the analog output signal, $OUT_{COS} - OUT_{SIN}$. This is phase delay is caused by the signal process time or output update rate of the sensor.

The signal process time of the sensor T_{PHI} is a constant delay expressed in µSec. The signal process time is determined by the bandwidth of the filter. The filter setting of the sensor is programmable. Note that a capacitor and series, pull-up or pull-down resistor on the output also has an influence on the signal delay.

In this example with the filter setting programmed at high bandwidth, the sensor output update rate is 12µs.

For a speed = $5'000\ RPM = 83.3Hz$

$$1\ Revolution = \frac{1'000'000\mu s}{83.3Hz} = 12'000\mu s$$

$$PHI = \frac{360°}{12'000\mu s} \times 12\mu s = \ 0.36°$$

For a speed = $25'000\ RPM = 416.6Hz$

$$1\ Revolution = \frac{1'000'000\text{s}}{416.6Hz} = 2'400\mu s$$

$$PHI = \frac{360°}{2400\mu s} \times 12\mu s = \ 1.8°$$

In this example with the filter setting programmed at low bandwidth, the sensor output update rate = 65µs.

For a speed = $5'000\ RPM$

$$PHI = \frac{360°}{12'000\mu s} \times 74\mu s = \ 2.22°$$

For a speed = $25'000\ RPM$

$$PHI = \frac{360°}{2'400\mu s} \times 74\mu Sec = \ 11.1°$$

So, the signal phase shift error PHI[°] is the absolute angle offset error (Magnet angle vs. Sensors output angle) in function of the magnet rotation speed.

Figure 27 gives the phase shift error for Low bandwidth at 25’000 RPM. B SIN (blue) and B COS (red) is the magnetic field applied to the sensor by a full 360° turn of the magnet. OUT SIN Sensor (green) and OUT COS Sensor (purple) are the sensor outputs proportional to the applied magnetic field with a 65µs delay from the sensor process time.

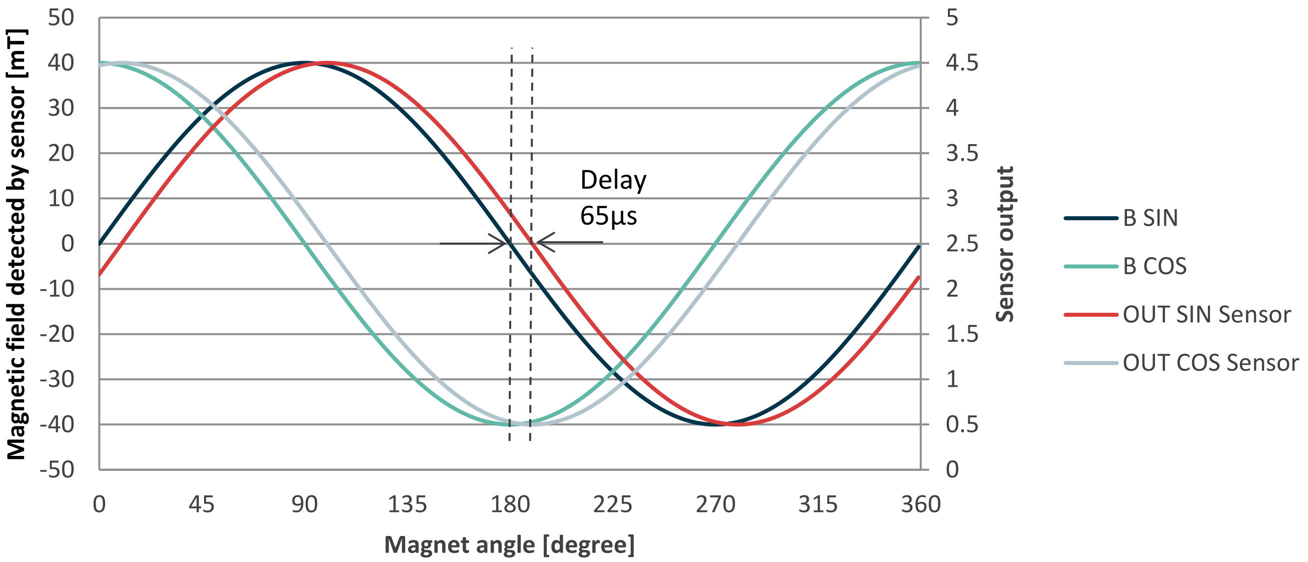


Figure 27 MLX90380 phase shift error for Low bandwidth at 25’000 RPM

Important: the motor control algorithm can account for the signal delay. As such, this effect can be nullified.

5.3.4. Magnet thermal drift

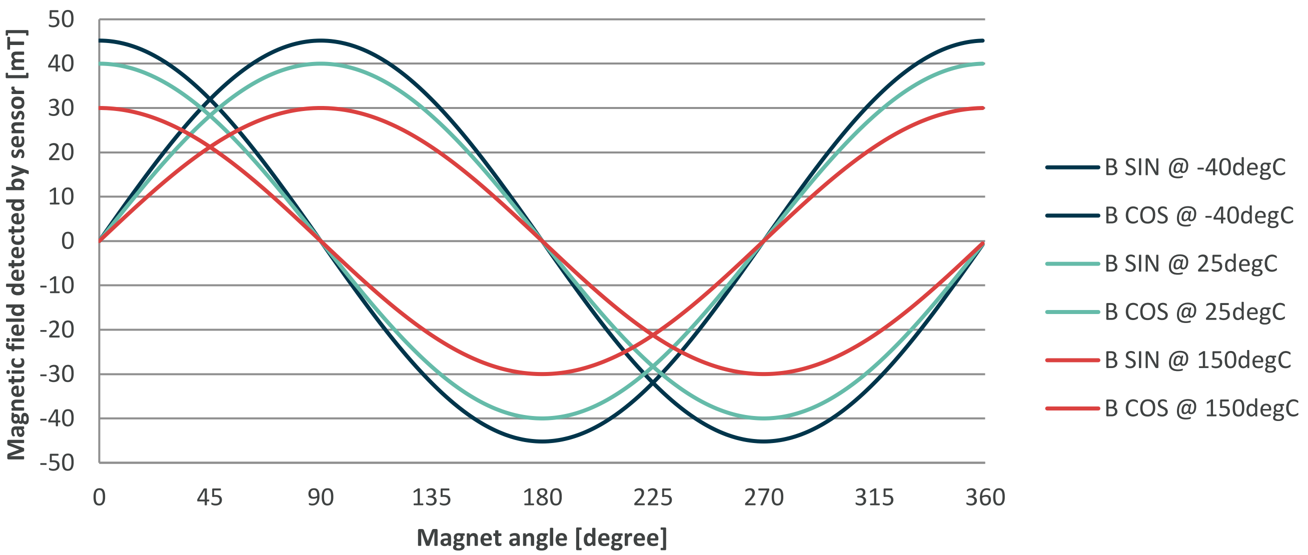


Figure 28 MLX90380 & Magnet thermal drift

Permanent magnets lose some of their strength over temperature and over time. Because of this the amplitude of the flux density B sin and B cos seen by the sensor varies over time by thermal and aging effects. As the OUT_1 and OUT_2 output voltages are proportional to the applied magnetic field, also the sensor outputs will vary over time by thermal and aging effects of the magnet.

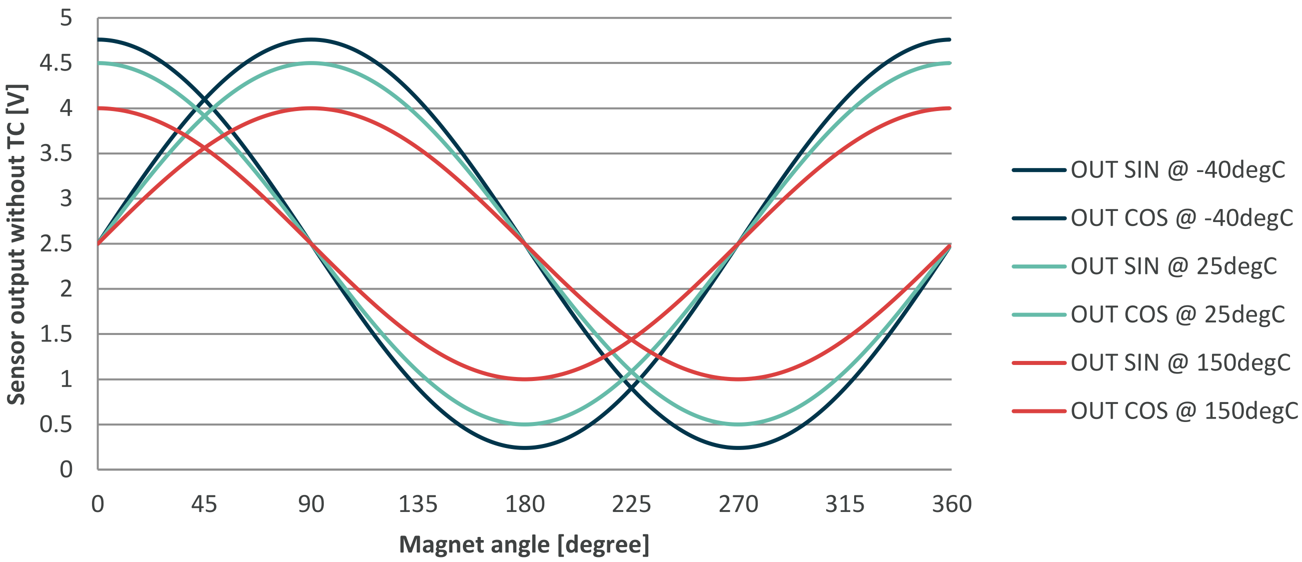


Figure 29 MLX90380 & Magnet thermal drift – without TC

Figure 29 gives the resolver output signal over temperature. Increasing temperature gives lower field strength and thus lower signal amplitudes. The latest Melexis products (latch/switch, linear and resolver) have internal magnet compensation. This is not shown in this figure. For applications with linear hall or resolver, the benefit is the 'raw' sine & cosine signal have an as-big-as-possible output, maximizing readout resolution.

The angle α is calculated from the arctangent of SIN over COS:

$$\alpha = \arctan\left(\frac{B_{SIN}}{B_{COS}}\right) \text{ or } \alpha = \arctan\left(\frac{OUT_{SIN}}{OUT_{COS}}\right)$$

This feature thus has improved thermal accuracy. The arctangent operation is performed on the ratio of OUT_{SIN}/OUT_{COS}. Thus, the angular information is intrinsically self-compensated vs. flux density variations, thermal or ageing effects, affecting both signals.

The resolver sensors with their sine/cosine signals on a single sensor have the greatest benefit from this feature. For rotary position sensor based on linear Hall sensors, the part to part variations caused by the semiconductor process spread will play a part in the performance improvement.

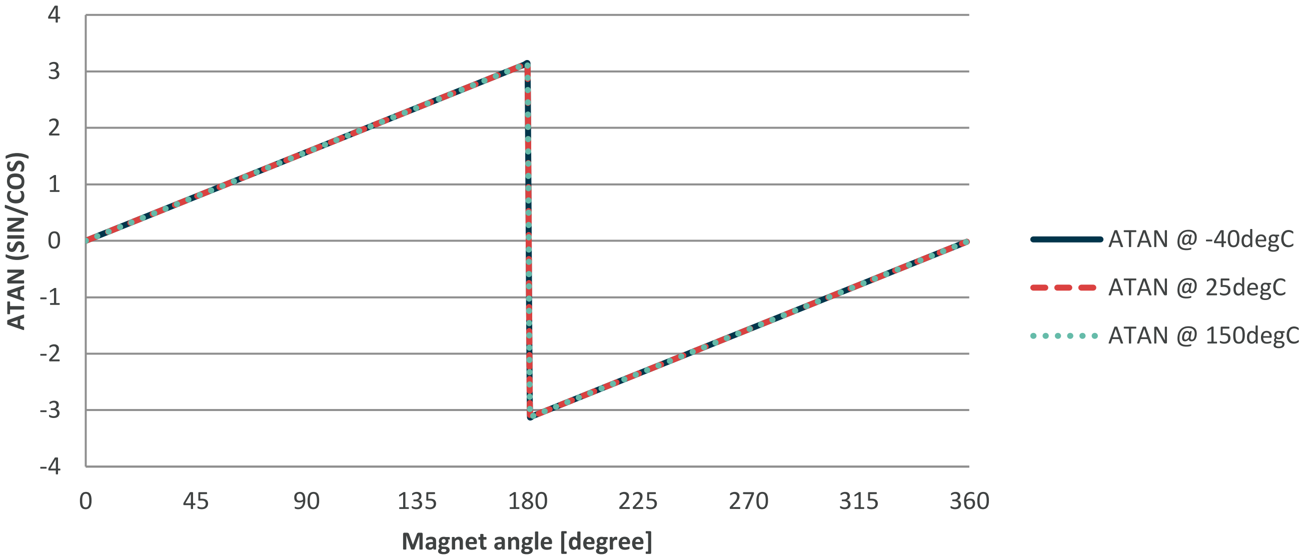


Figure 30 gives an angle output independent from temperature.

Two closing remarks: First, all latest Melexis products enable magnet thermal drift compensations. As such, they ensure the analog output signal span is as big as possible, maintaining as much resolution as possible for the readout circuit. Second, the control algorithm should apply for linear hall and resolver the min-max algorithm of MLX90381-End-of-line-calibration-application-note.pdf

6. Conclusion

As we have seen, motor driver can be supported by position sensors to meet specific application requirements related to the position, torque and speed control.
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