KMZ60 Application Note

KMZ60: Contact less magnet angle sensor

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Application Note

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Summary

This document explains the functionality of the KMZ60 angular sensor and gives the user helpful information for the design-in process of the device by several application and circuit examples. The document is illustrated with diagrams and figures to underline the given information. Further the functional background of the magnetoresistive effect (MR) will be explained.

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1. Introduction

1.1 The magneto resistive effect

Magnetoresistive sensors (MR sensors) of NXP Semiconductors make use of the fact that the electrical resistance of certain ferromagnetic alloys, such as permalloy, is influenced by the external magnetic fields. This solid state magnetoresistive effect – or anisotropic magnetoresistance (AMR) – is easily realized in thin film technology, allowing the production of precise but also cost effective sensors.

The purpose of this paper is to provide the necessary background for system design with NXP's KMZ60 magnetoresistive angle sensor.

1.1.1 Advantages of MR technology

As the magnetoresistive effect is naturally an angular effect, its utilization for contactless angle measurement systems fits perfectly. The underlying principle is simple: the electrical resistance of the permalloy strip changes with the angle between the internal magnetization vector in the strip and the vector of the electrical current flowing through it. Consequently, to achieve accurate measurements, the only condition to be met is that the internal magnetization vector of the permalloy must directly follow an external magnetic field vector. This is ensured when using external field strength much higher than the internal magnetization. As this strong external field saturates the sensor, the actual field strength has no impact on the measurements. Only the direction of the field is evaluated. This leads to the following advantages of the magnetoresistive angle measurement systems:

- Independence of magnetic drift during life time
- Independence of magnetic drift with temperature
- Independence of mechanical assembly tolerances
- Independence of mechanical shifts caused by thermal stress

Additionally, MR based systems show the same advantages as all other contactless measurement systems; they are free of wear and they can be completely encapsulated by non magnetic material making the sensor modules robust regarding contamination and mechanical destruction. All these advantages recommend magnetoresistive angle measurement systems for application requiring very robust and precise but also cost-effective solutions. This, for example, is the case in all automotive applications. All NXP angle measurement sensors and systems cover the automotive requirements.

1.1.2 Angle measurement with MR technology

Magnetoresistive sensors (MR sensors) of NXP Semiconductors make use of the magnetoresistive effect, the property of a current carrying magnetic material to change its resistance in the presence of an external magnetic field. Fig. 1 shows a strip of ferromagnetic material, called permalloy.

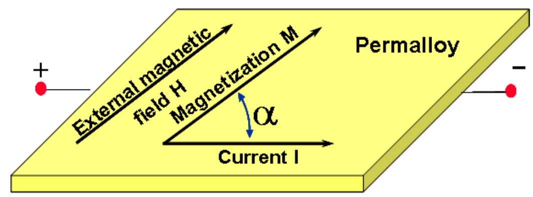


Fig. 1: The magnetoresistive effect in permalloy.

Assume that, when no external magnetic field is present, the permalloy has an internal magnetization vector M parallel to the current flow ($\alpha = 0$). If an external magnetic field is applied, parallel to the plane of the permalloy but perpendicular to the current flow, the internal magnetization vector of the permalloy will rotate around an angle α. As a result, the resistance R of the permalloy will change as a function of the rotation angle α, as given by:

$$R = R_0 + \Delta R_0 \cos^2 \alpha \qquad (1)$$

with

$$\alpha = 0° \quad => R_{max}$$

$$\alpha = 90° \quad => R_{min}$$

R_0 and ΔR_0 are material constants. With the material used by NXP, ΔR_0 is in the order of 2% to 3%. It is obvious from this quadratic equation that the resistance to magnetic field relation is non-linear. It becomes also clear that the magnetoresistive effect is naturally an angular effect recommending its utilization for angle measurement applications. Here the external magnetic field carries the measurement information between sensor and physical value to be measured.

Having this principle of operation in mind, it becomes clear that the precondition to achieve accurate measurements is that the internal magnetization vector M must directly follow the vector H of the external field. This can be achieved by applying an external field H much higher than the internal field of approximately 3kA/m. When using the KMZ60 for BLDC applications or angle measurement, it is recommended to provide an external field of at least

$$H \geq 25kA/m \qquad (2)$$

In this case the two vectors M and H are virtually parallel to each other.

Normally, the external magnetic field is generated by permanent magnets, e. g. samarium-cobalt (SmCo) types. Fig. 2 shows a basic set-up, where the angular position of a rotating shaft is measured with the help of the permanent magnet fixed to it.

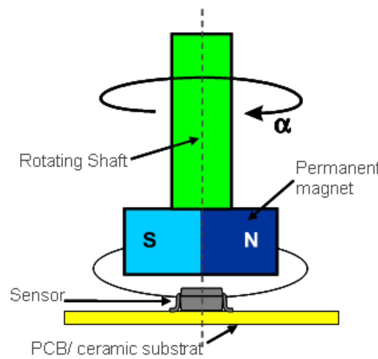


Fig. 2: Basic arrangement of sensor and magnet for contact less angle measurement.

The magnetoresistive angle sensors of NXP Semiconductors are etched on a silicon substrate, with four permalloy strips arranged in a Wheatstone bridge configuration which are connected to the sensor supply voltage V_{CCS} and to the sensor ground potential GNDS. This is shown in Fig. 3.

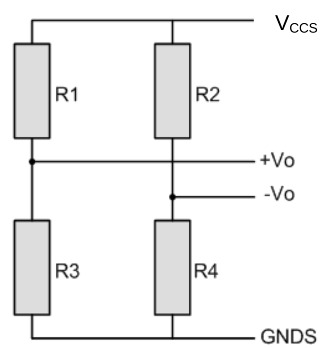


Fig. 3: Four permalloy strips in a Wheatstone bridge configuration.

According to the basic relationship given by Equation (1), the differential output signal (+Vo, -Vo) of such a Wheatstone bridge is proportional to $\sin 2\alpha$. This means that a sensor comprising one Wheatstone bridge can measure an angular range of 90°. This is visualized in Fig. 4.

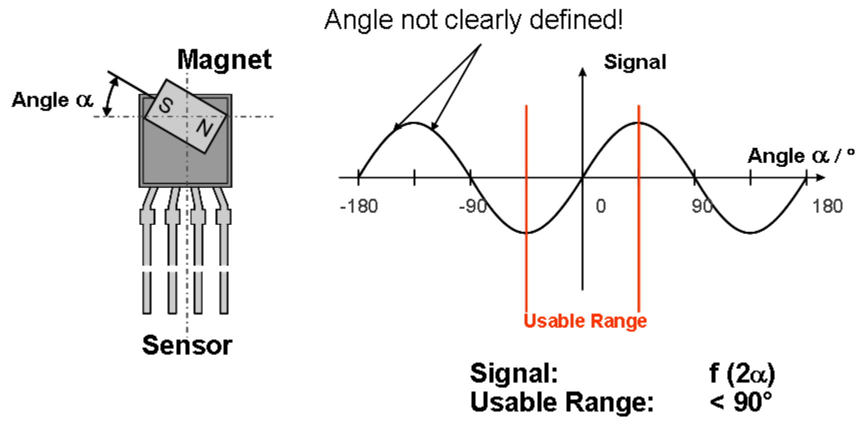


Fig. 4: Output signal from a single Wheatstone bridge sensor.

The limited angular range can be extended to 180° measurement range by using a two-bridge arrangement combined with a signal evaluation explained below. Fig. 5 shows the principle.

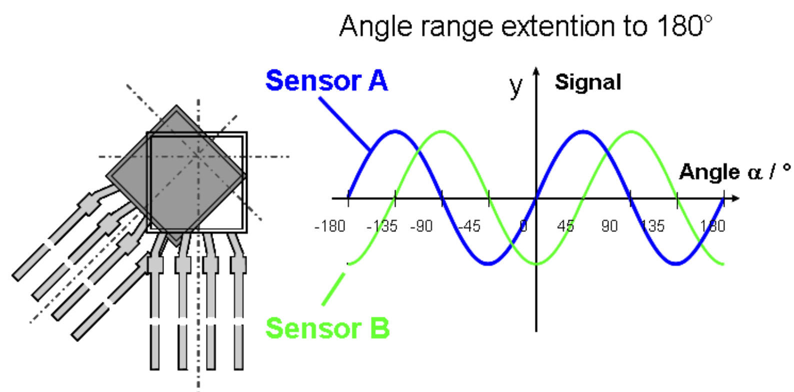


Fig. 5: Output signal from a double Wheatstone bridge sensor.

The two sensor bridges are positioned at an offset angle of 45° to each other. In this arrangement, two output signals show an electrical phase shift of 90°. The two signals are therefore proportional to sin2α and cos2α, respectively. It can be proved easily that these two signals now allow an evaluation of a 180° angular range.

Even in this arrangement, the signal amplitudes will change with the temperature. However, both bridges are processed in the same thin film process steps on the same substrate and they will therefore show very similar characteristics. The KMZ60 angle sensor has a temperature compensation implemented which can be used to compensate the effect of decreasing amplitudes at increasing ambient temperature. This will be explained in more detail in chapter 3.3.1.

Assuming that both output signals have no offsets or offsets have been compensated previously, the output signals can be described mathematically as follows:

$$X(\alpha,T)=X_0(T)\sin 2\alpha \qquad (3)$$

$$Y(\alpha,T)=Y_0(T)\cos 2\alpha \qquad (4)$$

Assuming further that the amplitudes of both signals are really identical ($X_0=Y_0$), because the sensor is integrated on one chip and both bridges are supplied by the same voltage, the unknown angle α can be determined without any error from the signals X and Y as given by Equation (5):

$$\alpha=\frac{1}{2}\arctan\left(\frac{X}{Y}\right) \qquad (5)$$

Of course, due to the non-ideal manufacturing process, a real sensor will not show the ideal behavior assumed above because it is affected by offsets and gain error. These effects are discussed in chapter 4.1.

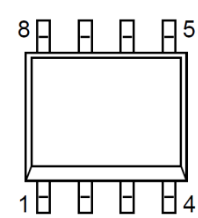
2. Angle sensor KMZ60

2.1 Introduction

The KMZ60 is a magnetic angle sensor system. The magneto-resistive sensor bridges and the integrated analogue signal amplifier are combined in one single SO8 package.

This angular measurement sensor provides two sinusoidal ratiometric analogue output signals, with a phase shift of 90 degree. The KMZ60 can be used in a temperature compensated operational mode as well as in a non-compensated mode by enabling or disabling the TCC_EN Pin.

Table 1. Pinning information KMZ60

Pin	Symbol	Description	Simplified package outline
1	TCC_EN	Enable TC compensation	
2	VOUT1	Cosine channel output	
3	GND	Ground	
4	VOUT2	Sine channel output	
5	VTEMP	Temperature reference output	
6	GND	Ground	
7	V_{CC}	Supply voltage	
8	POWERDOWN_EN	Enable power-down mode	

The KMZ60 must be connected to a supply voltage (V_{CC}) between 2.7V and 5.5V at pin 7 and connected to ground (GND) at pin 3 and pin 6. The angle of the rotating magnetic field is measured by the KMZ60 and converted into a sinusoidal and cosine output signal which are available at pin 2 (cosine) and pin 4 (sinusoidal) as shown in Fig. 6. To enable the temperature compensation (TC, for detailed information see chapter 3.3.1) TCC_EN (pin 1) must be connected to V_{CC}. To disable the temperature compensation TCC_EN (pin1) must be connected to GND. Pin 1 must be either connected to V_{CC} or GND. It is strongly forbidden to let pin 1 unconnected due to EMC reasons. Nevertheless the TCC_EN pin has for safety reasons an internal pull-up circuit. Therefore the device will be in temperature compensated mode in the case of an open connection at pin 1.

Additionally to the magnetic field angle information the KMZ60 provides a temperature dependent output signal VTEMP at pin 5. The output voltage depends on the internal junction temperature of the KMZ60 ASIC. The VTEMP output voltage is available in both operational modes (enabled/disabled TC).

In the case that signals provided by the KMZ60 are not needed the device can be set into power down mode by connecting POWERDOWN_EN pin 8 to V_{CC} supply. The minimum voltage level to set the device into power down mode is V_{CC}-0.6V. If power down mode is not needed pin 8 must be connected to GND.

For a detailed description of the electrical circuit diagram see chapter 3. Fig. 6 shows the output signals of VOUT1 and VOUT2. For illustration both output signals are affected by an offset VOoff1 and VOoff2.

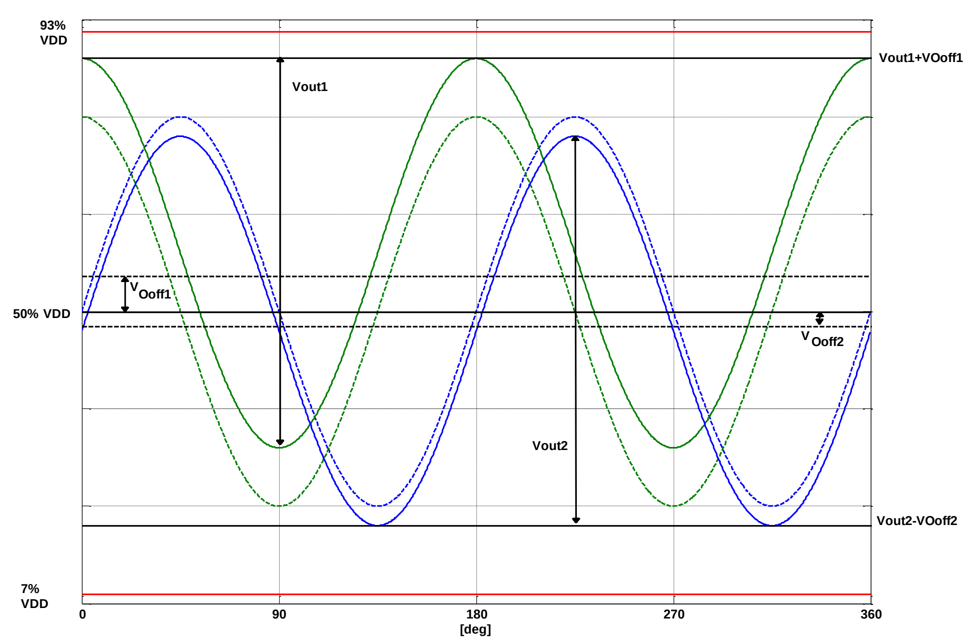


Fig. 6: KMZ60 output signal

The output signal is valid between the output minimum limit of 7% V_{CC} and maximum limit of 93% V_{CC}.

2.2 Application area

The KMZ60 magnetic field angle sensor is designed for brushless DC motor applications as well as for angle measurement setup. The following section gives an introduction to the main application areas. Of course there are more applications thinkable which are not mentioned here, but the basic system setup will be similar to the explained examples.

2.2.1 Brushless DC Motor application

As mentioned before, the KMZ60 is designed for BLDC application for rotational speeds up to 25.000 rpm. The basic BLDC setup is shown in Fig. 7.

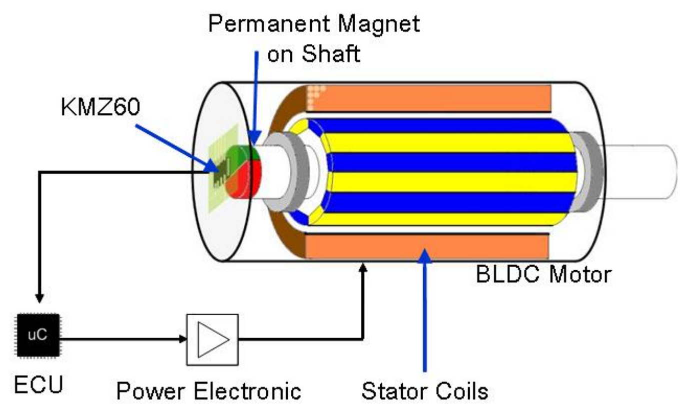


Fig. 7: Basic BLDC motor setup with KMZ60.

The two output signals of the KMZ60 are connected to an analogue-digital converter in an engine control unit (ECU) where the angle calculation from the two signals is made as explained in chapter 1.1.2. Based on the measured and calculated position of the rotor of the BLDC motor measured by the KMZ60 the relating coils are activated and the BLDC motor starts to rotate. The major advantage of the KMZ60 sensor used in a BLDC application is the availability of a continuous signal with high accuracy. This allows a sinusoidal commutation of a BLDC motor with the following advantages:

- Lower current consumption due to precise commutation information.
- Lower noise due to lower vibration of the motor axis based on a prices commutation.
- Smaller motor designs with high output torque due to better effectiveness of BLDC motors with sinusoidal commutation.

Due to the physical constrains of the MR technology explained in chapter 1.1.2 the KMZ60 has a valid measurement range of 180°. Therefore the BLDC application areas for the KMZ60 are motors with an even number of pole pairs. For an odd number of pole pairs the rotor position is not clearly defined. This restriction is explained in Fig. 8. The blue vertical curves show the commutation points of the different motor setups. The red curve is the measured angle of the KMZ60 which must be at least congruent at one point with the blue curve to make a commutation of a motor possible. This is only the case for motors with even pole pairs.

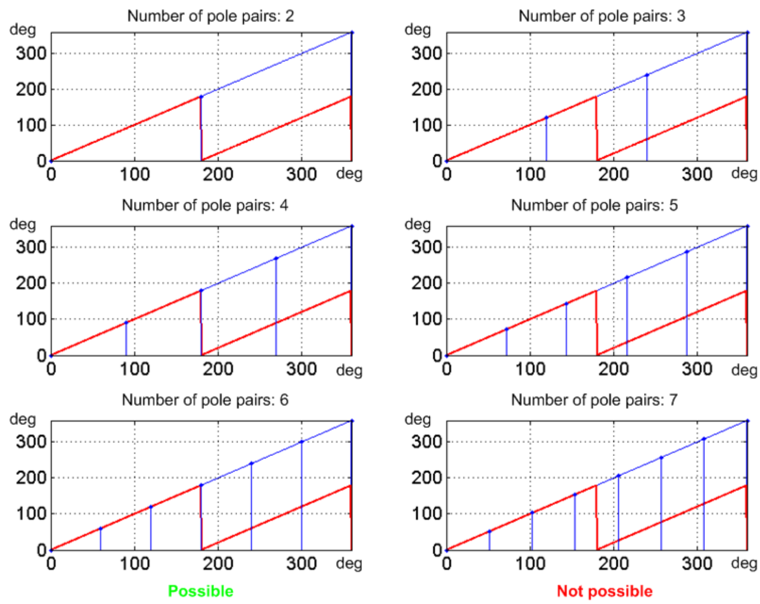


Fig. 8: Restriction of KMZ60 to an even number of pole pairs of BLDC motors

2.2.2 Additional requirements for high performance angular measurement

As mentioned before the MR technology provides the possibility for a direct measurement of the magnetic field direction. To reach high accuracy the magnetic field has to be saturated which means for the KMZ60 a magnetic field of minimum 25kA/m.

2.2.3 Angular measurement applications

The KMZ60 sensor is originally designed for BLDC application. Nevertheless the KMZ60 is still an angle sensor. Therefore it can be used to measure the angle of a magnetic field in several applications like throttle vales, window wiper applications and steering wheel position. All these applications have the same basic measurement setup, shown in Fig. 2. The window wiper and steering application is shown in Fig. 79.

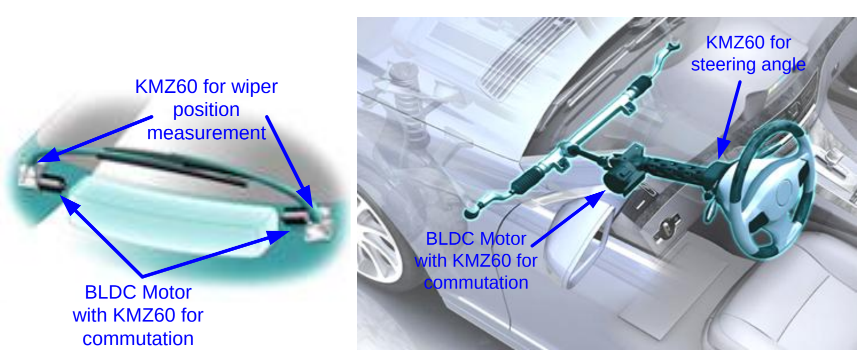


Fig. 9: KMZ60 in window wiper application and steering application.

2.2.4 Key parameters

Table 2 contains the key parameters of the KMZ60 as well as the limits for additional electronic devices which are recommended for high performance functionality.

Table 2. KMZ60 Key parameters

Symbol	Parameter	Conditions	Min.	Max.	Unit
V_{CC}	supply voltage		2.7	5.5	V
T_{amb}	ambient temperature		-40	150	°C
n_H	magnetic field rotation frequency		0	25000	rpm
H_{ext}	external magnetic field strength	[1] see note	25	-	kA/m
$\Delta\alpha$	angular inaccuracy	[2] see note	-0.1	0.1	degree
$C_{block(ext)}$	external blocking capacitance	[3] see note	100		nF
$R_{L(o)ext}$	external output load resistance	[4] see note	5	∞	kΩ
$C_{L(o)ext}$	external output load capacitance	[5] see note	0.5	10	nF

[1] Induced voltage from a rotating strong magnetic field may impact the performance but without damage.

[2] Value calculated only with third and fifth harmonic of the spectrum of output signal amplitude $V_{O(VOUT1)}$ and $V_{O(VOUT2)}$ by ideal homogeneous field.

[3] Between supply V_{CC} and pin GND, soldered close to the package.

[4] Operating as sink or source.

[5] Between pin VOUT1 and pin V_{CC} or pin GND and pin VOUT2 and pin V_{CC} or pin GND.

2.3 Block diagram KMZ60

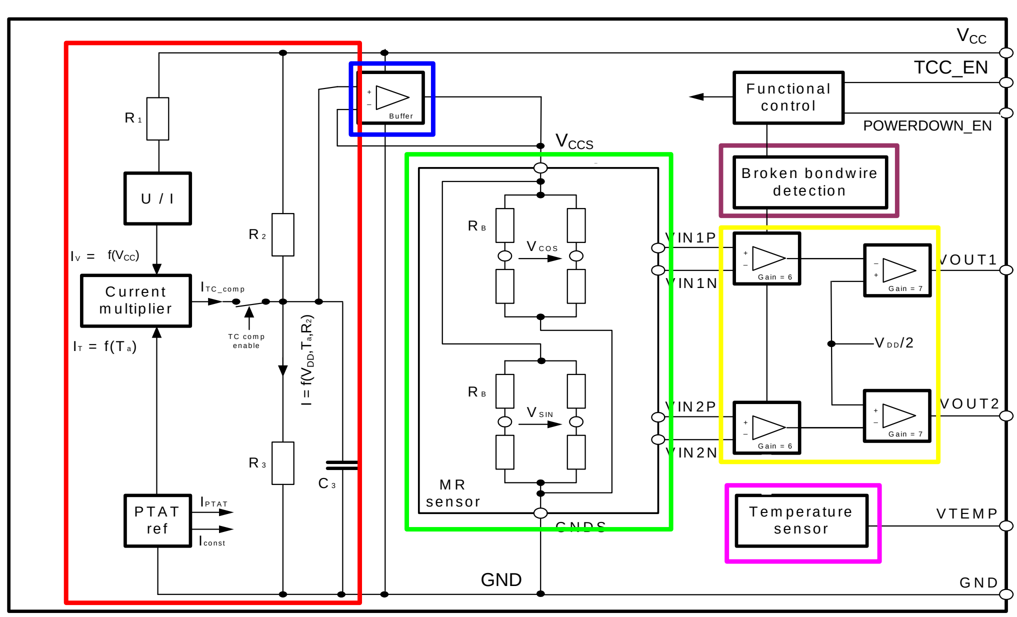


Fig. 10: Block diagram.KMZ60

Fig. 10 shows the complete circuit of the KMZ60. The different parts of the device are marked in different colors for explanation. The block diagram consisting of the MR sensor element (green) realised by two interleaved Wheatstone bridges for cosine and sine signals and the supporting functions for control and signal amplification. The temperature compensation circuit (red) generates a reference current proportional to absolute temperature, an U/I converter and a current multiplier are generating the reference current which is supply voltage, temperature and resistor dependent. This reference current controls the supply voltage of both sensor bridges to compensate their temperature coefficient (TC) via a supply buffer (blue). For noise and EMC suppression low pass filtering of the bridge supply is implemented. The bridge output voltages are amplified by a constant factor of 42 and fed to the rail-to-rail output buffers (yellow). The single-ended outputs are capable to drive inputs e.g. of an external Analog to Digital Converter (ADC) referenced to the V_{CC} supply. For an optimal use of the ADC input range the cosine and sine output voltages are tracking ratiometric with the supply voltage. To achieve good signal performance, both signals are matched in amplitude and phase. The amplifier bandwidth is sufficient for low phase delay at maximum specified speed of rotation. Higher rotation frequencies than specified may be achieved, if an additional phase shift is no problem within the application.
Pin TCC_EN is used to enable or disable the temperature coefficient compensation via the functional control block. If TCC_EN is connected to V_{CC}, the temperature coefficient of the MR sensor signal amplitude is largely compensated by the amplifier. If TCC_EN is connected to GND potential the amplified sensor signal with its negative temperature coefficient is available at the outputs VOUT1 and VOUT2. (For circuit diagram information see chapter 3.3)

Pin VTEMP delivers a temperature dependent output voltage independent of the chosen functional mode (purple). The VTEMP output should be connected to GND potential if not used.

The POWERDOWN_EN input (via functional control block) switches the device into power-down mode and sets the outputs VOUT1 and VOUT2 to high impedance. Pin VTEMP will be drawn to the GND ground level via an internal resistance. It should be connected to GND potential if not used. An implemented broken bond wire detection (brown) for all internal connections to the MR sensor is drawing the output voltages VOUT1 and VOUT2 to the GND ground level and disables pin VTEMP in case of a failure.

3. Introduction to KMZ60 application

3.1 System Block diagram KMZ60 Application

The main purpose of KMZ60 angle sensor is to measure the angle of a magnetic field from a permanent magnet which is rotating above the sensor. This setup can be used to measure the position of a rotor of a brushless DC (BLDC) motor as shown previously in Fig. 7.

A BLDC motor mainly consists of a stator (not rotation part) containing a certain number of pole pairs which generate a rotating magnetic field by switching the coils to the motor supply voltage in a certain order. The second part is the rotor, which consists of a shaft and a certain number of permanent magnets. These magnets are forces to follow the rotating field of the coils and therefore the rotor starts.

A BLDC motor is basically a synchronous machine which means, that the rotation frequency of the rotor is equal to the rotation frequency of the magnetic field generated by the coils of the stator. Therefore the rotor frequency and the rotation direction can be controlled easily by the stator coils.

To drive a BLDC motor, the position of the rotor must be known. The better the position of the rotor is known, the better and smoother the commutation of the coils can be done.

A common commutation method is called block commutation. For block commutation the position of rotor is detected by three Hall switches which are positioned in the stator with typically 120° displacement to each other. Each Hall element provides a digital signal depending on the direction of the rotating magnetic field. The detection of the rotor is not very accurate due to the low angle resolution of the Hall switches which also affects the performance of the commutation of the motor. Therefore a continuous signal with high resolution as it will be provided by the KMZ60 leads to high accuracy of the motor control, low power consumption and low noise emission of the motor itself. The basis block diagram for such a motor management system is given in Fig. 11.

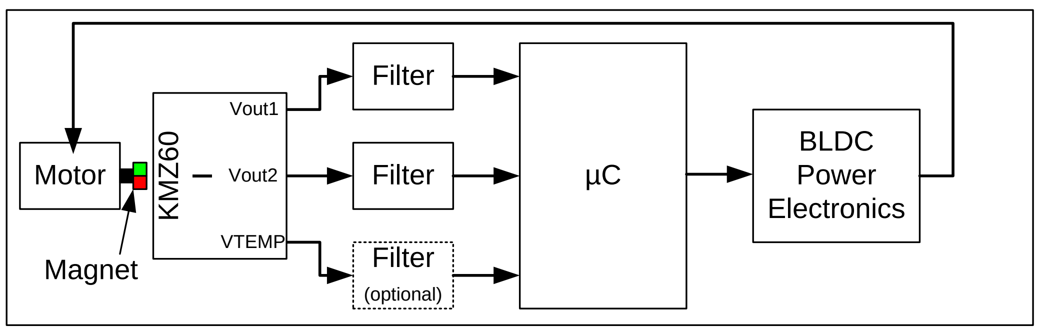


Fig. 11: System block diagram with KMZ60 for BLDC motor.

For EMI reasons and signal performance analogue filters can be used between the KMZ60 and the microcontroller. Based on the rotor position the BLDC motor is powered by the BLDC power electronics. The filters for VOUT1 and VOUT2 have to match for high performance.

Beside the BLDC motor application the KMZ60 can be used to measure the position of an actuator such as throttle valves, window wiper and steering wheels etc. Most of these actuators use an electrical driven motor, e.g. a BLDC Motor in combination with a gear box. To reach high resolution and high performance in such a system normally two sensors are used, one for the actuator position and in case of a BLDC motor one for the rotor position detection. This basic arrangement is shown in Fig. 12.

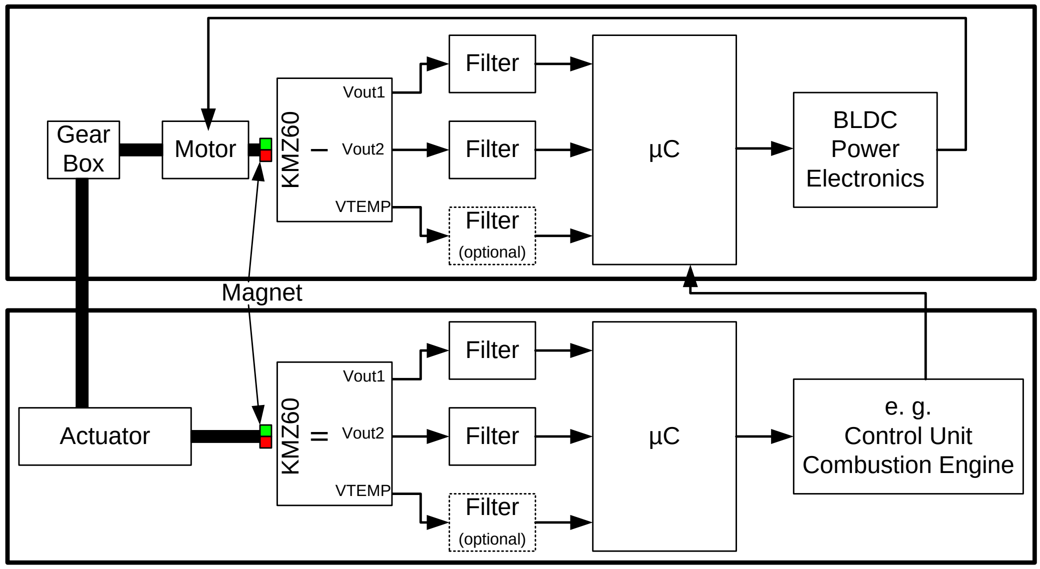


Fig. 12: System block diagram with two KMZ60 for BLDC motor and angular measurement application.

The BLDC motor is connected via a gear box shaft to an actuator. The actuator itself uses a KMZ60 to detect the position. The basic electronic setup could be the same as for BLDC applications. In this case a two stage controller algorithm (Control unit for combustion engine and BLDC motor controller or a single µC) operates with a communication interlink between these systems which leads to an overall close loop control system.

3.2 Ratiometric Outputs

The KMZ60 provides three ratiometric output signals. The relative output level of the KMZ60 depends on the supply voltage. This counts for Vout1, Vout2 and VTEMP. The ratio between V_{CC} to Vout1 and Vout2 respectively V_{CC} to VTEMP is independent on the supply voltage, which is the main advantage of a ratiometric circuit. This is important in the case that the ADC reference of ECU is related to the supply voltage V_{CC}. Fig. 13 shows the output signals of Vout1 and Vout2 as ratiometric voltage levels for supply voltages V_{CC} of 3.3 V and 5V. The red horizontal line marks the $V_{CC}/2$ level. The offset compensated output signals are symmetrical to the $V_{CC}/2$ level. If an ADC with a separate reference voltage will be used, it is recommended to supply the KMZ60 with this (buffered) reference voltage.

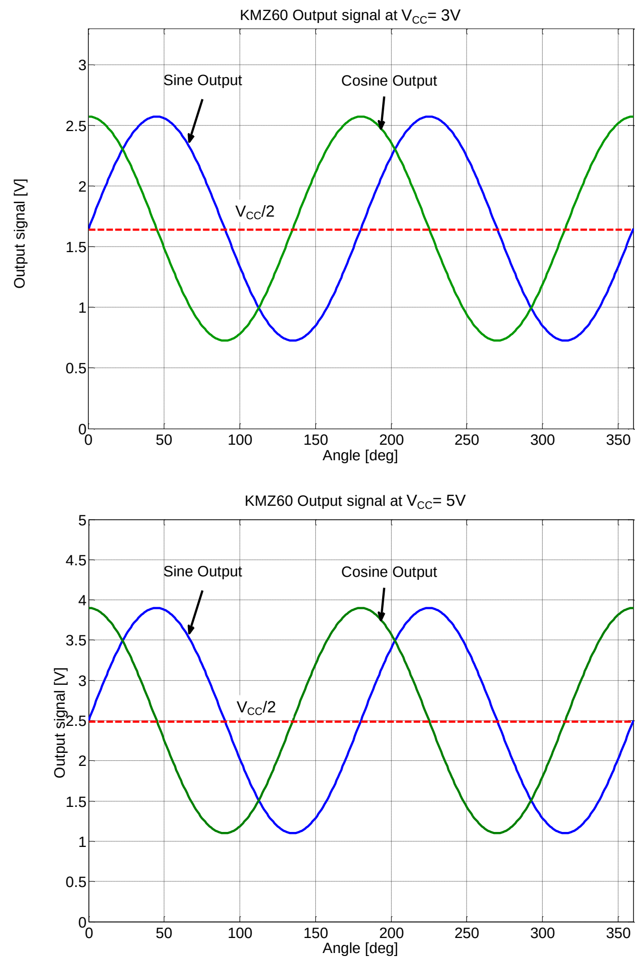


Fig. 13: KMZ60 with 3.3V and 5V supply voltage.

3.3 Basic schematics for different functionality

In this section the different application modes of the KMZ60 are shown as circuit diagrams. The different circuit diagrams combine the KMZ60 with a microcontroller and additional resistors and capacitors.

3.3.1 KMZ60 with TC compensation

The KMZ60 provides two different functional modes which can be selected by pin 1 (TCC_EN). If pin 1 is connected to V_{CC}, the device operates in the temperature coefficient (TC) compensated mode. The basic circuit diagram for the KMZ60 connected to a microcontroller is shown in Fig. 14.

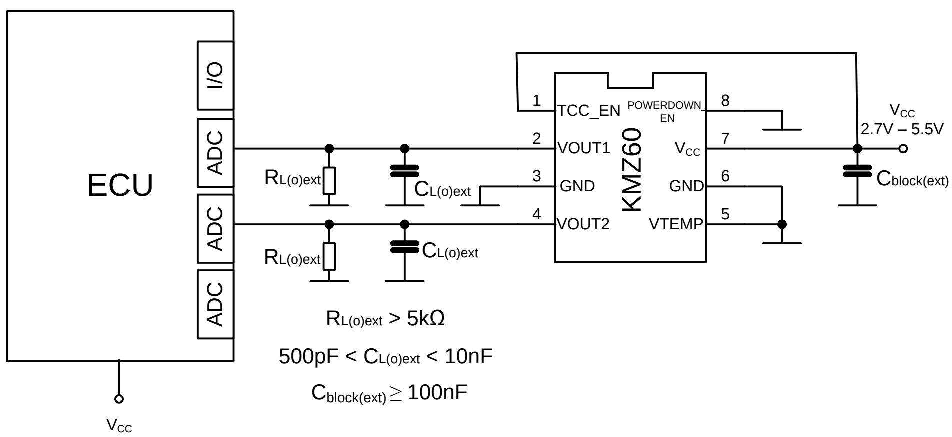


Fig. 14: Application circuit diagram for KMZ60 with TC compensation.

In this functional mode the influence of a changing ambient temperature on the output signal amplitude at Vout1 and Vout2 is largely compensated. Therefore maximum amplitudes of Vout1 and Vout2 are almost the same over the full specified temperature range which leads to an optimum usage of the voltage range for ADC conversion in a microcontroller.

The disadvantage is that the TC compensation is not ideal due to a light non-linear behavior of the MR element itself. This additional non-linear effect, coming from the TC compensation, results in a higher angle error with one-point calibration in comparison to a calibration with more supporting points. This effect is of less importance for BLDC applications with implemented offset calibration after each rotation cycle, because the calibration will directly take place at each temperature on the fly.

Please see KMZ60 data sheet for further information on output levels with TC compensation.

Additional capacitors $C_{L1(ext)}$ and $C_{L2(ext)}$ at pin 2 and pin4 are needed as load capacitors to fulfill EMI demands. Both resistors and capacitors have to match for best performance.

3.3.2 KMZ60 without TC compensation

The temperature coefficient (TC) compensation can be switched off by connecting the TCC_EN pin to GND potential. In this case the output signal amplitude will decrease with increasing temperature related to the temperature coefficient of the MR sensor. In this case the angle accuracy might be slightly reduced due to the limited resolution of the used ADC.

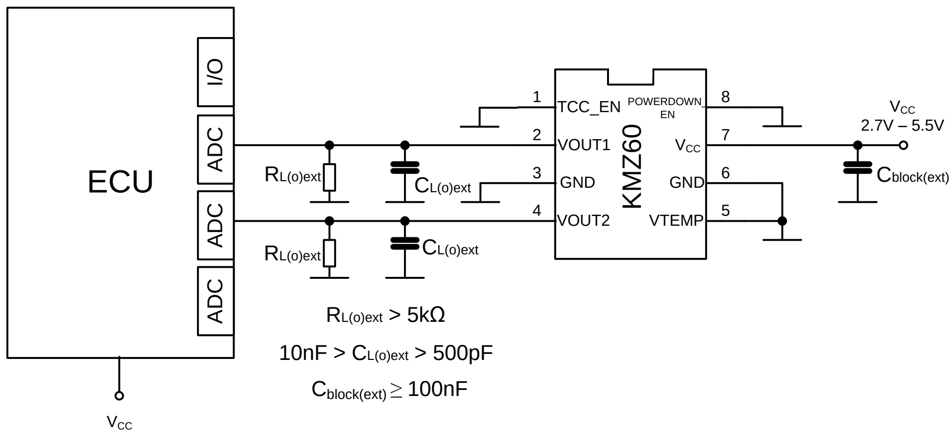


Fig. 15: Application circuit diagram for KMZ60 without TC compensation.

Please see KMZ60 data sheet for further information on output levels without TC compensation.

Additional capacitors $C_{L1(ext)}$ and $C_{L2(ext)}$ at pin 2 and pin4 are needed as load capacitors to fulfill EMI demands.

3.3.3 KMZ60 - Power down mode

The KMZ60 device provides the possibility to switch off the device if no angular information is needed. This could be the case when a BLDC motor or an actuator is not needed and the overall power consumption should be reduced. By connecting the POWERDOWN_EN pin to an output of the microcontroller which provides a signal at KMZ60 V_{CC} level the device can be sent into power-down mode.

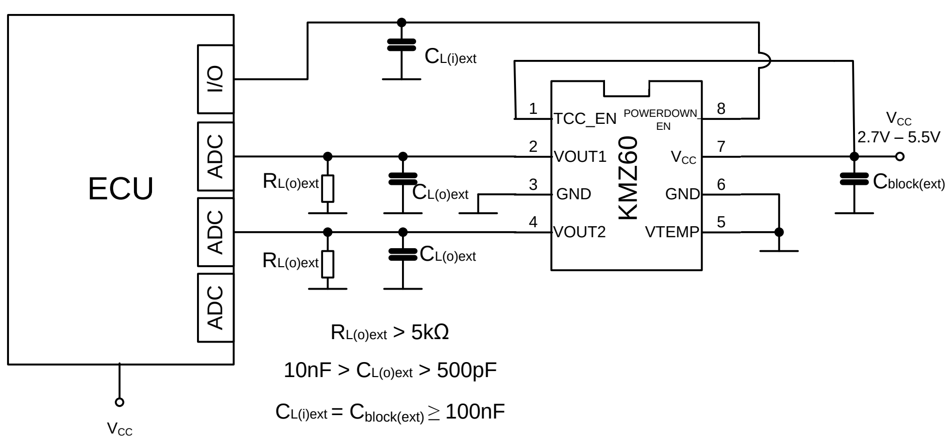


Fig. 16: Application circuit diagram for KMZ60 with Power-Down Mode and TC compensation.

The outputs VOUT1 and VOUT2 are set to high impendence to avoid power consumption across the load resistors at the outputs. The VTEMP output is drawn to GND by an internal resistance of 20kΩ. By switching the voltage level at POWERDOWN_EN pin to GND the power down mode will be disabled and the KMZ60 provides the specified output signals.

A capacitor $C_{POWERDOWN\_EN}$ at pin 8 is needed to fulfill the EMI demands.

3.3.4 KMZ60 – Temperature reference VTEMP

Additionally to the output voltages containing the angle information at VOUT1 and VOUT2 a temperature dependent voltage reference output is available at VTEMP (pin 5). This output signal provides for both functional modes (with and without TC compensation) a voltage output level related to the junction temperature on the KMZ60 ASIC. The output is made ratiometric to the supply voltage V_{CC} to fit to the ratiometric ADC input of the ECU. A capacitor C_{VTEMP} at the VTEMP pin is needed for stability reasons and to fulfill the EMI demands. The maximum load resistor at the VTEMP output must be between min 20kΩ and max. 100kΩ to get a linear behavior at the output.

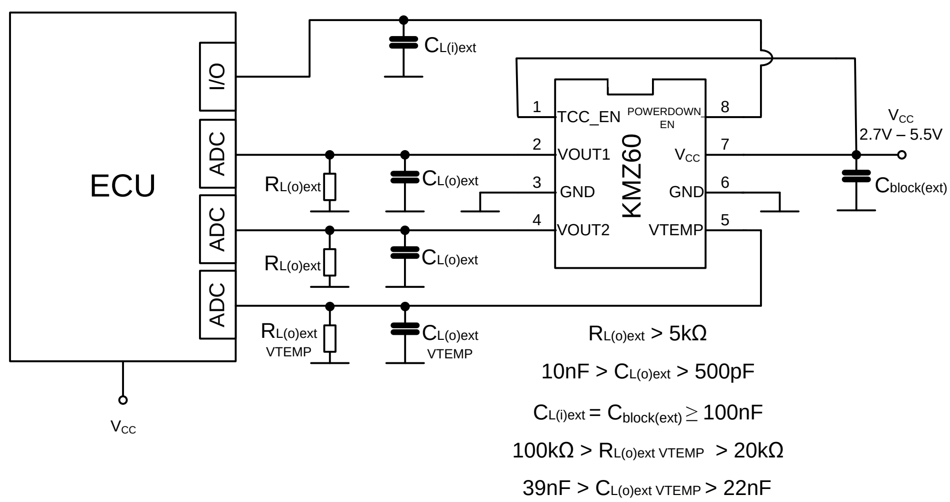


Fig. 17: Application circuit diagram for KMZ60 with Power-Down-Mode and TC compensation and temperature dependent output signal VTEMP.

Fig. 18 shows the output voltage behavior of VTEMP signal over temperature. The red curves are the limiting values; the blue curve is the average value.

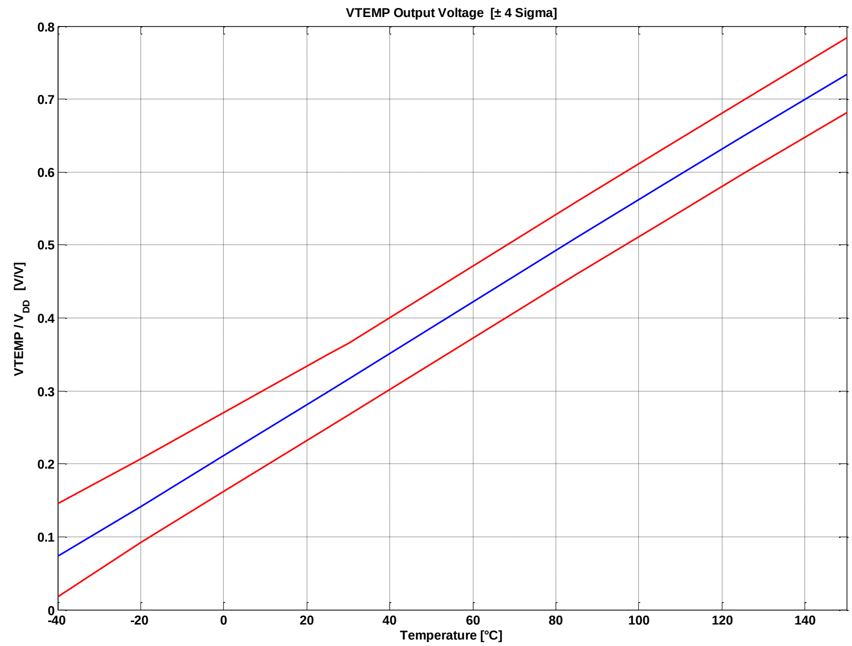


Fig. 18: VTEMP output voltage.

The internal temperature of the KMZ60 can be calculated from the output voltage in the following way:

Calculation of VTEMP by formula

In this section, the calculation of the actual internal temperature of KMZ60 by a mathematical formula will be explained.

The linear temperature coefficient of VTEMP voltage is varying with the supply voltage due to the ratiometric behavior of VTEMP. Therefore the supply voltage V_{CCref} during calibration of VTEMP has to be taken into account which is normally known. The supply voltage depending linear temperature coefficient TC_{ref} of VTEMP can be calculated by the following equation 6:

$$TC_{ref} = 0.0121 - 0.0004 * \frac{V_{CCref}[V] - 2.7V}{3V} \quad (6)$$

From the formula can be seen, that a higher supply voltage leads to a lower TC_{ref}.

For the following calculation of the temperature based on VTEMP output signal it is assumed, that the supply voltage V_{CC} during normal operation is the same as during calibration. Therefore it counts:

$$V_{CC} = V_{CCref}$$

The output behavior of VTEMP can be described by a linear approximation given in equation 7:

$$T_{VTEMP} = Tref + \frac{(VTEMP/V_{CC}) - (VTEMP_{ref}/V_{CC})}{(VTEMP_{ref}/V_{CC}) * TC_{ref}} \qquad (7)$$

where

T_{VTEMP} is the calculated temperature [°C] based on the VTEMP [V] output voltage,
T_{ref} is the temperature [°C] at which the one point calibration is done,
$VTEMP/V_{CC}$ is the normalized VTEMP [V] output voltage at application temperature,
$VTEMP_{ref}/V_{CC}$ is the normalized VTEMP [V] output voltage at calibration temperature and
TC_{ref} is the linear temperature coefficient of VTEMP [V] calculated from equation 6.

If the VTEMP output is not needed, it should be connected to GND ground level or preferably to V_{CC}.

4. Application Robustness

4.1 System Accuracy

4.1.1 Sensor KMZ60

There are three different errors that may be caused by non-adequate magnetic field arrangements.

These are:

- Form deviations of the sensor signals (no sinusoidal shape) and hysteresis of the sensor response if the magnetic field H does not saturate the sensor.
- Form deviations of the sensor signals caused by a non-symmetrical sensor to magnet arrangement (inhomogeneous magnetic field).
- Influence of external magnetic fields distorting the primary field used for measurements.

The influence of external fields can not be described in general as these effects depend on the actual measurement set-up. Therefore this item is not discussed within this paper. The only possibility to get rid of external fields or to limit its impact is to use some kind of a magnetic shielding.
In addition to these magnetic effects, there are some non-ideal properties of the KMZ60 sensor affecting the system accuracy. These are discussed in section

Less Magnetic Field Strength

A complete saturation of the sensor would require the usage of an infinite magnetic field. Consequently, a complete saturation is impossible in practice and errors caused by fewer magnetic fields have to be taken into account. The magnetic field strength, which is proposed in this paper, is a compromise between the remaining error and magnet costs. An insufficient magnetic field shows two effects. The first one is the signal form error caused by a non-sinusoidal shape of the output signals. Due to its geometrical nature, the maximum and minimum values will always occur at the same locations for every sensor. Maximum values occur at the mechanical angles of 11.25°, 33.75°, 56.25°, 78.75°, 101.25°, 123.75°, 146.25° and 168.25°. No measurement errors occur at 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5° and 180°.
At the recommended magnetic field strength of 25 kA/m, the measurement error is less than 0.04° and therefore negligible. The signal form error is reversible and does not depend on the history, as it is the case for hysteresis effects.

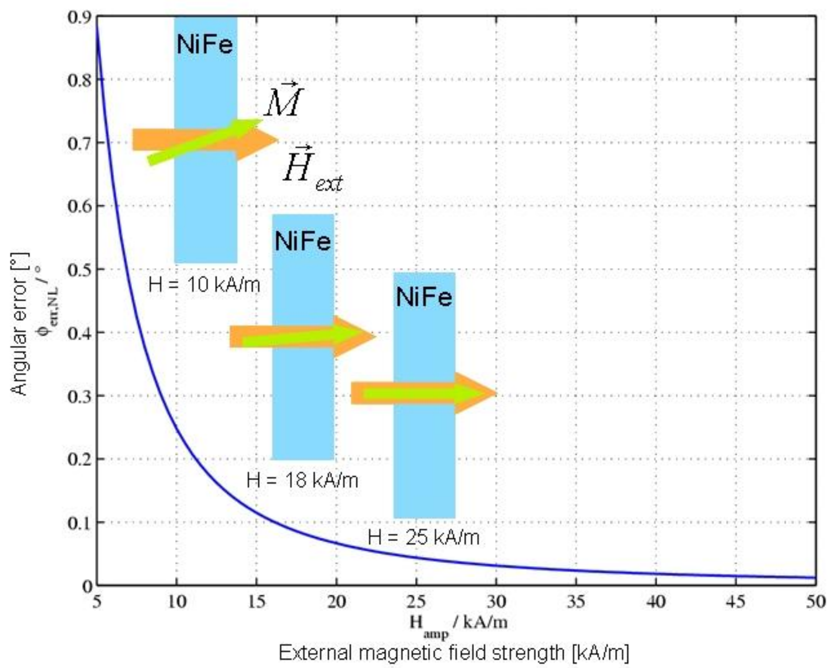


Fig. 19: Influence of external magnetic field strength on angular error.

It is obvious that the measurement error caused by signal form errors can be neglected when using a magnetic field larger than 25kA/m.
Another argument for using strong magnetic fields is the lower impact of external magnetic stray fields.
This is especially an issue when using an unshielded application set-up.

Effects of Inhomogeneous Magnetic Fields

The sensor signal will get deformed even if sensor and magnet are not precisely aligned, which also may cause measurement errors. The reason for these deformations is that then the sensitive part of the sensor is not completely placed in the homogeneous part of the magnetic field, or, in other words, the relevant part of the magnetic field used for measurements has become inhomogeneous. As the actual angular error resulting from an inhomogeneous field depends on the specific set-up and field strength, it cannot be calculated in general.

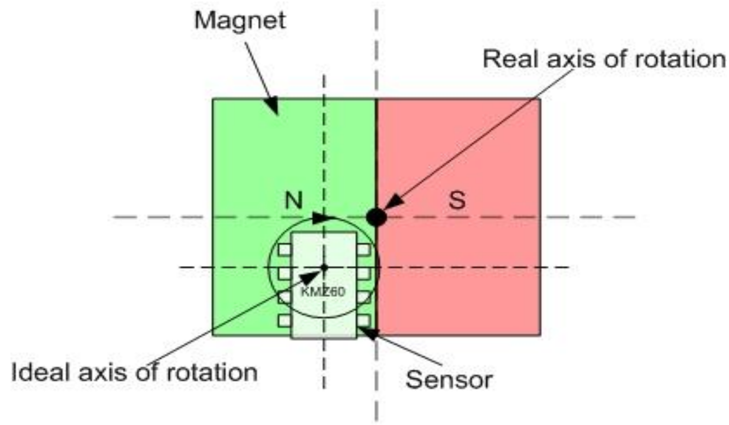


Fig. 20: Basic BLDC motor setup with KMZ60.

Non-Ideal Properties of the Components

Due to production scatter, the KMZ60 does not generate ideal output signals but shows some variations in performance. Since continuous improvement is the target of this sensor, please refer to the latest data sheet of the KMZ60 to get current data. In the following sections, the different effects and their impact on system accuracy are described in general.

Offset and Offset Drift

The sinusoidal output signals of the KMZ60 may show offsets that limit the accuracy of the system.
From the application point of view, the offset of each channel can be subdivided into two parts: a constant portion, which is virtually eliminated by trimming and a portion that changes with temperature. Note that the temperature dependent portion is zero at the temperature where the sensor system will be calibrated. Introducing an offset Δx and Δy into the mathematical description of both signals gives:

$$X = X_0 \sin 2\alpha + \Delta x$$
$$Y = Y_0 \cos 2\alpha + \Delta y$$

The absolute angular error caused by offsets is also a function of the actual angle. It is calculated as follows:

$$\Phi_0(X_0, Y_0, \alpha, \Delta x, \Delta y) = \left| \frac{1}{2}\arctan\left(\frac{X_0 \sin 2\alpha}{Y_0 \cos 2\alpha}\right) - \frac{1}{2}\arctan\left(\frac{X_0 \sin 2\alpha + \Delta x}{Y_0 \cos 2\alpha + \Delta y}\right) \right| \quad (8)$$

Start-up Error for BLDC motor applications

The offsets of the sine and cosine output signal have the biggest influence on the start-up error for e. g. a BLDC motor application. The start-up error is defined as maximum deviation by calculating the angle from the offset voltages $V_{offset(VOUT1)}$ and $V_{offset(VOUT2)}$ and the peak-to peak signal amplitudes $V_{o(VOUT1)}$ and $V_{o(VOUT2)}$.

$$\Phi_{START-UP} = 160 \cdot \frac{\sqrt{\left(\left(V_{offset(VOUT1)}\right)^2 + \left(V_{offset(VOUT2)}\right)^2\right)/2}}{V_{Vo(VOUT1)} + V_{Vo(VOUT2)}} \quad (9)$$

The start-up error for a one point calibration is also shown in the KMZ60 data sheet.

Different Signal Amplitudes

Although processed at the same time and on the same silicon substrate, both Wheatstone bridges may show slightly different signal amplitudes. The angular error caused by this effect is as follows:

$$\Phi_{Amplitudes}(\alpha, A) = \left|\alpha - \frac{1}{2}\arctan\left(A\frac{\sin 2\alpha}{\cos 2\alpha}\right)\right| \quad (10)$$

with: $A = \frac{X_0}{Y_0}$ Ratio of the signal amplitudes

The differences of both signal amplitudes can be easily corrected by multiplying Y_0 with the ratio of both amplitudes A.

$$Y_{cor} = A * Y_0 \quad (11)$$

Then it counts $Y_{cor} = X_0$.

4.2 Offsetdrift and TC of Output Signal Offset

To calculate the drift of the output signal offset over a certain temperature range the specified temperature coefficient (TC) of the output signal offset TCV_{offset} can be used. The TCV_{offset} is related to V_{CC} and is given by separate formulas, one if temperature compensation is ON and one if the temperature compensation is OFF. When the temperature compensation is ON the TC of output signal offset is defined as

$$TC_{Voffset} = \pm\left(0.443 \cdot 10^{-6}\,\frac{V/V}{K^2} \cdot T + 0.34 \cdot 10^{-3}\,\frac{V/V}{K}\right) \quad (12)$$

and if the Temperature Compensation is OFF as

$$TC_{Voffset} = \pm 0.153 \cdot 10^{-3}\,\frac{V/V}{K} \quad (13)$$

where T is the temperature and V/V/K are the units of the coefficients.

Because the behavior of the TC of the output signal offset is symmetric to ground the positive function results to the maximum limit and the negative function to the minimum limit. Based on the known TC the calculation of the drift of the offset is possible and is explained in a given example as following.

For example: The Offset V_{offset}(T0) = 10mV/V of a KMZ60 device was measured at a certain temperature T0=25°C and from -40°C till 85°C is the temperature range of interest. An integration of the $TC_{Voffset}$ formula leads into a description of the offset drift and for the case Temperature Compensation is ON into

$$V_{offset}(T) = \int TC_{Voffset} dT = \pm\left(\frac{1}{2} 0.443 \cdot 10^{-6} \frac{V/V}{K^2} \cdot T^2 + 0.34 \cdot 10^{-3} \frac{V/V}{K} \cdot T + C\right) \quad (14)$$

where C is the constant value due to integration. When T is set to T0 and V_{offset}(T0) to the measured value the integration constant C can be evaluated. Where T is related to 0°C, in that way T=25°C can be assumed as T=25 Kelvin.

For this example the maximum drift of the device is shown with the red curves in figure 21. The blue circle represents the measured value of the offset at T0 and the green and blue lines are the maximum absolute values of the offset as specified in the datasheet. This implies that the green and blue lines are representing the absolute maximum respectively minimum offset values in consideration of all possible drifts.

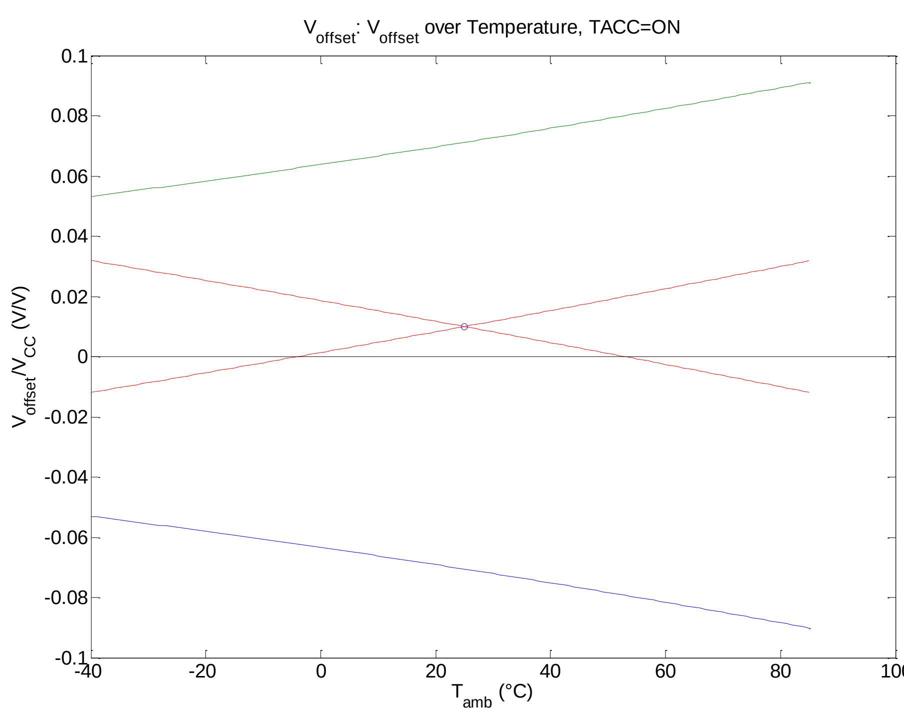


Fig. 21: V_{offset} with an example for the offset drift, temperature compensation is on.

4.3 Drift of V_o and TC of peak-to-peak Output Signal Amplitude

The normalized TC of the peak-to-peak output signal amplitude TCV_o is given if temperature compensation is ON as

$$TC_{Vo\_min} = -20.141 \cdot 10^{-9} \frac{V/V}{K^3} \cdot T^2 - 6.499 \cdot 10^{-6} \frac{V/V}{K^2} \cdot T - 0.456 \cdot 10^{-3} \frac{V/V}{K}$$
$$TC_{Vo\_max} = 51.268 \cdot 10^{-9} \frac{V/V}{K^3} \cdot T^2 - 12.563 \cdot 10^{-6} \frac{V/V}{K^2} \cdot T + 0.504 \cdot 10^{-3} \frac{V/V}{K} \quad (15)$$

and if Temperature Compensation is OFF as

$$TC_{Vo\_min} = 6.159 \cdot 10^{-6} \frac{V/V}{K^2} \cdot T - 2.749 \cdot 10^{-3} \frac{V/V}{K}$$
$$TC_{Vo\_max} = 3.184 \cdot 10^{-6} \frac{V/V}{K^2} \cdot T - 1.239 \cdot 10^{-3} \frac{V/V}{K} \quad (16)$$

To calculate the drift of the peak-to-peak output signal amplitude out of the specified TCV_o it is possible to do the same way as for the offset drift in section 4.2.

Hence the TCV_o has to be integrated and with the measured values of T0 and V_o(T0) the integration constant C can be evaluated. The result for T0=25°C and V_o(T0)=0.57 V/V is shown in figure 22.

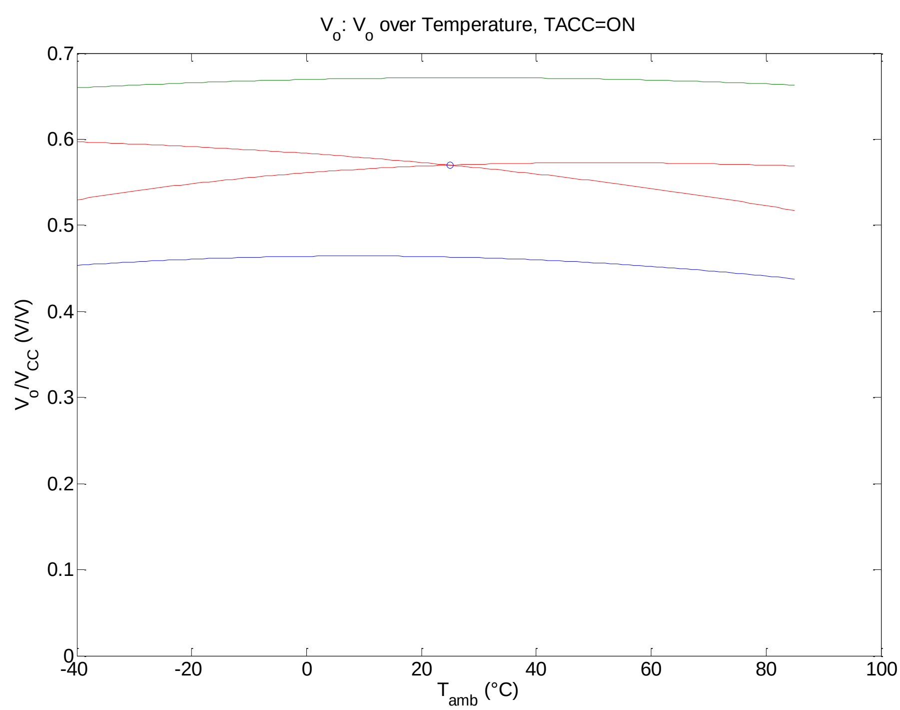


Fig. 22: V_o with an example for output signal drift, temperature compensation is on.

4.4 PIN classification

This chapter investigates each pin of the KMZ60 package related to the system behavior in the case of a disturbance or malfunction (e. g. short circuit between pins, EMI, etc.) which affects the performance of the device.

In this context a system will be defined as an electrical combination of the KMZ60, a microcontroller and additional components (e. g. resistors, capacitors, etc.) as shown in chapter 3.

For each pin different classes (see Table 3) are defined and described in Table 4 and a certain detection action is given.

Definition of classes:

Table 3. Failure class definition

Class	Description
A	**Correct Functionality**: The device is working according to specification
B	**Damaged**: The device shows damage with substantial extends. Functionality is not given anymore.
C	**Instable behaviour of KMZ60**: The output signals are showing an instable behaviour. Signals are possible which are not according specification.
D	**Sensitive to EMI, EMC or floating input signals**: The device is affected by EMI, EMC or by a floating input signal. Signals are possible which are not according specification.
E	**Wrong functionality of KMZ60**: The device provides wrong information. One or more signals are not according specification.

Table 4. PIN classification

Pin Number	Function	Class	Description	Detection action
1	TCC_EN	C	No Effects	Check the output signal amplitude of VOUT1 and VOUT2 and VTEMP via direct ADC conversion
			Output signals are not working according spec	Check the output signal amplitude via direct ADC conversion
2	VOUT1	C	See pin 1	See pin 1
		D	EMI on POWERDOWN_EN (switches to Power down) VOUT1 and VOUT2: larger angular error than specified.	Check if the output signal amplitudes are in the specified range.

			EMI on VTEMP	Calculate the average signals at same temperature values to check its plausibility.
		E	VOUT1 and VOUT2: no correlation between magnetic field and signal output level. VTEMP: high impedance to V_{CC}	Compare VOUT1 and VOUT2 signal against specification via ADC conversion. Compare VTEMP signal against specification via ADC conversion.
3	GND (auxiliary)	A	See pin 1 and pin 2	
4	VOUT2	C	See pin 1 and pin 2	See pin 1 and pin 2
		D		
		E		
5	VTEMP	C	See pin 1 and pin 2	See pin 1 and pin 2
		D		
		E		
6	GND	A	See pin 1 and pin 2	
7	V_{CC}	D	See pin 1 and pin 2	See pin 1 and pin 2
		E		
8	POWERDOWN_EN	C	See pin 1 and pin 2	See pin 1 and pin 2
		D		
		E		

A damage (B) may occur if the device is placed 180 deg rotated (wrong connection of pins) and the supply current is not limited to 100mA.

5. Demo Kit

5.1 KMZ60 hand-driven demo kit

For application and demonstration support a demo kit is available. This chapter gives a short introduction to the demo kit. For a detailed description please ask for KMZ60_Demoboard_Quick_Installation_Guide.pdf.

The KMZ60 demo kit consists of a PCB which will be connected by an USB cable to a computer. The attached CD contains the software which is necessary to drive the demo. Fig. 23 shows the PCB.

Fig. 23: KMZ60 hand-driven demo board.

The demo software gives users the possibility to test the different operational modes of the KMZ60 (with or without temperature compensation mode) as well as the power down functionality and the temperature depending output VTEMP. Also a software offset cancellation is possible to investigate the effect of an offset calibration. The user can communicate with the demo board via a comfortable graphical user interface. The output signals are shown in three different modes, as digital output voltages, as angle information, as XY-plot and in an oscilloscope window.

For further information please contact NXP Semiconductors:

www.nxp.com

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7. List of figures

8. List of tables

9. Contents

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