Chances of XMR-Sensors in Automotive Applications

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Abstract: Over the years AMR-Sensors have been widely used for robust and safety critical automotive applications. Since new technologies have been released by competitors, GMR and TMR-based Sensors have been benchmarked to allow a classification. This article provides a summary of various scenarios for typical sensor applications.

1 Introduction

Since 1995, first applications have been developed on AMR technology (Anisotropic Magneto Resistance) at Bosch. The feedback coming from the corporate research teams clearly identified the advantages compared to state of the art Hall-Sensor based incremental measurement systems. The confidence on the robustness and reliability of this technology also allowed an introduction in safety critical applications as power steering. In the following years a lot of suppliers began research and development on the optimized AMR structures and design to improve its signal quality and reliability. Originating from the very successful hard disc drive heads production, GMR technology (Giant Magneto Resistance) showed a high potential to increase the system performance for automotive applications. As a consequence Bosch also started to develop a GMR-stack (spin valve type) and industrialized it together with Infineon. The opportunity to combine the stack with logical function blocks made possible the first monolithic, so called “smart sensors” with sensor element, signal conditioning and interface. In 2008 the first TMR (Tunnel Magneto Resistance) sensors have been introduced by NVE and later by TDK EPC. The technology is derived also from the advanced hard disc drive heads for automotive qualified applications and combines the benefits of AMR and GMR in one new technology. The previous mentioned technologies allow to build so called XMR-Sensors where X means any type of a MR-technology.

2 Sensor Technology Comparison

The AMR effect was first discovered by William Thomson in 1856 but was later called ordinary magneto resistance (OMR). [01],[02] The AMR effect shows a resistance change which is dependent on the angle between the direction of electric current and orientation of magnetic field. To remove the non-linear characteristics stripes of aluminum as an ideal electrical conductor are placed equidistant and inclined at an angle of 45° on the NiFe (permalloy) resistor substrate, the so called barber pole structure.

The quantum mechanical magneto resistance effect GMR was simultaneously and independently discovered in Fe/Cr multilayers by Albert Fert and Peter Grünberg. They have been awarded in 2007 the Nobel Prize in physics for their discovery of the GMR effect. The GMR effect is observed as strong change of the electrical resistance depending on the parallel or antiparallel magnetization alignment of the multilayers. Different types of GMR systems have been developed. Most important are Multilayer GMR and Spin valve GMR. Multilayer GMR employs ferromagnetic layers which are separated by a very thin non-ferromagnetic spacer. Spin valve GMR exhibit bi-stable behavior depending on the magnetization alignment due to the different coercivities of a free layer and pinned layer [03],[04],[05],[06]

The TMR is derived from a spin valve GMR sensor. A non ferromagnetic spacer has been replaced by an electrical insulating tunnel barrier and the current flow is perpendicular to this layers. [07],[08],[09],[10],[11],[12],[13],[14],[15]

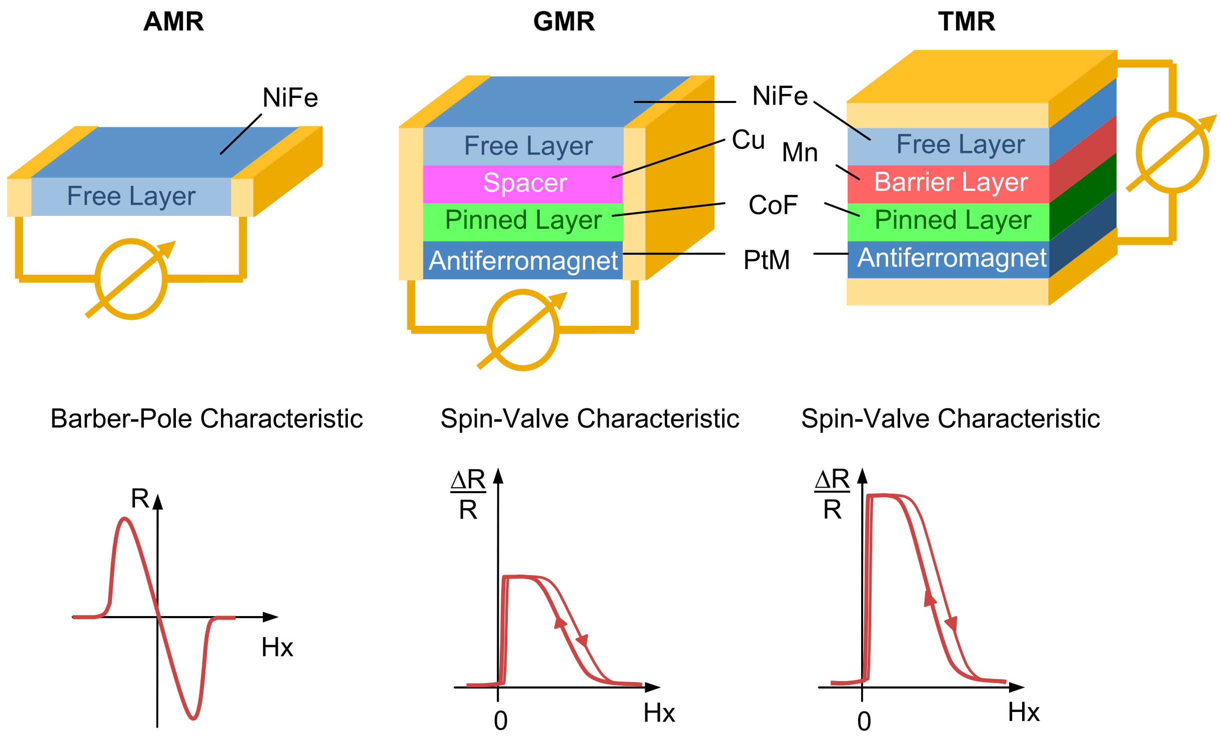

Figure 1 - Simplified sensor topologies and typical characteristics

Sensor Technology	**AMR**	**GMR**	**TMR**
Configuration	bare bridge	amplified bridge	bare bridge
Effect (ΔR/R) [%]	3	7	50
Signal Amplitude [mV/V]	13	33.6 [2)] (320)	330
Signal Temp.-Coeff. [%/K]	- 0.35	- 0.1 [4)]	- 0.2
Offset [mV/V]	± 2	± 6 [4)]	± 3
Offset Temp.-Coeff. [(µV/V)/K]	± 2	± 5 [2)] (50)	± 3
Field Range [kA/m]	25 … ∞	25 … 55	25 … (∞)
Temperature Range Ta [°C]	-40 … +150	-40 … +150	-40 … +150
Signal-to-Noise Ratio [dB]	65	70	90
Monolithic Integration of Logic	No [3)]	Yes	Yes
ISO26262 compliance possible	Yes	Yes	Yes

1) Sensitivity Conditions: Ta = 25 °C; Hext = 25 kA/m; VCC = 5 V
2) After amplification, value equalized for comparison purposes: (original value)
3) Will be available in early Beginning of 2012
4) After initial, non-volatile calibration

Table 1 - Comparison of sensor technologies. The parameters are technology specific typical parameters.

Figure 1 presents simplified topologies to explain the efforts to build a sensor. The AMR-Sensor layout is very simple regarding the number of layers and materials used. The production process is close to the common chip process of integrated circuits i.e. photolithography, material deposition and etching. The process for GMR and TMR is very similar but the number of layers is larger and a magnetization process after finishing the stack has been added. The higher cost for the production of GMR- or TMR-

Sensors can be compensated by chip size reduction. A TMR-Sensor can be realized in a 1/100 of an AMR-sensor area (~10µm^2).

The differences in the sensitivity or ΔR to R-ratio and amplitude at room temperature are the main features for a selection in an application. The 180°-periodic angular uniformity of an AMR or the 360°-absolut sensing capability of GMR or TMR are less important than it seems first hand. All sensor principles may be used in 360°-applications, sometimes with additional measures.

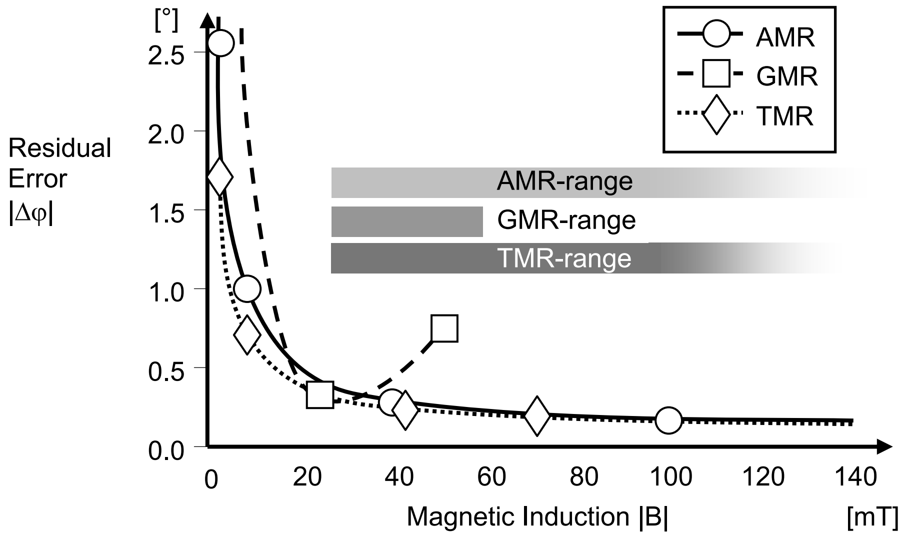

Figure 2 - Field range for the different sensor technologies and the resulting residual error over field strength.

Figure 2 presents the residual angular error over field induction and the typical allowed field strength windows for the sensor technologies. The lower field border is nearly identically for all three technologies but varies on higher fields. The GMR-stack is limited to 55 mT due to the possible flipping of the pinned layer of a spin valve sensor. AMR and TMR have no defined upper limit but current applications normally use NdFeB magnets with approximate maximum of 100 mT.

3 Requirements for sensor applications

Most automotive applications have high volumes and are cost sensitive. The best way to meet the resulting requirements for the sensors is to highly integrate these sensor elements with other electronic components. Depending on the requirements also pure Wheatstone bridges are still used for new applications. This is a result of an obligatory partitioning investigation and system simulation. The answer to the question which sensor technology to use in the front end is strongly influenced by market availability and project timeline. Due to a mismatch between project timeline and time for a new sensor development the decision for a new partitioning is oriented by the currently available sensors on the market. But for platform developments there is a chance to optimize the sensor concept to the needs of the project. Therefore a lot of system simulations have to be done to identify the most suitable configuration under some assumptions like cost minimum, functional optimization, maximum robustness and simplification of the whole system. Also the OEMs request for shorter time-to-market developments result in more and more lean and simplified systems to be customized easily and adopted quickly to a new platform.

To shorten the development time for new integrated sensors a high amount of re-useable design elements – so-called building blocks – have been developed (Figure 4). Now it is possible to assemble pre-developed blocks and merge it to new system. Figure 5 demonstrates some examples of possible configurations for a specific application.

Also safety critical relevant requirements have to be considered more and more for selection of a sensor configuration:

- High reliability over lifetime <0.2 ppm
- High ambient temperature profiles -40°C to +150°C
- ISO26262 compliance: Ability for Self check / Health monitoring / Redundancy

All three discussed XMR-technologies are suitable to meet the safety critical related requirements. But there are some more questions to be answered.

3.1 Analog or digital signal transmission

Due to the low signal amplitudes of bare sensor bridge signals (e.g. AMR ~100mV) the need of differential amplification and sampling should be investigated. Single ended signals may cause ground shifts and thus result in angle errors. Using a high precision sensor and transmitting analog low-voltage signals over long distances in a harsh environment will result in unusable measurements. So if the analog sensor is on the same PCB as the ECU (Electronic Control Unit) and very close to the ADC-Inputs, the signals may be transmitted in the analog domain. But tendencies are to switch as soon as possible from the analog to the digital domain to be more robust and cost effective. The efforts to keep analog signals clean and robust as good as possible are very high compared to the digital domain. But this brings us to the next question.

3.2 Location of the Analog-to-Digitals conversion

Definition of the location of an ADC (either sensor or microcontroller/ASIC) is robustness and quality driven, but may also be a commercial motivated question. For example safety critical systems often require high resolution and high precision ADCs, but not every microcontroller provides such an ADC. A selection of a high performance standard microcontroller device to fulfill the requirements for a suitable ADC is an expensive solution. Building an ASIC with a specifically designed ADC often collides with tough project timelines and budget limitations.

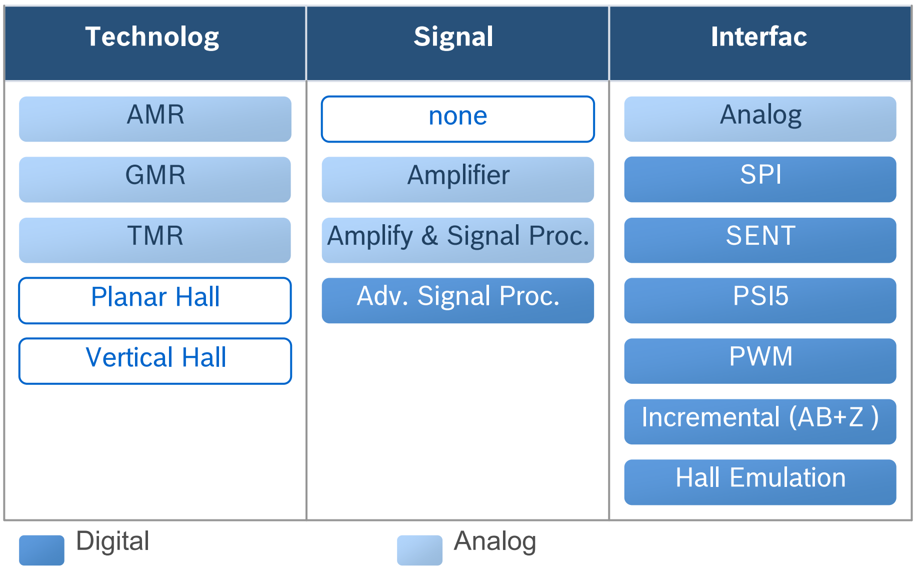

Figure 3 - Sensor Building Blocks

3.3 Interface and Signal processing

Based on the sensors which are available on the market and the application scenario developers have to consider the consequences of a specific system partitioning (Figure 5). Not every combination of sensor and ECU fulfills automotive requirements. System performance and also system cost are directly depending on the whole signal processing function blocks and its clustering in different subsystems. The questions regarding interface and required signal pre-processing is often a part of the OEMs requirements specification. The interfaces are OEM-like requested and so a sensor solution suitable for different OEMs needs to be multi-protocol capable. But for a system-solution consisting of sensor and ECU, the choice of an interface is optimized easier technologically and commercially for one system. The right side of Figure 3 presents a set of common physical and logical interfaces for the digital domain. Combining several interfaces in one smart sensor increases the sensor cost significant (Figure 5).

3.4 Sensor Technology and System Partitioning

The different primary properties of sensors often meet the requirements, so that no clear decision for one technology is possible. Based on the secondary properties of AMR, GMR or TMR technologies, selecting a technology will cause a completely different systems design. For example AMR technology still does not provide a monolithically so-called vertical integration of logic and sensor element on one die. GMR and TMR are based on chip-compatible processes and allow integration of functional blocks very easily. Combining AMR sensors with amplifiers or with a complete signal conditioning/-processing unit and interface function block requires a chip-by-chip solution. This is not an indicator for higher solution costs but often results in bigger chip-packages and reliability issues.

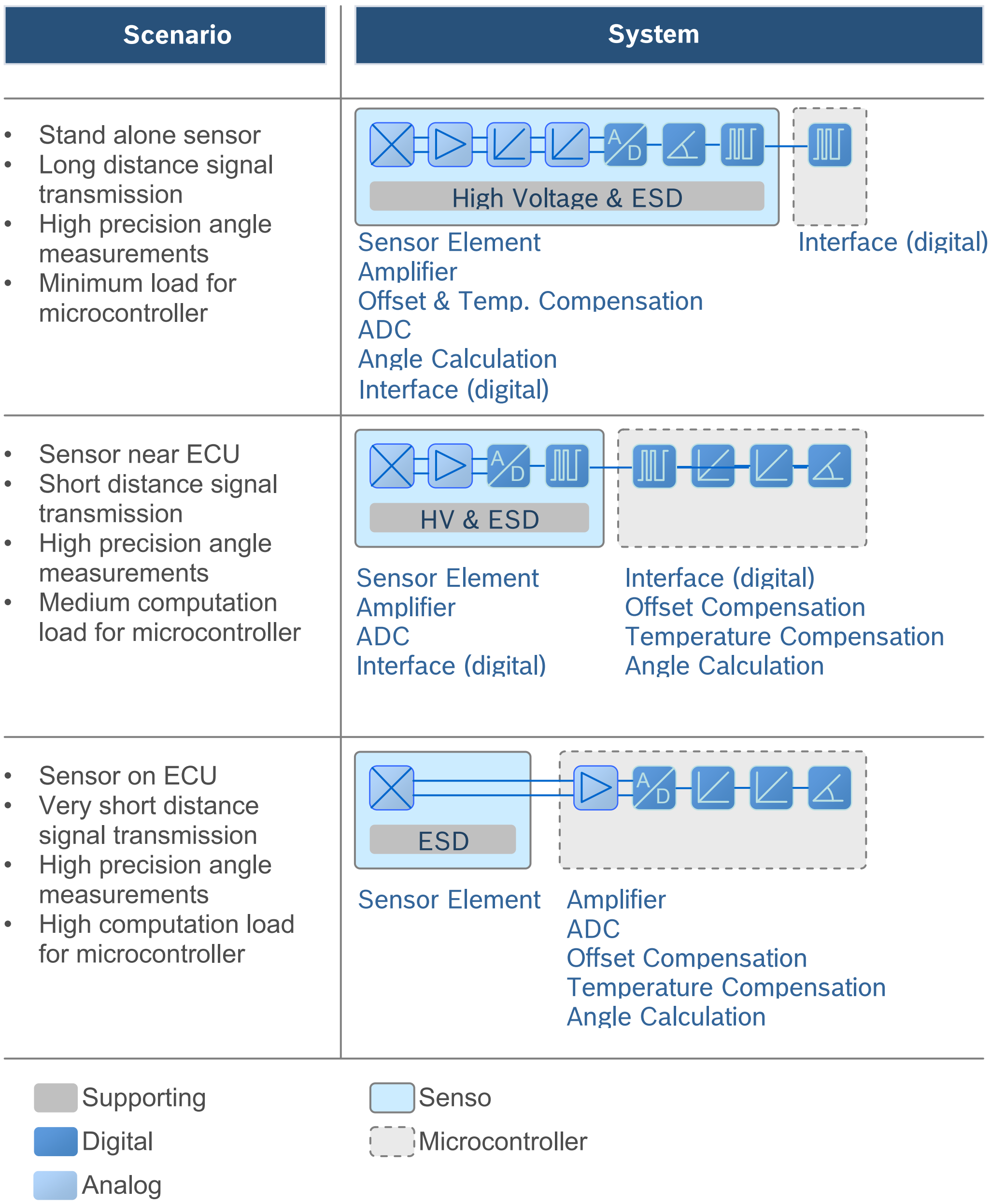

Figure 4 - System Partitioning

Signal quality issues regarding scaling errors between both bridge output signals, signal amplitudes and signal and offset drift are still in focus. But all these can be partially compensated with sufficient computation power on the microcontroller side. TMR with its high output signals and low drifts allows sampling without additional amplifiers. This is a big benefit regarding reliability, current consumption, noise and also resolution of the signal.

4 Design Aspects

In the beginning of introducing AMR-sensors, developers had to learn how to handle new requirements. Saturating a sensor with a defined minimum field strength was one of this new requirements. It was getting more attention when the GMR was planned to use in the first applications because of its upper field strength limits. It was completely new to handle both field limits and keep the mechanics as simple as for AMRs. Axial movement had to be reduced to a minimum and also the axial, two pole magnetization had to be changed to a diametral, two-pole magnet pill. Also the magnet supplier had to learn how to specify and verify these quality relevant parameters as field homogeneity and field strength window. The field strength window depends on the real magnetic environment such as metallic shaft, housings and gear wheels, ….

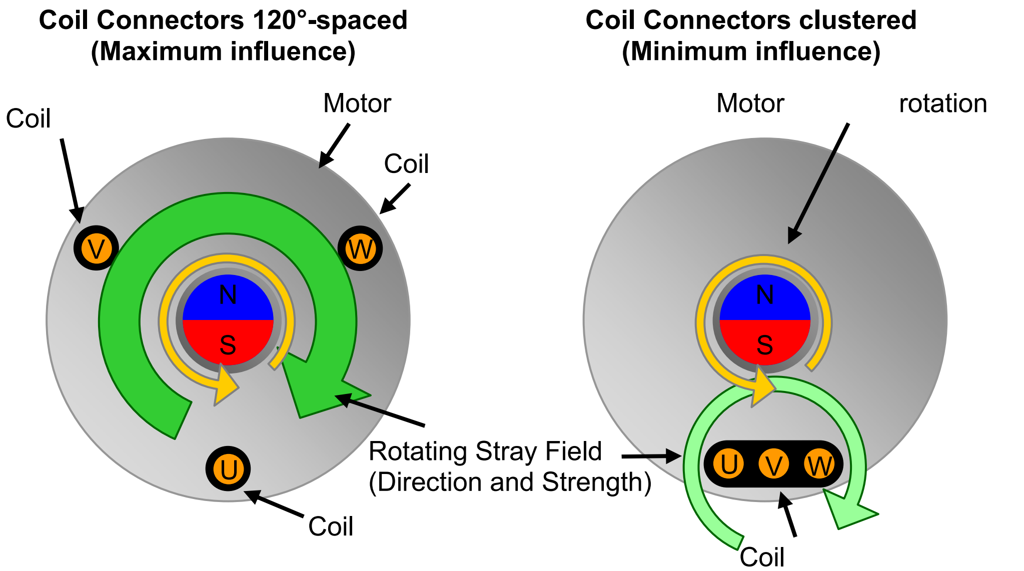

Figure 5 - Influence of the phase current and the position of the coil connectors

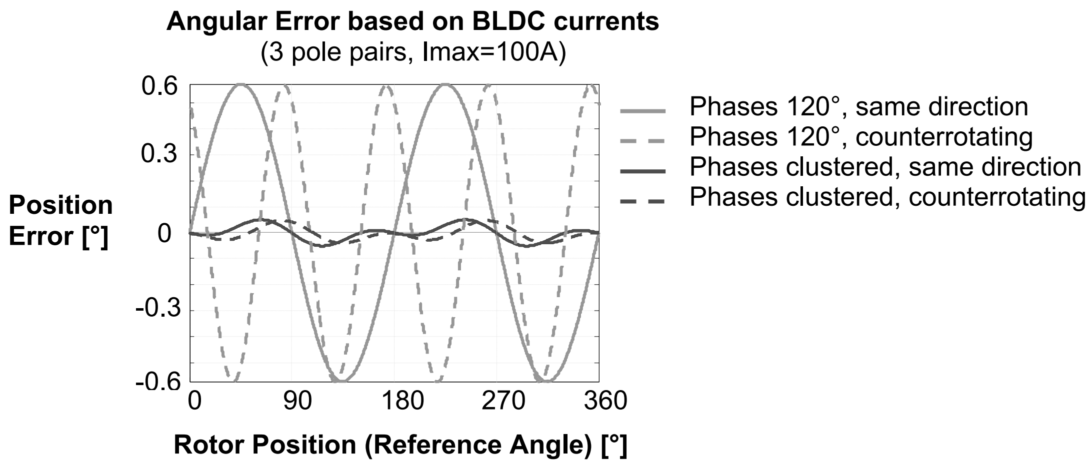

Figure 6 - Resulting angle error when applying 100A on coil connectors 30mm radius compared to 100mT field from the rotation magnet.

In addition motor designers had to learn how the arrangement of the phase current driven coil connectors influences the quality of angle measurements (Figure 5). Upon placing the connectors in 120° angles around the motor center, you see a rotating stray field which is superpositioned with the magnet's rotating field. The resulting angular error shows a harmonic which is N+1 or N-1 of the pole pair number (N) of the rotor (Figure 6). Reduction of this effect can be achieved by clustering the coil connectors and partially compensating the self emitted stray field. This allows the reduction of the angular error by ~80-90%.

5 Examples for XMR-Applications

XMR sensors are used often in safety critical applications (Figure 7). Most of the absolute angle measurements are done for sensing a rotor position of a BLDC-Motor (Brushless DC) or determination of a steering angle or gear position. The wiper is a less safety critical application with ASIL-A classification, which is the lowest level of safety classification. Several other applications like pumps or actuators like gear shift, clutch and seats) mostly use AMR-Sensors but will move to GMR due to higher integration resulting in cost reduction. Wheel-speed, Steering Angle Sensor and Active Power Steering (EPS, Electric Power Steering) are part of the ESP/ESC-System (Electronic stability control) and being classified with ASIL-D which is the highest safety critical classification. This requires highest reliability, redundancy and long term stability requiring low changes over lifetime.

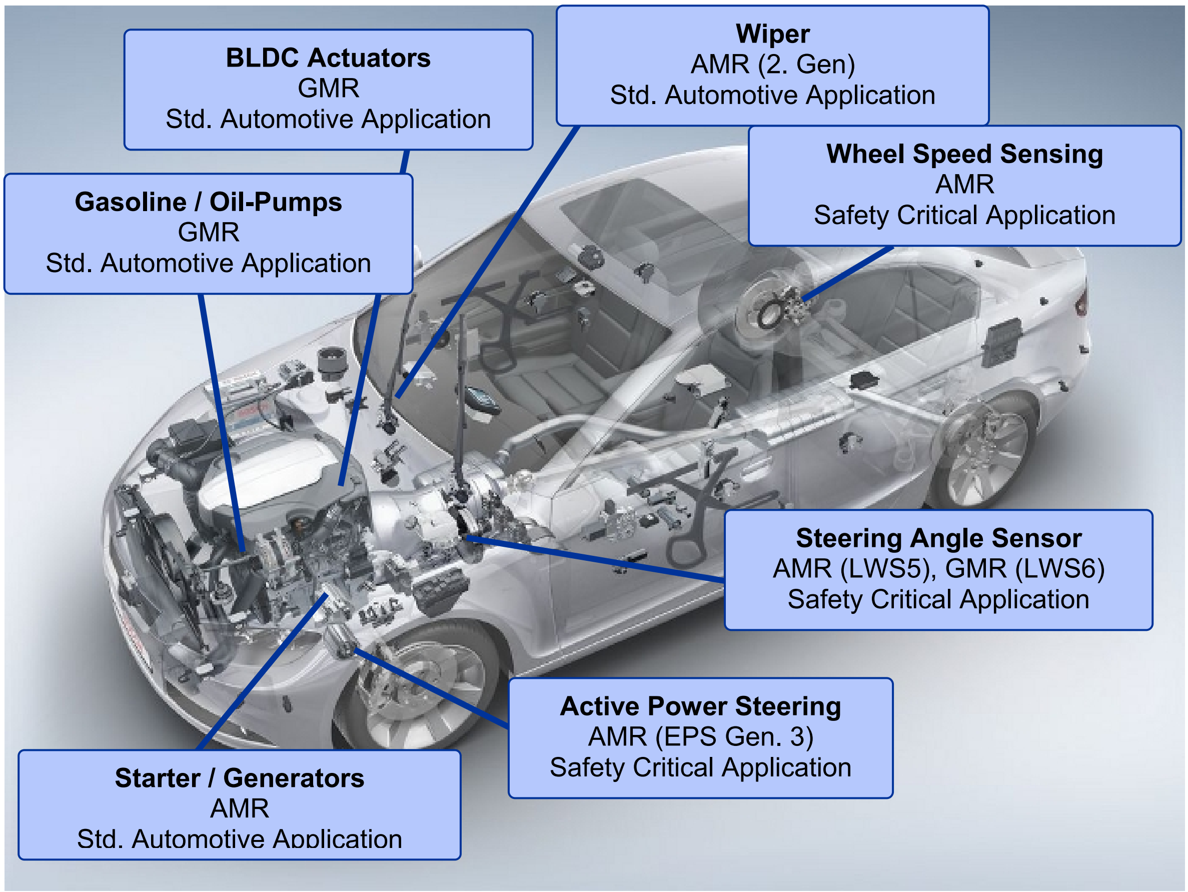

Figure 7 - Automotive Applications with XMR-Sensors

6 Conclusions

Based on extensive technology evaluations different aspects for technology selection have to be considered: availability of the technology, robustness, reliability and system cost. AMR still keeps the leading position for highly reliable and precise absolute angle measurement systems. Even for semi-integrated sensors (bridge plus amplifier) on two separate dies, this technology seems to be competitive for the next years. Today GMR sensors provide the best technology for highly integrated systems with big amount of logic cores on it. Disadvantages like magnetic field limitations and higher residual errors can be neglected for low cost applications. Still in the beginning, TMR technology seems to be a young but powerful successor for AMR and GMR. It combines the high integration and 360° absolute measurement capabilities of GMR and the robustness and low angular error as AMR. First results also indicate a good reliability for this young technology.

A clear winner of this comparison can not be named due to the specific pros and cons of each technology. The application of a technology depends on long term strategies of the manufacturers. For near term projects AMR and GMR-sensors will be the preferred solution. For new platforms the competition will be harder since TMR will be introduced in the market.

7 Literature

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