

Contactless, high-precision position sensing with Hall and TMR technologies

V1.0

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Authors

Frederik Berstecher, Product Line Manager – Fast Hall Sensors bei TDK-Micronas
Marcus Meyer, Head of Project Engineering bei TDK Corporation – Japan



Sensors with vision –

How TDK-Micronas and Rutronik are shaping the future of position measurement together

The demands placed on modern position sensors are increasing rapidly, especially in safety-critical automotive applications such as brake-by-wire, electric parking brakes and steering systems. With the shift towards electromobility and increasing system integration, accuracy, installation space, EMC stability and material availability are becoming increasingly important.

The white paper "Contactless, high-precision position sensing with Hall and TMR technologies" offers an in-depth comparison between Hall and TMR technology as well as practical guidance on selecting the right sensor architecture. After all, choosing the right technology is highly application-specific. Whether robust Hall sensors, high-precision TMR variants or hybrid architectures with maximum redundancy: this white paper, you will learn how safety and performance goals can be optimally combined.

Partnership with regional strength and European perspective

TDK-Micronas and Rutronik, both headquartered in Baden-Württemberg and deeply rooted in the European electronics market, are combining their expertise to support customers along the entire supply chain. The long-standing partnership is based on innovative strength, proximity to the automotive sector and a deep understanding of the requirements for developing forward-looking mobility applications.

TDK is a leading supplier of Hall and TMR-based position sensors and contributes not only technological expertise but also a broad portfolio of reference designs and design-in support. For Rutronik, this partnership is a strategic building block in supplying customers with powerful, scalable and future-proof sensors 'Made in Europe'. In an increasingly challenging geopolitical environment, the partnership specifically strengthens resilience and the ability to act within global supply chains.

Manuel Gauß

Senior Manager Product Marketing
Analog & Sensors at Rutronik

Jeannette Raquet

Line Managerin for TDK-Micronas
at Rutronik

Hall-effect or TMR-based position sensors are widely used in the automotive industry.

But what exactly is the difference between the two technologies – and when is it worthwhile to combine them?

The demand for high-precision and robust position sensors for safety-critical applications such as brake-by-wire, electric parking brakes and steering systems is growing rapidly. Particularly in the field of electromobility and increasing system integration, high demands are placed on accuracy, installation space, safety and material availability. Hall and TMR-based sensors offer different advantages in terms of sensitivity, interference immunity and system costs. This white paper compares both technologies and shows how they can be combined to meet safety and performance goals equally.

Position sensing in transition

The increasing electrification of vehicle systems – for example, actuators, brake-by-wire or EPS – requires high-resolution and functionally safe sensor solutions. In addition to high angular resolution and low latency, reliable operation under harsh environmental conditions, such as temperature stress and electromagnetic interference (EMC), must also be ensured. Moreover, there are increasing requirements for functional safety (e.g. ASIL-D), diagnostic capability, system redundancy and energy efficiency.

Integration is also becoming increasingly important: compact assemblies and PCB-less designs require flexible mounting concepts. At the same time, the choice of magnet is becoming more important, as ferrite magnets are increasingly seen as an economically viable alternative to rare earths.

TDK develops and manufactures solutions based on Hall and TMR technologies that meet these requirements. To better understand the potential of these solutions, it is worth taking a look at the physical principles and differences between the two approaches.

Technological fundamentals: Operating principles – Hall vs. TMR

Hall sensors are based on the classic physical principle that a voltage is generated across the direction of current flow in a current-carrying semiconductor when a magnetic field acts perpendicular to it. The vertical Hall plates used by TDK-Micronas, a TDK Group company, enable the detection of magnetic fields at the chip level. Compared to classic 'horizontal' designs, this offers advantages in terms of geometry, stray field immunity and signal quality. Through the clever arrangement of several Hall elements, both linear and rotational movements can be precisely mapped – even in three dimensions (multidimensional Hall sensor).

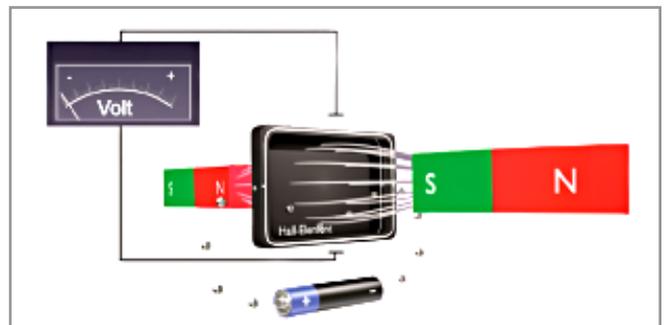


Figure 1: Hall sensor measuring principle

TMR (Tunnel Magneto Resistance) sensors utilize the quantum mechanical effect of electrons tunnelling through a thin insulating layer between two ferromagnetic layers. The change in resistance of this structure depends on the angle of the magnetization directions of both layers relative to each other. TDK uses precision-manufactured thin-film stacks to achieve maximum sensitivity and accuracy. This technology is ideal for high-resolution angle measurements with minimal noise, requiring no external signal amplification.

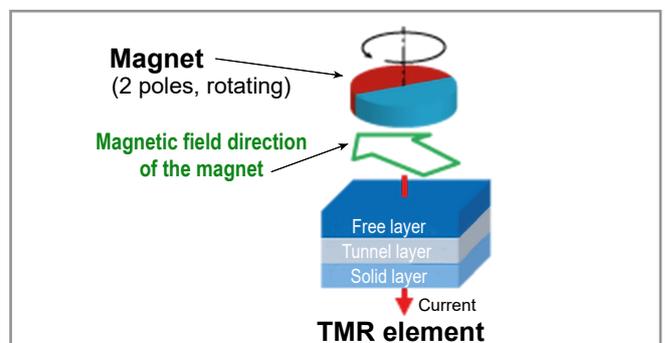


Figure 2: TMR sensor measuring principle

Both technologies have advantages and disadvantages. Hall sensors impress with their high robustness, established CMOS-compatible manufacturing technology, low costs and good integration into applications that place less critical demands on accuracy. Three-dimensional measurability with corresponding signal processing also opens up flexible application possibilities.

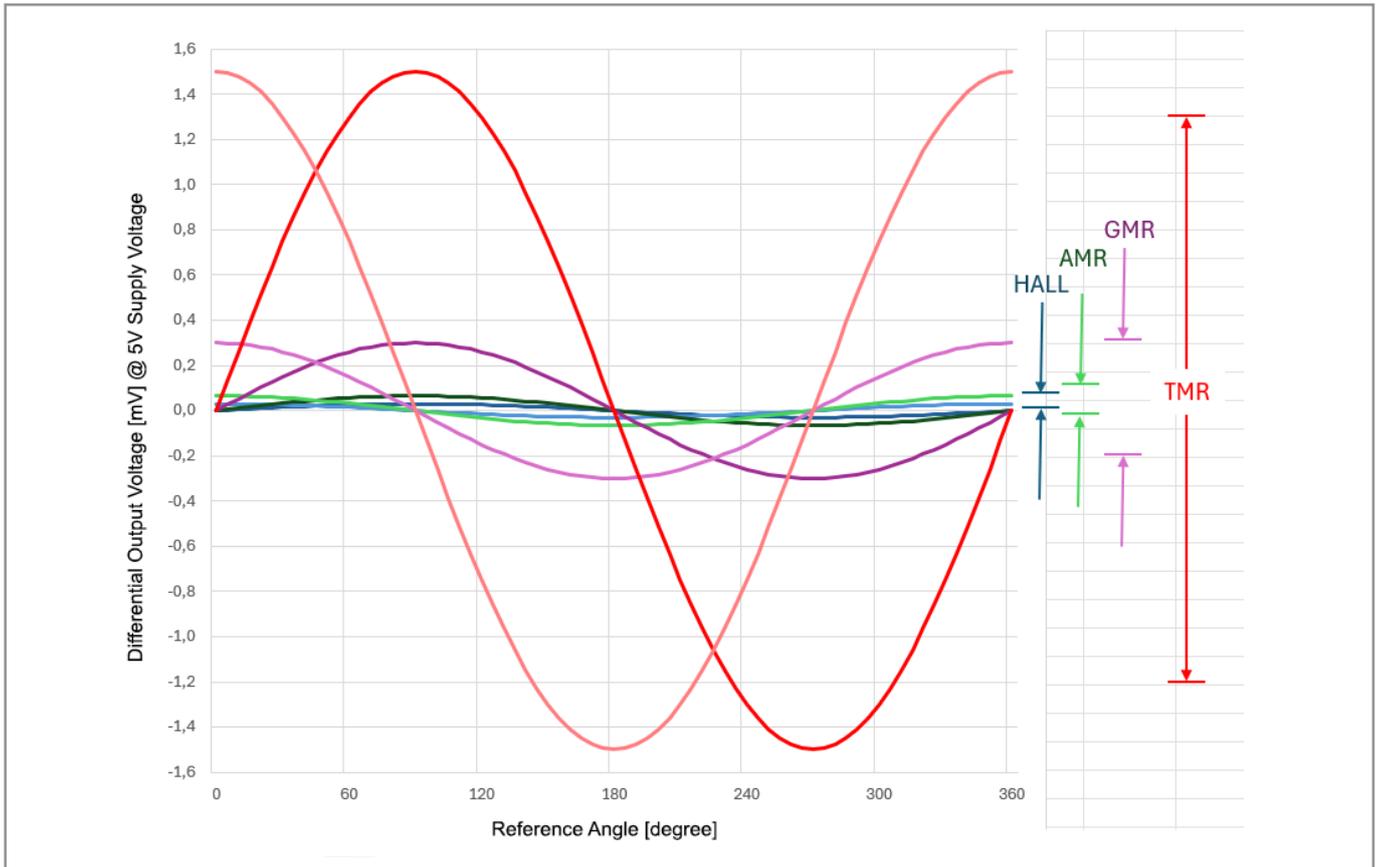


Figure 3: Comparison of the output signals from Hall and TMR sensors in relation to the reference angle position – shown as differential output voltage (mV) versus angle (degrees)

TMR sensors offer significantly higher sensitivity and accuracy, especially in applications that require high angular resolution (e.g. $\leq 0.1^\circ$) (see Figure 3). Due to their high signal strength, no preamplification is required, making them ideal for dynamic or safety-critical applications. The low temperature drift is another advantage of TMR sensors. Table 1 provides an overview of the respective advantages of the technology and the comparable properties.

Advantages of 2D Hall	Comparable properties	Advantages of TMR
Intrinsic stray field immunity (SFI) (with only one component)	High angular accuracy at system level (after dynamic error compensation)	High angular accuracy (after static error compensation)
Integrated error compensation with analog sensor (programmable)	Short delay time and small variation (TMR dominated by LP filter on the output)	Best signal-to-noise ratio
High EMC robustness with analog sensor (optimized for remote setup)	On- and off-axis measurement configuration (Hall sensor for digital only)	Direct μ C connection without the need for an amplifier
Wide magnetic field operating range (5 to 250 mT)	Support for ASIL-D and Fail-Operational Systems	Very low power consumption (for discrete sensor)
PCB-free solution with SFI enables small form factor	Both sensor technologies can be optimized for ferrite	Extremely compact housings
High cost efficiency (for sensor + ASIC)		High cost efficiency (for discrete sensor)

Table 1: Comparison between Hall and TMR sensors: Overview of the advantages of each technology and their similarities

The application focus of both technologies is on steering, electric motors and actuators, and brakes.

Stray field compensation for Hall and TMR sensors

Modern braking systems must provide reliable position data even under electromagnetic stress. The ability of a sensor to compensate for external magnetic fields directly influences signal quality and system stability.

Hall and TMR sensors take fundamentally different approaches to interference stray field compensation: while TMR solutions rely on architecture-based or application-specific concepts, Hall sensors suppress stray fields at the chip level.

Although TMR sensors inherently have a very high signal-to-noise ratio, they do not feature active compensation at the chip level. In the event of strong stray field influences, they therefore require additional compensation strategies via a suitable system architecture (see Figure 4).

TMR sensors in stack design offer an effective solution for stray field compensation thanks to their differential signal processing. Two sensors are arranged vertically in opposite directions on the circuit board. The master sensor is located near the magnet, while the slave sensor is on the opposite side. While the measurement relevant magnetic field component varies due to the different distances, an external stray field has an almost identical effect on both sensors. These interference influences are largely eliminated by the software-based differentiation of the two sensor signals. The difference between the determined angle values serves directly as a measure for the correction value to compensate for the stray field effect. The software also handles signal processing, including offset and gain correction, orthogonality adjustment and angle calculation, as well as optional functions such as harmonic compensation. Safety-related functions (FuSa) are also implemented in the system. This design does not require complex hardware and enables robust, interference-tolerant angle measurement without external shielding.

Linear TMR sensor pairs enable intrinsic stray field suppression through differential signal processing. Typically, two TMR cells are positioned laterally offset along the magnetic field path in radial off-

axis configurations. The sensor bridges are designed inversely so that uniform external stray fields largely cancel each other out in both signals. Although both sensors detect the same stray field, their sensed magnetic field components differ from each other due to their relative position to the magnet. Subtracting the signals suppresses effects at the signal level and provides a stable differential signal that represents the pure sensed magnetic field component. The software performs separate signal processing for both channels – including offset and gain correction, orthogonality compensation and angle calculation. This method is particularly suitable for applications with dynamic magnetic field gradients and high EMC exposure, offering high accuracy with minimal hardware requirements.

Linear TMR sensors with differential evaluation offer a robust solution for stray field compensation, which can be implemented both on the hardware side and via model-based software. For this purpose, two XY-sensitive TMR cells are arranged in such a way that they detect both the measurement relevant magnetic field and similar homogeneous external stray fields. Differential amplifiers subtract the signals from both sensors ($U_{x1}-U_{x2}$, $U_{y1}-U_{y2}$), effectively filtering out field-related offsets. The software takes care of further signal processing, such as offset, gain and orthogonality correction, as well as angle calculation. Additional functions such as harmonic compensation and functional safety monitoring (FuSa) can be implemented if required, but are not mandatory. For applications with application-related asymmetry, caused for example by the installation position or temperature effects, model-based field compensation can also be performed in the control unit. This uses a previously calibrated system model to correct any remaining deviations. This method is very flexible, but requires validation at component or vehicle level. The result is a highly accurate, interference-stable sensor signal with minimal hardware requirements.

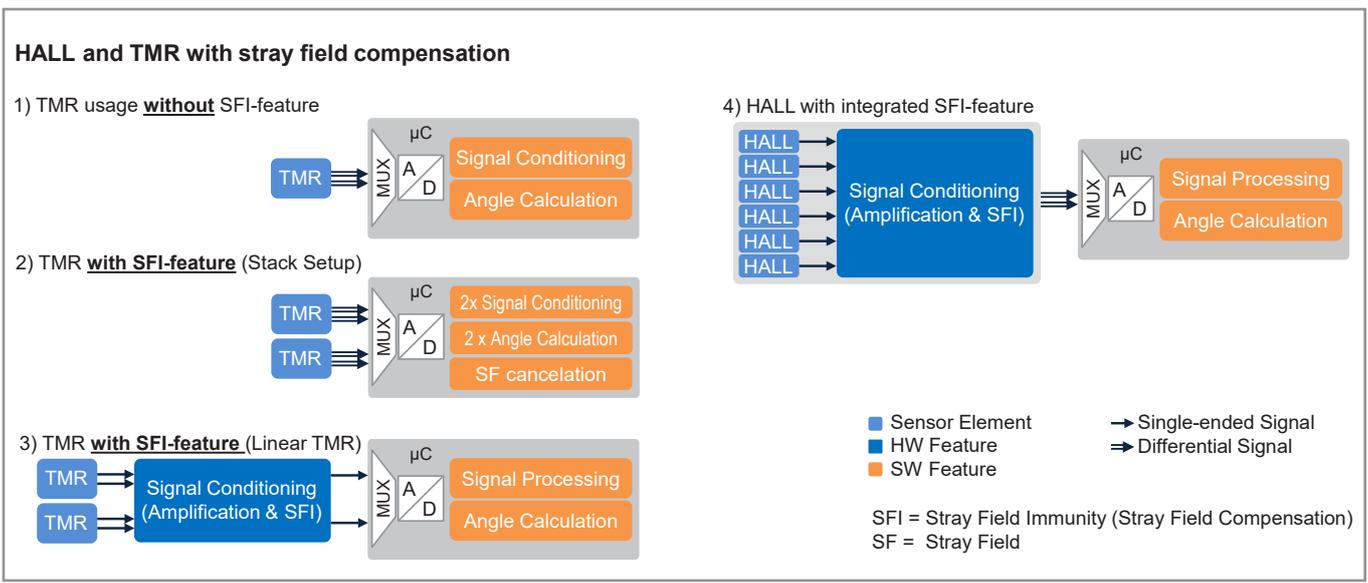


Figure 4: Overview of stray field compensation strategies for Hall and TMR

The **Hall sensors** in the HAL 302x series feature integrated stray field compensation directly at chip level. This is based on a hexagonal 6ZD cell structure with six symmetrically arranged Hall elements, whose signals are evaluated differentially internally. This allows homogeneous external magnetic fields – such as those caused by DC or AC stray fields – to be suppressed mathematically within the sensor itself. Signal processing takes place entirely within the chip. A sin/cos transformation is used to separate the target field from the stray magnetic field. Gain, offset, orthogonality and zero index are programmable. This results in a highly accurate, interference-compensated output signal that already meets the requirements of ISO 11452-8 at the component level – without any external shielding or calibration. The signal remains stable even under unfavorable conditions such as small air gaps or an asymmetrical magnetic arrangement.

Typical residual errors for interference fields of 4.000 A/m are less than 0.1°. In addition, FuSa functions (functional safety) are integrated, offering extended diagnostic coverage and simplifying external safety monitoring at the control unit level. In addition to angle calculation, the software also performs optional dynamic error compensation for maximum measurement accuracy.

Ferrite magnets are an economical and readily available alternative to NdFeB magnets. Both Hall and TMR sensors can be optimized for use with them. Their advantages include independence from rare earths, high temperature stability and cost certainty.

The lower magnetic field strength can be compensated for by system calibration or signal amplification.

Technology recommendation based on application context

Selecting the right sensor technology for position measurement and automotive applications requires careful evaluation of technical and normative requirements such as accuracy, EMC robustness, installation space, safety requirements and system costs.

Hall sensors are particularly suitable for applications with medium angular resolution, in EMC-critical environments or where installation space is limited.

The HAL 302x series offers integrated stray field compensation and is qualified according to common automotive standards – ideal for compact, robust designs with solid basic safety and redundant design.

TMR sensors such as the TAS series enable maximum angular resolution ($\leq 0.001^\circ$), wide bandwidth and dynamic, energy-saving signal processing. They are the preferred choice for applications with the highest requirements for functional safety, diagnostic capability and response speed – such as in brake-by-wire or steering systems. The sin/cos output, combined with minimal power consumption, enables precise control and, at the same time, standard-compliant safety in accordance with ISO 26262.

Safety-critical applications benefit particularly from the combined use of both technologies. Dual-stack architectures enable mutual monitoring, improve EMC robustness and increase diagnostic capability – while minimizing additional costs and complexity. This allows redundancy, functional safety and accurate angle detection to be efficiently combined – a decisive advantage for modern control and safety applications.

Application	Preferred solution	Reasons for Hall	Reasons for TMR
Brake-by-wire (EMB, EMB)	TMR/Hall or Hybrid	Stray field tolerance, large magnetic field operating range for high air gap variations, integrated amplifier with HV resistance and EMC robustness for remote setup, safety-relevant	Highest precision and bandwidth, direct μC coupling, safety-relevant
Steering systems (EPS, RWS)	TMR/Hall or Hybrid	Stray field tolerance, safety (ASIL-D) with integrated safety monitoring, full feedback for single-sided PCB assembly, low latency	High angular resolution, low noise, low latency, dynamic sensing, safety (ASIL-D)
E-motor position feedback	TMR/Hall	Stray field tolerance, high accuracy in mechanical tolerances, integrated amplifier with HV resistance and EMC robustness for remote setup, integrated fault compensation	TMR for precise sin/cos signals, on- and off-axis integration possible

Table 2: Technology recommendation by application context

For efficient system design, it is advisable to plan the sensor architecture early on for redundancy and diagnostic capability. In cost- and space-critical applications, the Hall sensor remains the first choice. For safety-related applications with the highest demands, however, the targeted or combined use of Hall and TMR technology is the key to a powerful, standard-compliant and competitive solution.



	Fast Analog Hall Sensor		Analog TMR Sensor				
Product Name	HAL 302x 	HAR 3025 	TAS2240 	TAS4240 	TAS8240 	TAS214x 	TAS414x 
Number of Sensing elements	3 or 6 Z-plate	2x 6 Z-plate	2 HB	4 HB	8 HB	2 FB	4 FB
Angle Error (mit Stat. comp.)	$\leq \pm 0.6^\circ$		$\leq \pm 0.5^\circ$			$\leq \pm 0.3^\circ$	
Angle Error (mit Dyn. comp.)	$\leq \pm 0.1^\circ$ (gain, offset, phase)		$\leq \pm 0.1^\circ$ (depending on SW implementation)				
Output	Analog, Diff. or SE amplified 4 V _{PP} Sin & Cos	2x Analog, Diff. or SE amplified 4 V _{PP} Sin & Cos	Analog, Single Ended 1.5 V _{PP} Sin & Cos	2 x Analog, Single Ended 1.5 V _{PP} Sin & Cos	4x Analog, Single Ended 1.5 V _{PP} Sin & Cos	Analog, Differential 3 V _{PP} Sin & Cos	2 x Analog, Differential 3 V _{PP} Sin & Cos
Measurement Config.	On-axis						
Magnetic Field Range	5 ... 250 mT (programmable)		20...80 mT (typical), 80...130 mT (extended range)				
Redundancy	-	•	-	•	•	-	•
Functional Safety (syst)	ASIL C	ASIL D	ASIL B	ASIL D	ASIL D	ASIL B	ASIL D
Self-Diagnosis, (FSM)	•	•	-	-	-	-	-
Stray field immunity	•	•	At system level				
Integrated Capacitors	-	-	-	-	-	-	-
Package	SOIC8	QFN24	DFN4	DFN8 / TSSOP8	QFN16 / TSSOP16	DFN8 / TSSOP8	QFN16 / TSSOP16

Table 3: Overview of TDK-Micronas' combined sensor portfolio with a focus on application-specific system solutions and hybrid architecture approaches (Source: TDK-Micronas)

Conclusion and recommended action

The selection of Hall or TMR technology must be made with consideration for the specific context and the intended application. The following applies:

- **Hall sensors** are suitable for robust, compact systems with moderate to high accuracy requirements.
- **TMR sensors** are the first choice for high-precision, dynamic and safety-critical applications.
- **Hybrid architectures** offer an optimal balance of precision, redundancy and EMC stability.

Recommendation for selection

1. Define the application requirements (accuracy, EMC, safety level, installation space, costs).
2. Use the table to evaluate the appropriate sensor family.
3. Consider hybrid solutions if redundancy and/or maximum accuracy is required.
4. Use available reference designs and evaluation boards for system validation.
5. Consult TDK-Micronas for customised/customized design-in support.