

High speed permanent magnet synchronous motor with a shaft sensor

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Abstract

For the vector control of a Permanent Magnet Synchronous Machine (PMSM), an actual position information of the rotor and its speed has to be known, as well as the current in two phases. This work deals with a development of high speed PMSM with a shaft sensor. Design of the motor as well as the principle of the sensor are introduced. A real motor is tested using a vector control implemented on the Field Programmable Gate Array (FPGA) and a functionality of the sensor is verified. Finally, design of the high speed PMSM prototype is evaluated and based on the achieved results, suggested design improvements are proposed.

Key words: Field programmable gate arrays, hall effect devices; machine vector control; permanent magnet motors

1. Introduction

In the last three decades, PMSMs took their market share of electrical rotating machines. Their main advantage is good performance in relation to their compact size, high efficiency, large torque to inertia ratio and high power density. For these reasons, they are mainly used in high performance industrial applications.

One of the new emerging trends is a usage of high speed PMSM. This type of PMSM offers even a better performance of power density to weight ratio. A good comparison between other types of electrical rotating machines and high speed PMSM can be found in [1]. For example, PMSM with nominal speed of 240 000 revolutions per minute and weight of 1,4 kg can offer a power of 3 kW. The main usage of these high speed PMSM is in turbo-compressor applications [2], a combined heat power sources applications [3], as a micro-milling spindle [4] and so on.

However, there are also drawbacks in using PMSMs. Aside the growing cost of permanent magnets on the market, there are other aspects that requires an attention of potential user.

The most important issue is related with the control of a PMSM. To be able to successfully operate a PMSM using a vector control, an actual position information of the rotor and its speed has to be known, as well as the currents in 2 phases. Measuring currents require current probes, that are usually already a part of the frequency inverter. But to measure a rotor position, an implementation of position encoder in the PMSM design is required. Such an implementation increases the demand for the space, maintenance, temperature stability and also robustness of the system to possible vibrations.

For these reasons, a lot of effort was dedicated to development of a sensorless control of PMSMs. There are a lot of papers dealing with a control at an operational speed, at a low speed and at a standstill, but not many techniques are developed for the high speed applications.

Furthermore, a regular position encoders have their limits given by the maximum readable speed of the motor. This speed is around 60 000 to 100 000 revolutions per minute, while giving a 12-bit resolution of a position. Higher rotations are possible at the cost of a lower resolution.

This paper deals with a design of a high speed PMSM with a shaft sensor, that should correctly read a rotor position up to 200 000 revolutions per minute. In the future, a proposed design will be used for the evaluation of sensorless control algorithms.

2. Design of the motor

This part of the paper introduces a mathematical model of a PMSM to help to understand the necessity of the information about a rotor position. Furthermore, this section explains a principle of the position encoder and contains a proposed high speed PMSM design.

2.1. Mathematical model of PMSM

The model of PMSM is derived in direct and quadrature (dq) axes, which is a coordinate system associated with the rotor. In such a concept, both the controllable currents can be dealt as a DC. Two of the main equations follow [5]:

$$v_{qs}^r = (R_s + L_q p)i_{qs}^r + \omega_r L_d i_{ds}^r + \omega_r \lambda_{af} \quad (1)$$

$$v_{ds}^r = (R_s + L_d p)i_{ds}^r - \omega_r L_q i_{qs}^r \quad (2)$$

where v_{qs}^r and v_{ds}^r are stator voltages in the rotor reference, R_s is a stator resistance, L_d and L_q are stator inductances in the rotor reference, respectively; i_{qs}^r and i_{ds}^r are currents in the rotor reference, ω_r is a rotor mechanical speed, λ_{af} is an armature flux linkage from the permanent magnet and p is a Laplace operator.

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Because these currents are not measurable in the rotor reference frames, but in the stator reference frames, they have to be calculated using a Park transformation:

$$\begin{bmatrix} i_{qs}^r \\ i_{ds}^r \\ i_0 \end{bmatrix} = \frac{2}{3} T_{abc} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \quad (3)$$

$$T_{abc} = \begin{bmatrix} \cos \theta_r & \cos \left(\theta_r - \frac{2\pi}{3} \right) & \cos \left(\theta_r + \frac{2\pi}{3} \right) \\ \sin \theta_r & \sin \left(\theta_r - \frac{2\pi}{3} \right) & \sin \left(\theta_r + \frac{2\pi}{3} \right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (4)$$

where i_0 is a zero sequence component representing imbalances in the a, b and c phase currents, T_{abc} is a transformation matrix, i_a , i_b and i_c are measurable currents in the stator reference frame and θ_r is the angle representing actual rotor position in relation to the stator reference frame.

In (1) and (2) stator resistances, rotor inductances and armature flux linkage are given by the motor design. Therefore, the only unknown parameters are actual stator currents in two phases (i.e., i_a and i_b), actual rotor position θ_r and actual motor speed ω_r . These values have to be known for the vector control operation. More information about modeling of PMSM can be found in [5].

2.2. Design of PMSM

A part sectional view of the proposed design of high speed PMSM is shown in Fig. 1. Further on, the design will be described using a half sectional view located in Fig. 2.

The stator core is symbolized by the light gray color. There are also two covers, both of them depicted with dark gray, which are used to enclose the stator core. Both the stator core and covers are made from aluminum. Full length of the motor is 90 mm and its outer diameter is 93 mm.

A rotor made from titanium (light blue) is located in the middle, supported by two ball bearings (red). Balls in the ball bearings are made from a ceramic material, so that a magnetic field of the motor doesn't influence their functionality. A titanium rotor is necessary to overcome high centrifugal force during the high speed mode of operation. A section of the coil pair is colored by orange color.

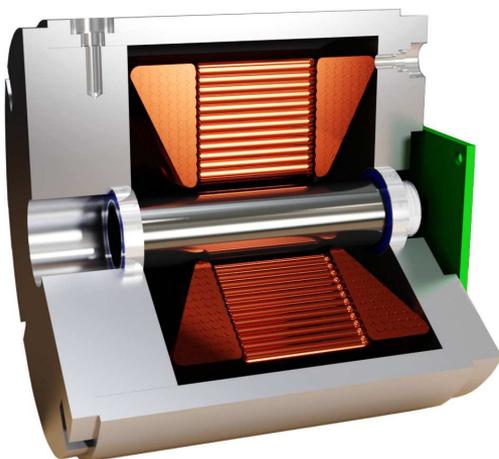


Fig. 1. 120° sectional view of the PMSM.

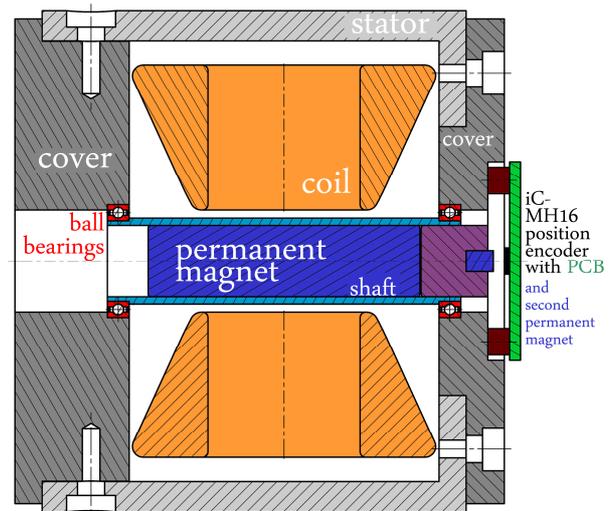


Fig. 2. Half sectional view of the PMSM.

There are two neodymium magnets (dark blue). First, the main magnet, is located in the center of the image and is glued inside the titanium rotor. The magnet is diametrically magnetized allowing it to create a torque when the coils are powered by sinusoidal currents.

The second magnet is glued inside the aluminum shaft (purple), which is also glued inside the titanium rotor. The purpose of this magnet is to provide a reference rotating magnetic field for the position encoder. Its magnetization is same as the magnetization of the main magnet.

The position encoder (black rectangle) is in front of the second magnet, soldered on the PCB (green). Component name is the iC-MH16 from the iC-Haus company. It is centered by four spacers so that the middle of the magnet is in line with the center of the position encoder.

A principle of the position encoder, also called angular hall encoder, is based on the hall effect and will be described using Fig. 3. Here, diametrically magnetized magnet is on the left side of the picture. The position encoder is on the right side and it contains two pairs of symbolically depicted squares with different colors. These squares are representing hall sensors. Each pair reacts to the rotating magnetic field, creating an own sinusoidal signal. Because the maximum strength of the magnetic field is heading in only one direction, signals are shifted to each other by 90 degrees. Therefore, combining those two signals, a rotating space vector can be created. This space vector has the same direction as the magnet and so the rotor.

Moreover, the position encoder is generating two incremental signals, namely A and B, and one zero position signal Z. By proper settings, it is possible to read up to 12-bits position information, that is a resolution of approx. 0,087 degrees. A completed PMSM is shown in Fig. 4.

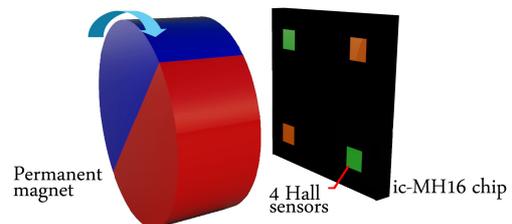


Fig. 3. Principle of the position encoder.

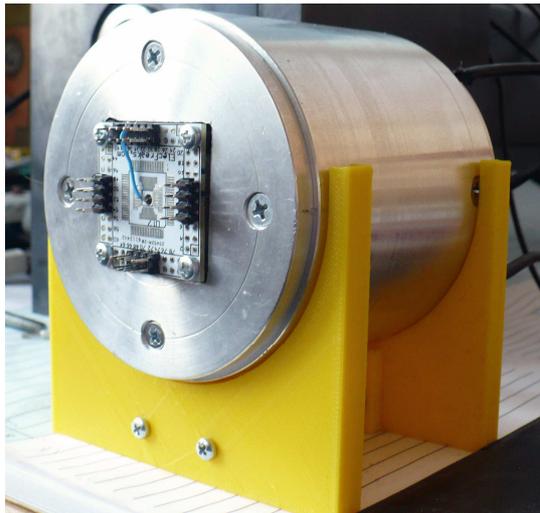


Fig. 4. Experimental high speed PMSM with a shaft sensor. Visible connector pins are for connection to the readout circuit board.

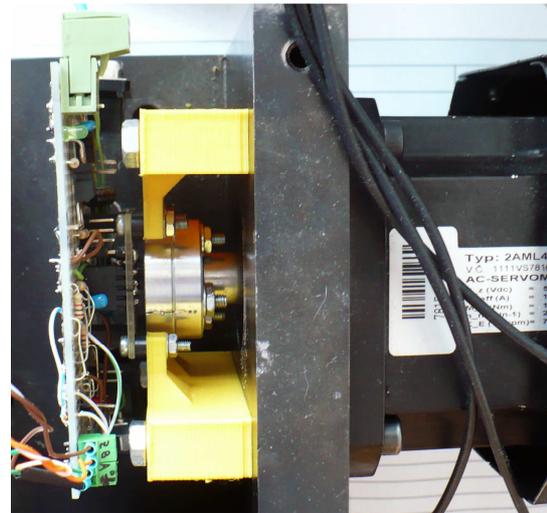


Fig. 5. High speed PMSM VUES Brno with the adapted shaft and the angular hall encoder.

3. Experiments

All tests were performed using a National Instruments PXIe-1071. To be able to control speed of the PMSM, vector control was implemented on FPGA NI7854R. The control algorithm contained inner loop for the current control and outer loop for the speed control. Whole control algorithm was timed to execute every 3,250 μ s. Signals from the control loop were used to modulate currents with 15kHz PWM.

To be able to evaluate a correctness of the position information, a second position encoder was mounted to the PMSM manufactured by VUES Brno. This motor was originally equipped with a regular position resolver 1.5" RE 3620.10.15 Micronor and a 12-bits tracking resolver-to-digital converter AD2S1200. Therefore, two position information were available from the same motor. The shaft of the motor was equipped with an aluminum part containing a neodymium magnet as a source of the rotary magnetic field (see Fig. 5).

A sampling time was set as 50kHz, which seemed to be adequate for the chosen speed that was set as 100 rotations per second. The read out position information from both sensors is in Fig. 6. After setting the same zero position for both encoders, it is clearly visible, that outputs from both of them are almost identical.

The next test was conducted to evaluate an encoder response under a varying speed. Therefore, the speed was set as to change from 37 rotations per second to 93 rotations per second. The recorded data are visible in Fig. 7. Because the mechanical time constant of the motor is around 1,3 seconds, the response to a speed change command is relatively fast. The saw-tooth pattern is caused by the fact, that the speed is calculated after every full revolution. It is visible, that both sensors have a slightly different dynamic response to a speed change. This can be caused by slightly different zero position of both encoders, and therefore one encoder has finished calculating the speed earlier than the other one. An improvement for this measurement will be mentioned in the last section.

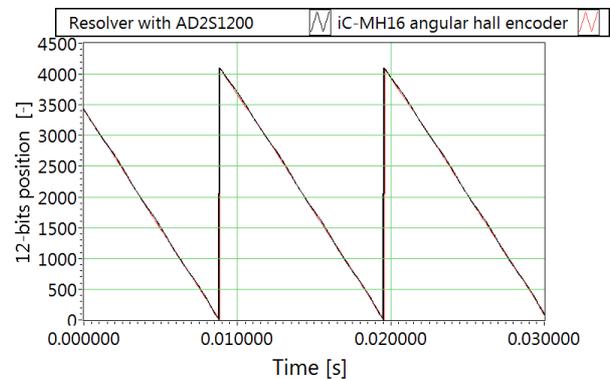


Fig. 6. 12-bits position information from two encoders.

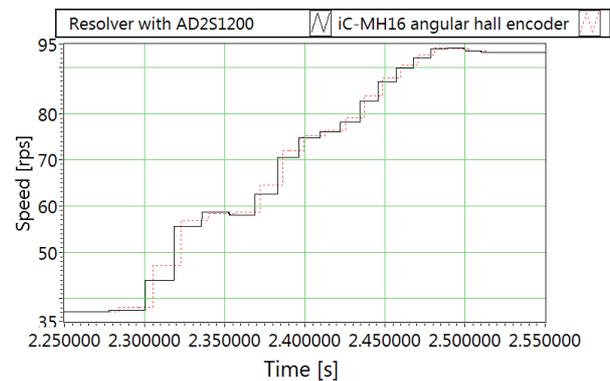


Fig. 7. Response of two position encoders under a speed change.

Following these initial tests, a final evaluation was conducted on the experimental high speed PMSM. After a sensor calibration for the rotary magnetic field of high speed PMSM, the target speed was set as 230 rotations per second. Data of a position change are available in Fig. 8. It is clearly visible, that the angular hall encoder has no problems with reading a position of the rotor. Since the speed is calculated from the position, it has a similar progress as in Fig. 7 for a varying speed, and therefore showing a figure is not necessary.

Based on these results, a design of the high speed PMSM with a shaft sensor seemed to be valid.

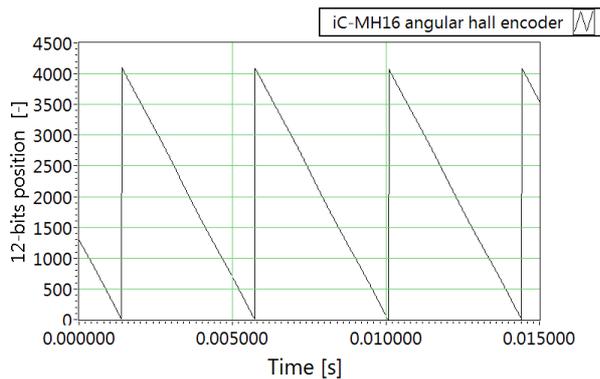


Fig. 8. 12-bits position information from the high speed PMSM.

4. Conclusions

Proposed design of the high speed PMSM with a shaft sensor was introduced. Its main parts were described and a principle of the angular hall encoder was explained. The correctness of reading a position information was evaluated with a second position encoder and the VUES Brno motor. Dynamical capabilities of the encoder were tested as well. Following these initial tests, a final evaluation was conducted on the experimental high speed PMSM. Based on the results, a design of the high speed PMSM with a shaft sensor seemed to be valid.

Calculating a speed only after every full revolution in a connection with a fast control loop doesn't have a good influence on a motor dynamic. In the future, some other technique to measure the speed of PMSM will be used, e.g. a moving window average. Such a change should improve a response of the control algorithm.

Gluing a magnet inside a rotor is a problematic procedure. Because the magnet doesn't have an exactly same outer diameter as the hole in the rotor, centering magnet is not ideal. This leads to unbalanced shaft and deterioration of dynamic properties of the motor. Therefore, some improvements have to be considered for the future designs.

After some improvements, using a second magnet may not be necessary. The magnetic field of the main magnet is strong enough to give a good position result, if the angular hall encoder is incorporated with the motor design. However, a possibility of disturbance by magnetic field of the powered coils have to be considered. Also, manufacturer's instructions mentioning an ideal size of the magnet as from 3 mm to 6 mm. Different size could possibly have an influence on the maximum readable speed, that is 200 000 rotations per minute.

After improving control capabilities of the vector control algorithm, the motor will be tested for the maximum achievable speed. This will also test the capabilities of the angular hall encoder. Furthermore, experimental high speed PMSM will be used for the sensorless control strategies, which are currently under development.

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Nomenclature

i_0	zero sequence current (A)
i_{as}	stator current in phase a, stator reference (A)
i_{bs}	stator current in phase b, stator reference (A)
i_{cs}	stator current in phase c, stator reference (A)
i_{ds}^r	stator current in d-axis, rotor reference (A)
i_{qs}^r	stator current in q-axis, rotor reference (A)
L_d	stator inductance in d-axis, rotor reference (H)
L_q	stator inductance in q-axis, rotor reference (H)
p	Laplace operator
T_{abc}	Park transformation matrix
v_{ds}^r	stator voltage in d-axis, rotor reference (V)
v_{qs}^r	stator voltage in q-axis, rotor reference (V)
θ_r	actual rotor position (rad)
λ_{af}	armature flux linkage from permanent magnet (V·s)
ω_r	angular velocity (rad·s ⁻¹)

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