Abstract

Many synchronous electric motors require a very accurate position sensor compatible with a sinusoidal control. The purpose of such a control is to enable an efficient and smooth operation enhancing the comfort by limiting vibrations. In some cases related to mechanical constraints, we have to deal with through-shaft design. One can quote for examples power drives for Electric or Hybrid Electric Vehicles as well as for Electric Power Steering motor. More generally, these sensors need to keep a simple and robust design and a restricted number of parts as they are submitted to high vibration levels, a wide temperature range and speeds of several krpm.

In order to meet such requirements, MMT has developed a magnetic sensor principle offering a competitive alternative to the conventional inductive resolver type sensors. The basics of this solution is a through shaft angular position sensor using one or two Hall-effect probes. These Hall IC measure the angle of the magnetic field generated by a ring or a disc magnet. The magnetic field angle is shaped in order to meet very demanding accuracy requirements (+/−1° of electric error). The use of two probes allows enhancing even more the accuracy and provides as well the design with an intrinsic robustness against external magnetic perturbations coming from the motor coils.

The paper deals with this sensor principle showing that the challenge to meet less than +/−1° of electric error on rotary position sensors with motor mechanical shaft diameters up to 100 mm was taken up.

I. Multipolar through Shaft Standard Sensor

I.1. Overall Principle

Some through shaft standard rotary position sensors rely on a sensitive device placed on an outer diameter of a multipolar magnet ring and able to measure at least two components of the magnetic field at a single point providing an absolute position inside each pole pair (Figure 1).

Introduction

The need for sensor accuracy of less than +/−1° electric to control electric machines required from us to develop new sensor topology as an alternative to inductive resolver type sensor [1;2]. The key point was to keep the sensor architecture as simple as possible to be compatible with mass production process required in automotive field. Thus the rotary sensor is made of one magnet and two Hall IC. Starting with an analysis of the standard sensor topology using Hall-effect principle based on traditional magnetization, we will illustrate, in the first part of the paper, the reason why a new sensor topology was considered. The key features of this patented sensor architecture called MM126 [3] are the use of a specific magnetization and the use of 2 Hall probes, 90° electric shifted (i.e. the second probe is at a quarter period of the first probe). After explaining the theory of these features, the sensor robustness versus mechanical defaults, effects of the rotor speed and temperature thanks to prototype results will be illustrated.

Figure 1. Through shaft rotary position sensor principle
In such sensors, the output signals can be either an analog sine/cosine voltage or directly an angle (Analog, PWM,...) coming from a CORDIC algorithm (COordinate Rotation Digtal Computer) or a Look-Up-Table to solve the arctangent calculation of the sine/cosine signals ratio.

I.2. Case of a Small Pole Pitch Magnet with Radial Magnetization

![Figure 2. Magnetic field components over 72° of a 5 pole pair through shaft position sensor with radial magnetization.](image)

![Figure 3a. Non-linearity of the sensor without gain factor](image)

![Figure 3b. Non-linearity of the sensor with gain factor](image)

For small pole pitches a ring magnet magnetized with a classical radial magnetization has both magnetic components measured by the sensitive device close to perfect sine and cosine profiles. Unfortunately the amplitude of both components is slightly different as shown in Figure 2 what could lead to an inaccurate sensor illustrated by a non-linear variation of the magnetic angle over the mechanical stroke as shown on Figure 3. It is well known that using a gain factor already implemented inside the Hall IC before making the angle calculation can lead to a significant improvement as demonstrated in Figure 3a and Figure 3b. Figure 2 provides the example of the two magnetic field components for a small ring magnet with a shaft diameter of 16 mm. Figure 3a and 3b show the theoretical field rotation and sensor non-linearity without gain factor showing the benefit by decreasing the electric error from +/-8° electric (Figure 3a) down to less than +/-0.1° electric (Figure 3b).

![Figure 4. Prototype of the BLDC motor with its integrated analog position sensor and non-linearity measurement of the sensor with gain factor](image)

Of course in real life, the magnet inhomogeneity, the mechanical defaults during the magnetization as well as the magnetization harmonics can lower the performances. On Figure 4, one can see the electric error measured on a 5 pole pair sensor in a through shaft configuration showing a maximum error of +/-2.4° electric to be compared to the theoretical +/-0.1°.
I.2. Case of Large Pole Pitch Magnet with Radial Magnetization

When the shaft diameter is getting higher with a low number of pole pair as you can find it in the machines used for the targeted automotive applications, the harmonic content of both magnetic components generated by the magnet and seen by the sensitive device is getting more and more important. In Figure 5 the phenomenon is illustrated on a 6 pole pair radially magnetized magnet where we can easily recognize strong H3 harmonic magnetic components.

Figure 5. 6 pole pair radially magnetized magnet (inner diameter 100 mm) - magnetic field components over 60°

Such non-sinusoidal magnetic component profiles lead to a non-linear magnetic angle variation over 60° and consequently a non-linear position sensor even with an appropriate gain factor as illustrated in Figure 6. Such a theoretical electric error of +/-0.55° cannot be acceptable for a smooth and efficient motor control.

Figure 6. Non-linear magnetic angle variation and non-linearity of the rotary sensor using a radially magnetization

II. Multipolar through Shaft Sensor Solution for Demanding Accuracy Requirement

Knowing the requirement of accuracy in the field of position sensor dedicated to motor control which is typically below +/-1° electric, MMT developed a specific sensor design using both a specific magnetization pattern and a two-probe principle.

II.1. Sinusoidal Magnetization

In order to reduce the harmonic content of the signal seen by the probe, the magnet is magnetized with a continuously variable magnetization direction as illustrated below. The main benefit is to get a very linear magnetic angle variation even for large pole pitch. Of course in the scope of industrial applications this magnetization process is compatible with mass production requiring the use of standard ring magnet and reliable magnetizing fixture.

Figure 7. Example of sinusoidal magnetization pattern for a 5 pole pair magnet

Figure 8. Electric error for conventional and sinusoidal magnetizations for a 3 pole pair configuration

Figure 9. Measured non-linearity over 360° on a 6 pole pair rotary position sensor with a specific magnetization.

In order to illustrate the benefit of such a magnetization, the case of a 3 pole pair configuration and the related calculated electrical error according to the magnetization type were considered. We can clearly see in Figure 8 that the sinusoidal magnetization gives us the best chances to reach our accuracy target and to absorb defaults coming from real life. Indeed whatever the diameter the sinusoidal magnetization allows reaching magnetic components as pure as possible leading to a theoretical 0° electrical error.
Indeed as already illustrated the real life can be very different especially due to the inherent residual magnetization harmonics effects. Then applied on the previous 6 pole pair configuration, this sinusoidal magnetization gives us a maximum +/−1.1° electric measured on a prototype (Figure 9) but still not enough for the motor control purpose.

II.2. Two-Probe Principle

As seen before, there is still a gap to fill in if we want a competitive rotary sensor for motor control.

In that scope, MMT has developed a solution based on a signal combination of the normal and tangential magnetic components of two Hall ICs placed at n.90° electric (Figure 10) as already described in [3, 4].

Based on the previous results one can write the magnetic components for both probes (1) and (2):

\[
\begin{align*}
B_{n1} &= h_1 \cos(\theta) + h_2 \cos(3\theta) \\
B_{t1} &= h_1' \sin(\theta) + h_2' \sin(3\theta)
\end{align*}
\]  
\tag{1}

\[
\begin{align*}
B_{n2} &= -h_1 \sin(\theta) + h_2 \sin(3\theta) \\
B_{t2} &= h_1' \cos(\theta) - h_2' \cos(3\theta)
\end{align*}
\]  
\tag{2}

Using this configuration and a simple algebraic signal combination (3) which can be done by the motor microcontroller or an integrated microcontroller:

\[
\begin{align*}
B_n &= B_{n1} + B_{n2} \\
B_t &= B_{t1} - B_{t2}
\end{align*}
\]  
\tag{3}

it is then possible to get proper sine and cosine signals (Figure 11) having same amplitude and low harmonic content that enable to deduce (after processing via CORDIC algorithm or look-up-table) the position with a non-linearity below +/− 1° electric. In Figure 12 the benefit on the sensor non linearity is obvious after comparing the same period before (dotted curve) and after combination.

Another feature of this solution is to drastically reduce effects of a homogeneous external magnetic stray field, which can be very interesting in the case where the sensor is closely coupled to an electric motor in order to reduce the effect of the field generated by coils. Indeed if we come back to equations (1) and (2) when an external homogeneous magnetic field is applied (Figure 13), and still by considering the cross-combination (3) influences from both harmonics content and stray field can be lowered:

Figure 10. Principle of higher accuracy through shaft sensor applied to a 1 pole pair magnet with a second Hall probe located at 90° mechanic (=90° electric) from the first one.

Figure 11. Measured output signals after components combination (3) on a 6 pole pair configuration with a specific magnetization.

Figure 12. Measured non-linearity over a period on a 6 pole pair rotary position sensor with the 2-probe principle and without (dotted curve).

Figure 13. 2-probe principle configuration with external homogeneous magnetic stray field.
Of course the stray field is seldom homogeneous all the more it comes from the coils of an electric motor. Therefore according to the motor topology there are specific positions to locate the sensor. The target is to tend to an “as homogenous as possible” stray field seen by both probes or where the stray field is the lowest.

### III. Sensor Principle Robustness

In this part the sensor robustness is illustrated when submitted to different operating conditions such as rotating speed influence as well as mechanical tolerances on probe positioning. This part is as well the opportunity to demonstrate how versatile the sensor technology is via several configurations with various shaft diameters and number of pole pair.

#### III.1. Sensor Accuracy over Speed

All the measurements shown before were done at 120 rpm but an important point for a position sensor aimed at controlling a motor is to check the behavior according to the motor speed.

Here a 5 pole pair configuration designed to control a synchronous electric machine with a shaft diameter of 60 mm is considered. The rotor is made of an isotropic hard ferrite magnet. The sensor nominal accuracy was measured at +/-0.3° electric at 120 rpm. We can see in Figure 14 the sensor components as well as the output magnetic angle over 360° with its 5 periods. The sensor output can be a ratiometric voltage (direct Hall IC outputs) which can feed the microcontroller of the BLDC or for example a PWM output in case the Arctangent calculation is directly integrated on the sensor PCB via a dedicated microcontroller.

Then measurements up to 10 krpm were carried out and as we can see the sensor accuracy is not affected by the rotating speed. One as to underline the sensor accuracy shown in Figure 15 is the relative sensor accuracy. Indeed there is of course a time delay which is intrinsic to the Hall IC and which increases with the rotating speed. This time delay is proportional to the speed and can be easily compensated in the microcontroller.

#### III.2. Sensor Accuracy with Mechanical Defaults

The main points regarding the mechanical tolerances are the influence of a default on the electrical perpendicularity between both probes and influence of a tolerance on the radial position of the sensitive part of the sensor.

##### III.2.1. Default of Perpendicularity between both Probes

Here a 1 pole pair configuration with a shaft diameter of 50 mm is considered. As explained in paragraph II.2, both probes have to be located at 90° electric which means 90° mechanical for this 1 pole pair configuration. This sensor is able to provide an absolute position over 360°. The rotor is made of an isotropic injection-moulded NdFeB magnet. The sensor nominal accuracy was measured at +/-0.3° electric and based on standard positioning tolerances of pick and place machines we can see in Figure 16 the technology is robust against such a mechanical default.
The configuration is the 1 pole pair one like in the previous paragraph. A standard default we often have to face during the manufacturing or during the sensor lifetime is the radial tolerance between the rotor and the static part positions. Here a +/-0.25 mm and +/-0.5 mm radial shift and their influences on the sensor accuracy were considered. With +/-0.25 mm the sensor accuracy reaches +/-0.45° starting from +/-0.3° when centered. As shown in Figure 17, even if the sensor accuracy reaches +/-0.7° with 0.5 mm radial shift, the sensor technology is robust against such a default.

### III.3. Sensor Accuracy versus Temperature

The robustness of the sensor technology over the typical wide temperature range of the automotive industry has to be demonstrated. For this test another configuration is presented which is still a 1 pole pair one but designed to equip a 100 mm diameter shaft [4]. The magnet used was a ring magnet made of bonded NdFeB (40 g). From −40°C up to +150°C a less than +/-1° electric sensor non linearity is reached even for such a large diameter.

![Figure 18. Effect on the sensor accuracy of the temperature on a 1 pole pair configuration for a 100 mm shaft diameter.](image)

### Summary/Conclusions

In this paper a new rotary position sensor technology for motor control was presented. It is based on the use of the last generation of Hall-effect probes measuring the flux density in 2 or 3 axes to get access to the magnetic angle versus the mechanical position. A first benefit of a magnetic angle measurement is a reduced sensitivity to temperature. In order to achieve the +/-1° electric, MMT developed a specific magnetization pattern combined with the use of 2 measuring points. This new approach was clearly driven by the search of a better performance-to-cost ratio versus the inductive type sensor for a better fit to automotive industry requirements. Therefore the structure is simple with only one magnet and two probes. As illustrated throughout this paper with various examples, the technology is scalable from few millimeters outer diameters to large ones such as 100 mm and from 1 pole pair to several pole pair.
The angle calculation can be done directly on the microcontroller dedicated to the synchronous machine or in an integrated microcontroller on the sensor PCB. Moreover the sensor components are standard and can be sourced worldwide for a better flexibility for mass production. The specific magnetization is already in mass production in automotive transmission applications with sensors using only one probe. Compared to the existing solution, the arc-shaped of the sensitive part ensures a better serviceability for the assembly on the production line and for after-sales service. Finally another benefit of the presented technology is related to the low current consumption which is typically of less than 10 mA for each probe.

References
3. “Angular or linear magnetic position sensor not sensitive to external fields”, US 20120161755.

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Definitions/Abbreviations
BLDC - Brushless DC motor
CORDIC - Coordinate Rotation Digital Computer
Hall IC - Hall Integrated Circuit
PCB - Printed Circuit Board
PWM - Pulse width modulation
Rpm - Revolution per minute