

Introduction of a MR Rotor-Position Sensor for Off-Axis Application and Comparison to Competitive Technologies

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ABSTRACT

Due to regulations which limit the CO₂ emission of passenger vehicles in the upcoming years, hybrid cars are becoming more and more important. In this paper different concepts of hybridization are discussed with a link to the properties of the electric machine behind these hybrid concepts. Upon the basis of a generalized principle of operation of an electric machine the influence of position and speed data, acquired by a rotary position sensor, is presented with a detailed analysis of various sensor concepts. Therefore the major products used nowadays are presented with a brief introduction to the underlying measurement principle. Additionally a new semiconductor-based sensor concept is introduced with high measurement accuracy and of small form factor. The survey is finalizing with a systematic analysis of the different sensing technologies - considering integration of the sensor concepts, magnetic immunity of the measuring principles, sensor-cost and analysis of sensor accuracy. The data used to estimate the sensor accuracy have been experimentally acquired on a test rig at various speeds - up to 15,000 rpm - considering and monitoring also dependency of the accuracy on the rotary velocity of the shaft.

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INTRODUCTION

In 2009 the European Union has released regulations which limit the emission of CO₂ of passenger cars to 95g/km beginning in 2020. Historical data as well as the target values for 2012 and 2020 are shown in figure 1. The overall vehicle data show that the 2012 target has been missed by 1.2% already while it is obvious that the 2020 target cannot be accomplished just by optimization of the combustion engines and the drive train. Alternative Fuel Vehicles, including Electric vehicles (EV), gas, hybrid (HEV) and Plug-in Hybrid vehicles (PHEV), have already reached CO₂/emissions of 104.1 g/km in 2013 [1].

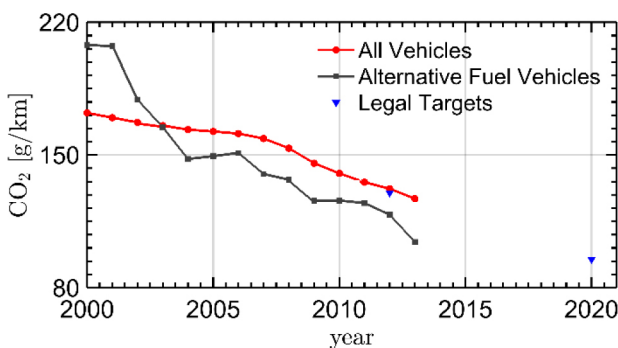


Figure 1. Data of CO₂ emission in Europe for the years 2000-2013 are shown for all vehicles as well as for alternative fuel vehicles only (including battery electric vehicles, hybrid and plug-in hybrid vehicles, LPG, bio-diesel, E85 and NG-biomethane). In blue are shown the legal targets for 2012 and 2020.

These data give rise to the importance of electric and hybrid electric vehicles for the upcoming years for the OEMs to focus on, in order to undercut the targets. The introduction of electric and hybrid electric vehicles is motivated by different principles: Increase of efficiency at energy conversion, adjustable during operation, energy recuperation. The new European drive cycle is focused on urban traffic and therefore the introduction of hybrid electric vehicles offers huge potential to reduce fuel consumption. Additionally the hybrid cars benefit from the highly efficient combustion engines explaining the overall attractiveness of the hybrid vehicle concept.

Due to these reasons several different hybrid electric vehicle concepts have been established within the past years which can also be arranged in different classes: serial-hybrid, parallel hybrid and powersplit hybrid concepts [2].

Additionally it is useful to split up the hybrid concepts by degree of electricity.

Mild-Hybrid vehicles are these concepts which make use of a starter generator. In case of belt-driven starter-generators (BSG) the adaptations made to normal combustion vehicles are minor. Mostly the normal generator is replaced by a starter-generator coupled via a belt to the drive train. This concept is part of the parallel hybrid family and offers - in combination with use of the 48V architecture - efficient energy recuperation, start-stop functionality and the ability of sailing/coasting [3,4]. Another mild-hybrid concept proposes the

electric engine placed between combustion engine and transmission, giving rise to the alternative name “integrated starter generator” or “crank starter generator” (CSG) [2].

Full-Hybrid cars increase the functionality further by enabling pure electric driving over short distances of a few kilometers and pure combustion driving as well as a combined driving mode. The vehicle infrastructure has to be further adapted to realize this concept. The high-voltage battery has additionally to be able to provide high power while offering a high capacity. The electric motors have to provide high electric driving power. Full-hybrid concepts can be differentiated in two concepts: Integrated motor generator (IMG) and separate motor generator (SMG) [5]. Within an IMG application the electric machine is inserted between the combustion engine and the transmission while for a SMG the electric machine is separated from the combustion engine and transmission and can be understood as an axle drive configuration.

Plug-In-Hybrid vehicles (PHEV) are Full-Hybrid cars which have been adapted. A common setting is that distances of approximately 50 km can be driven purely electric while long distances are covered by the combustion engine. Also the addition of an extra battery and a charging system is widely used [2].

In general it can be stated that the different hybrid concepts offer specific advantages and draw-backs. Due to battery performance and cost the overall cost of the concepts scales with the degree of electrification currently. Another issue to be considered is the weight and power requirements of the targeted vehicle. Small hybrid concepts like BSG are preferably used for small cars, e.g. light-weighted 3-cylinder cars, whereas for heavy high-performance cars an integrated solution is adventurous.

One essential part of the electric powertrain is the electric motor which is used in the different concepts. Even though a wide variety of electric motors are used in automotive applications, covering a range of 3 kW - 300 kW, the function can be described as shown in figure 2 [6,7].

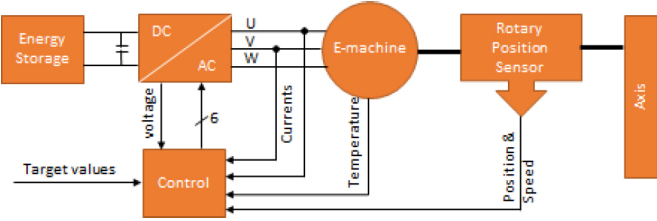


Figure 2. Schematic of the functional layout of the control of an electric machine including the flow of information of the different sensors.

The most prominent motors used nowadays are three-phase machines, current excited synchronous as well as asynchronous machines. Permanent magnet excited synchronous motors are the major type of electric motor which are used in hybrid vehicles. The motors suitable for the different concepts vary in their speed and their number of poles [6]. Driving a motor in general requires measurement of rotor position of $< 1.5^\circ_{el}$ for a synchronous machine. The performance of asynchronous machines in general is relying

more on accurate speed information, which can be derived out of precise position information. In regards to the operating speed it is possible to differentiate the motors. Parallel hybrid architectures, e.g. BSG architectures, are high-speed motors while the serial hybrid and axle drive architectures require less speed but high torque [7]. Typical values for the operation speeds are noted in table 1. Especially the axle drive application relies on accurate rotor position measurement as the power is directly transferred from the electric motor to one of the axes of the car.

Table 1. The table is listing major hybrid strategies, which are crank starter generator (CSG), integrated motor generator (IMG), separate motor generator (SMG) and belt-driven starter generator (BSG). Some of the properties of these strategies are listed to visualize the differences to the requirements for the electric machine of these concepts [2, 3, 4, 5, 6, 7, 8].

	CSG	IMG	SMG	BSG
Hybrid Concept	Mild-Hybrid	Full-Hybrid / PHEV	Full-Hybrid / PHEV	Mild-Hybrid
Architecture	Parallel	Parallel	Parallel	Parallel
Speed	7500 rpm	7500 rpm	15000 rpm	24000 rpm
Pole pairs	>6	$\sim 5-24$	~ 6	$2-4$
Output	10 – 15 kW	$>> 25$ kW	$>> 25$ kW	< 14 kW
Preferred Motor type	Synchronous	Synchronous	Synchronous	Asynchronous
Accuracy	$< 1.5^\circ_{el}$	$< 1.5^\circ_{el}$	$< 1.5^\circ_{el}$	$< 1.5^\circ_{el}$

Rotary Position sensors are essential in the electric drive train as they sense position and speed information which are used in the next step to commutate the motor. To understand where and how false measurements influence the machine, it is necessary to take a look on the operational principle of electric machines, here shown for a permanent-magnet synchronous electric machine [9].

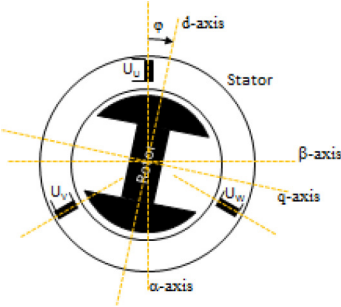


Figure 3. Schematic demonstrating the dependencies of the different coordinate systems used for control of the electric machine. The coils driven with U_u , U_v and U_w are defining a coordinate system with 120° shift between the axes. Upon this basis a new coordinate system is defined, made up out of the α - and β -axis. By rotation around the angle φ this system can be translated into a “rotor coordinate system” defined by the d- and the q-axis.

A coordinate system for a three-phase machine can be considered as three axis with 120° shift. First step is the coordinate transformation from the three axis coordinate system to a system with two perpendicular axes to align the coordinate system with the permanent magnet rotor which consists of two poles. This transformation is called Clarke-Transformation:

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = C \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_U \\ x_V \\ x_W \end{bmatrix} \quad (1)$$

The α - and β -axis are a coordinate system based upon the stator. A second transformation, the Park-Transformation, translates the stator coordinate system to a rotor based coordinate system. This transformation is a simple rotation of the α/β -coordinate system around the angle between rotor and α -axis.

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos \varphi(t) & -\sin \varphi(t) \\ \sin \varphi(t) & \cos \varphi(t) \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \quad (2)$$

In this Park-Transformation angular errors $\Delta\varphi$ directly contribute in a wrong transformation of the coordinate system.

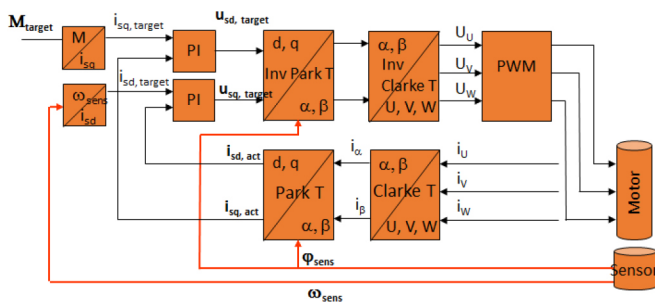


Figure 4. Detailed view on the control of the electric machine considering the information provided by a rotary position sensor, the angle φ_{sens} and the temporal change of angle - the speed - ω_{sens} . The red lines indicate where these information are processed to drive the machine [10].

Even worse the angular error contributes additionally in the inverse Park-Transformation which is carried out afterwards. The speed of the rotor $\omega = \frac{d\varphi}{dt}$ adds another ripple due to wrong calculation of the target current i_{sd} (cf figure 4).

Concluding it can be stated that inaccurate sensing of rotor angles results in efficiency loss of the electric machine, caused by ripple, or even in wrongly directed commutation. Beneath the efficiency aspect also the experience of the driver is a major issue as a torque ripple generates a less smooth motion and noise may be generated additionally. An important requirement to the sensor, beside its need for high accuracy of angle position φ and high resolution of rotary speed ω , is the robustness in regard to its area of application and the need of low-cost.

An alternative which is not considered is the sensor-less commutation. The current data that are acquired in the electric machine are widely used to calculate an angle of the rotor but these calculations are limited in accuracy at low speeds where an accurate commutation is fundamental. A further issue of the sensor-less concept is caused by high torque/high speed as soon as the metal

sheets of the motor get in satisfaction. Also the calculated angle data are commonly used to verify angle data acquired by a sensor in order to increase the functional safety classification of the system.

Within this paper different sensing technologies are discussed and compared to each other. Building on this fundamentals some empirical data of different sensor types are shown and compared and a new sensing concept will be presented.

GENERAL OVERVIEW

Multiple sensing technologies are suitable to be used as a rotary position sensor (RPS). Capacitive and Optical technologies are less suitable for the harsh environment in a vehicle due to the necessity of robustness against temperature, vibration, mechanical shock and dirt. The most used technologies are magnetic sensors, eddy-current sensors and reluctance resolver. In the following these state-of-the-art technologies are looked at.

Reluctance Resolver

Resolvers are functioning analogue to a rotating transformer. The basic physical principle underlying these devices is induction. A typical schematic of a resolver consists of two windings on the rotor, rotated around 90° to each other and at least one stator winding. In this very basic scheme the stator is excited by an AC voltage U_1 . In the two windings on the rotor are induced two voltages described by $U_{21} = U_1 \cdot \text{const} \cdot \sin(\alpha)$ and $U_{22} = U_1 \cdot \text{const} \cdot \cos(\alpha)$ [11]. Demodulation of the secondary voltages results in the sine and cosine voltages which are representing the rotation of the rotor. Performing a simple arctangent calculation on the two induced Voltages, $\varphi_{\text{rotor}} = \tan^{-1} \frac{U_{21}}{U_{22}}$, the rotation angle α can be calculated afterwards [11].

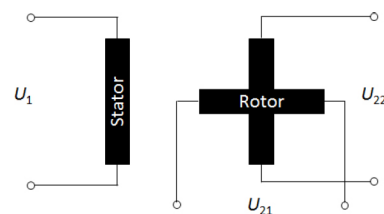


Figure 5. Operating principle of a classical resolver with a stator supplying a driving voltage U_1 and two secondary coils mounted to the rotor, sensing induced voltages U_{21} and U_{22} .

As this principle is not used in automotive application due to the need to contact the rotor a slightly modified product has been developed - the reluctance resolver. The fundamental principle is analog to the classical resolver but instead of mounting windings to the rotor all windings are mounted to the stator and a ferromagnetic target is used as rotor. This rotor is shaped specifically so that the air gap between rotor and stator changes periodically over a single revolution. The stator windings are arranged as bobbins completely around the stator with each excitation bobbin being surrounded by two secondary bobbins generating the induced sine and cosine signal [10].



Figure 6. Picture of a modern reluctance resolver as provided by TE Connectivity.

The calculations described for a classical resolver are therefore still valid also for reluctance resolver (as long as the rotor is correctly shaped) with the constant now containing additional parameters, e.g. the magnetic permeability of the rotor, distance, etc.

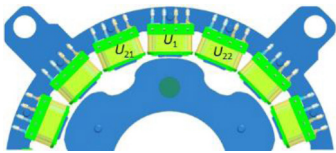


Figure 7. Schematic to illustrate operating principle of a reluctance resolver. Analog to figure 5, U_1 denotes the applied primary voltage while U_{21} and U_{22} denote the induced secondary voltages.

Eddy-Current Sensor

The second major sensor technology applied as a RPS in automotive is based on the eddy current effect. The very basic principle is based on the fact that a coil - driven by an AC current - generates an oscillating magnetic field. If a metallic target is near the coil, eddy currents are induced in the metal of the target. As these currents are circulating reverse to the currents in the coil, the inductance and the resistance of the coil are altered.

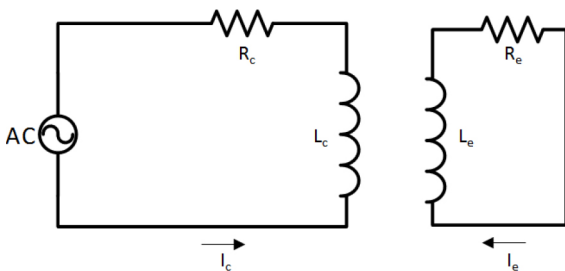


Figure 7. Operating principle of an eddy current sensor. The left parts describes the basic circuit of the sensor with the inductance L_c inducing a magnetic field in a metal target. The right circuit describes the equivalent circuit of the metal target.

The overall impedance of the coil can be described as [12]:

$$Z_{\text{eff}} = R_c + R_e + i \cdot \omega \cdot (L_c - L_e) \quad (3)$$

With the index c denoting the inherent resistance and inductance of the coil which is excited with an AC current of frequency ω . R_e and L_e are the resistance and inductance in the equivalent circuit

describing the metal target. The two last parameters are dependent on multiple factors as distance to target and target characteristics as permeability and resistivity.

Analog to the reluctance resolver it is possible to enable this technology for measurement of angles by making use of a special shaped target. By doubling the coils and the associated impedance measurement a sine and cosine signal are generated allowing the arctangent calculation afterwards.

Magnetic Sensors

Magnetic Sensors include a multitude of technologies and concepts for RPS application.

Hall Sensors

Hall sensors are the oldest ones and widely applied in small brushless DC motors in automotive applications. They are based on the Lorentz force occurring on charge-carrier transport.

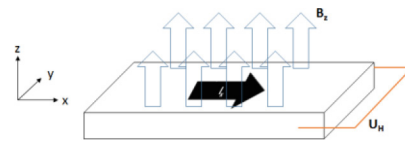


Figure 8. Operating principle of a Hall sensor plate. A magnetic field B in z -direction generates a Hall-voltage U_H in y -direction, when an electric current I is applied in x -direction [13].

From the Lorentz force it can be deduced that, considering a current in x -direction and a magnetic field in z -direction, a Hall voltage is generated:

$$U_{\text{Hall}} \sim B_z \cdot I_x \quad (4)$$

By mounting a permanent magnet on a rotating shaft and placing a Hall Sensor opposite of it. The component of the magnetic field, parallel to the magnet is rotating with the shaft and generating a Hall-voltage in the sensor. As the induced voltage is dependent only on the perpendicular component of the magnetic field a sine-dependency on the angle of rotation is provided.

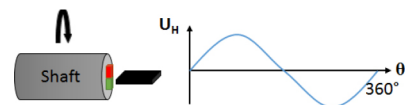


Figure 9. Operating principle of a Hall sensor in an End-of-Shaft application. The magnet at the end of the shaft provides a magnetic field which is rotating around the shaft-axis generating a sine-like induced Hall-voltage U_H in the sensor.

To improve the angle measurement and generate a unique result it is necessary to use two Hall plates separated by 90° , as it is implemented in some so-called 3D Hall sensors. Thereby again two signals are generated, shifted by 90° - a sine and a cosine signal which enable an arctangent calculation to derive an absolute mechanic angle. It is important to stress that Hall-based sensors are