Comparative study of different rotary position sensors for electrical machines used in an hybrid electric vehicle application

Christer Ebbesson*
Department of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University, Lund, Sweden
christer.ebbesson@gmail.com

August 31, 2011

Abstract

A key parameter to perform an accurate and efficient control of an electric machine is the position sensor. The sensor measures the angular position of the rotor shaft and there are several ways and techniques to do this.

This thesis aims to compare different position sensors with main focus on the resolver and Hall-effect sensor and other "new" sensor techniques. Various enhancement methods to improve the position information and prediction are also evaluated.

The results shows on best performance considering the torque quality when using the resolver as position sensor. The Hall-effect sensor can be improved with a observer, but the observer is not suitable for this type of application. The Hall-effect sensor has also a speed depended torque ripple that leads to harmonics at frequencies that relates to the speed of the unit which may causes problems. There are several "new" sensor techniques based on the theory of eddy-current that may be of interest since they are said to be more optimized for Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) applications.

1 Introduction

BorgWarner Inc. is a world leading company in powertrain solutions, i.e. engine, transmission, drive shafts, differentials, four-wheel-drive systems etc. At BorgWarner TorqTransfer Systems AB (former Haldex Traction Systems AB) facilities in Landskrona, Sweden, development of a prototype called electric All-Wheel Drive (eAWD) is in progress. The eAWD project is an electric drive system to be used in HV and HEV applications. Shortly, the current system consist of two PMSMs, one PMSM at 85 kW that is used for propulsion and one PMSM at 10 kW that is used for Torque Vectoring (TV)[1]. Another electrical machine that also is a part of the concept is the Integrated Starter-Generator (ISG) that is connected to the Internal Combustion Engine (ICE) and which can both charge the battery and supply power to the two electrical motors. A position

*Many thanks to Jonas Ottosson (BorgWarner), Gustaf Lagunoff (BorgWarner), Francisco Márquez (IEA)

[1] Torque vectoring is a new technology that provides the option to vary the amount of power sent to each wheel.

sensor is needed for each machine in order to control it accurately and with high dynamics.

This work aims to compare and evaluate different rotary position sensors that can be used to control a PMSM. Several simulations and tests are performed on a PMSM with different sensors implemented. Different hardware and software enhancement techniques are also included. The effect on the torque quality, for each sensor, is studied. Furthermore, other sensor techniques that may suit the eAWD project will also be investigated.

2 Sensors

Based on theory and information about those sensors that are implemented in the PMSM, models of those are built in Matlab®/Simulink®. Implemented position sensors are a Variable Reluctance (VR) resolver and three discrete digital Hall-effect sensors. An observer to improve the position from the Hall-effect sensors is also implemeted.

A variant of the resolver is the VR resolver. The excitation windings are placed in the stator instead of in the rotor and a sinusoidal shape disc is placed in the rotor. Due to Maxwell's equations, a magnetic flux always forms a closed loop where the reluctance[2] is lowest. So when the disc rotates, and the air gap between the disc and the stator output windings varies and thus varies the path where the reluctance is lowest. This makes the output signals varies in a sinusoidal way.

The Hall-effect was discovered in year 1879 by Edwin Hall and explains what is happening when a magnetic field is applied orthogonally to a metal plate. If a constant current flows through a piece of metal, the perpendicular voltage over the same metal will change with the variation in strength of the applied magnetic field [2, p. 1-2].

[2]Magnetic reluctance is analog to electric resistance

An observer is a powerful method to use for prediction of the position between two well known position states. There are 30° between the states and to estimate the position between these an observer can be used. Let

$$\theta_{obs} = \theta_{meas} + \omega_{meas} \cdot \Delta t \quad (1)$$

be the predicted position from the observer where θ_{meas} and $\omega_{measured}$ are the position and the speed information, respectively. In other words, the observer estimates the position between two stages based on the previous stage. This might seems like a good solution but its assumes that the speed is the same or almost the same during next state, i.e. no acceleration or retardation.

3 Results

The PMSM gives more torque ripple when running with the Hall-effect sensors, compared to the case when having the observer enabled or simulating with the resolver, as shown in figure 1

When the PMSM is running with the Hall-effect sensors, the mean torque response are lower than with observer enabled and for the resolver. Figure 2 shows the torque ripple for the same test case. Here are the ripple highest for the Hall-effect sensor, lower with the observer enabled and lowest when running with the resolver.

The torque ripple consist of some harmonics which is shown in figure 3. All sensors causes harmonics at multiples of the switching frequency, but the Hall-effect sensor has also a lot low frequency harmonics. Due to the low sampling rate at 100 Hz, this can not be seen in the measurement results.

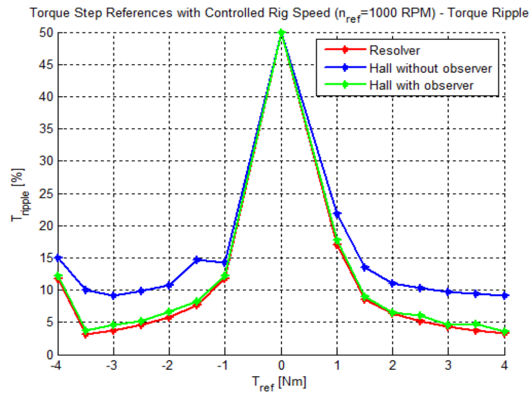

Figure 1: Torque ripple response simulation result.

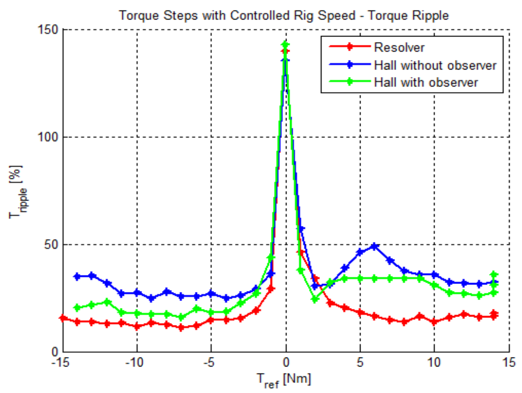

Figure 2: Torque ripple response test result.

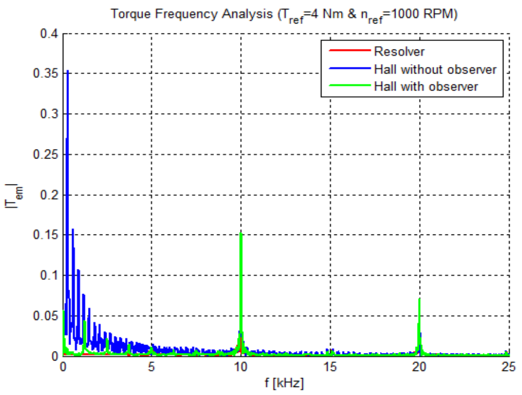

Figure 3: Simulation torque ripple frequency analyse.

4 Conclusions

The results shows consistently that the PMSM gives less mean torque and more torque ripple when running with the Hall-effect sensor. With the same torque reference and with the observer activated the results are a bit better in some cases but around zero speed when changing sign of the direction fast, the performance is really bad due to poor position prediction in that case. The reason for this is be the actual implementation of the observer and that it needs a more advanced or improved implementation. The TV application function is based on the fast changing sign of rotation direction and thus the observer may not be a good choice. The resolver showed the best results with lowest torque ripple, even if a lot of noise was measured on both excitation and position signals.

When the machine is running with the Hall-effects sensor at low speed, the machine is in between two Hall-states during a long time and thus the error in position is large during this time. This leads to larger drops in torque than when it is running faster. In other words, this results in a speed dependent torque ripple which frequency varies along with the speed. This behaviour can trigger resonances in the mechanical constructions that may cause vibrations and noise in the application.

In EV and HEV applications, Electromagnetic Interference (EMI) is a huge problem that needs to be taken into consideration in every design and construction step and when choosing components such as position sensors. Different parts of the system and construction, signals cables and all other equipment needs to be well connected and tightened to ground, but in car implementations are only a ±12V reference available. The absence of a stable ground that differs a lot in potential across the chassis of the car are not good. This will influence on the operation of the position sensor due to the relatively long distance between the sensor placement in the PMSM and the power electronic. A recommendation, to avoid or decrease the influence of this problem, is to have a good physical connection between the PMSM and the power electronics box, shielded cables and connectors and as short cables as possible. Good filtering and decoupling on both supply and signal lines are also preferred.

The Hall-effect sensors low-pass filters contributes to phase delays in the position signals that increases the torque ripple and since the electrical interface consist of three signals, each with a low-pass filter, the filter parameters may not be identical in all three filters. This may give a bad non-linear behaviour in the final position value and in turn, complicates the observer functionality since the prediction is done by the average speed between the previous two states.

I had high expectations of the encoder but due to lack of time and bad designed mountings, it could not be tested. Anyway, this type of encoder could not suit the next prototype of the eAWD project since the new design makes it impossible to access and mount the encoder in line with the rotor axle.

5 Future development

Alternative position sensors that could contribute to a lot of advantages to EV and HEV applications is the eddy-current based sensors. Sumida Components and Modules has design a inductive Rotor-Position Sensor (RPS), which they state is specially designed to work in hybrid electric vehicle applications. This sensor is based on the theory of eddy-current[3] losses. The eddy-current theory is well-known, but the application to use it to measure an angular position is a new area of use. Sumida's proposed design is shown in figure 4).

The sensing unit consist of an arrangement of planar coils which can contact less sense a rotating target. The target trace is shaped in a sinusoidal way and is made of a conductive material such as copper or aluminium and can be mounted in either metallic or plastic material [3, p. 5] [1]. The planar coils expose the target for a high frequency field and eddy-current is induced in the target. The eddy-current cause a opposite field which reduces the inductance in the coils. The coils are a part of a resonance circuit which changes frequency and phase as the inductance varies. This behaviour can be related to the angular position [3, p. 5].

Figure 4: Sumida Eddy current sensor [3, p. 3, 10].

[3]Also know as Foucault currents named after the French physicist Léon Foucault (1819 - 1868).

References

[1] Christian Ascher. Inductive rotor-position sensor for synchronous motors. *Electric and hybrid vehicle technology international*, page 189, July 2011.

[2] Edward Ramsden. *Hall-Effect Sensors: Theory and Application*. Newnes, second edition, 2006.

[3] SUMIDA. *Technical Information: Rotor Position Sensor*. SUMIDA Components and Modules GmbH, rev. 04 edition, 2010.