Sensorless Position Control of a PMSM for Steer-by-Wire Applications

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ABSTRACT This article shall present the design and implementation of a MATLAB/Simulink model for the sensorless control of a PMSM in a steer-by-wire application. Simulation results for position, speed and current loops in a closed-loop sensorless mode are shown. The sensorless method is based on the tracking of saliencies by high frequency injection.

Keywords steer-by-wire; sensorless; PMSM, high frequency injection.

1 INTRODUCTION

Research on by-wire technologies for automotive applications has increased during recent years due to the number of advantages which such systems have over conventional mechanical systems. Such advantages include better fuel economy and reduced gas emissions in throttle-by-wire, reduced risk of skidding in brake-by-wire and reduced volume required for the steering arrangement in steer-by-wire [1]. All by-wire systems can also be adjusted for improved vehicle dynamics and driver comfort. The main aim of these by-wire systems is to have driver inputs which are not mechanically coupled to the drivetrain of the vehicle but measured through sensors and driven electrically through the use of appropriate drive mechanisms [2].

The most challenging by-wire system to implement is steer-by-wire; this is due to the various sensors and actuators which need to be integrated in the system and due to the critical safety associated with the application. In order to facilitate the widespread use of steer-by-wire applications researchers must ensure that the resultant systems are both fault tolerant and with a response which is comparable to traditional power steering arrangements which are already available on the market [3].

In this research a simulation model in MATLAB/Simulink for the sensorless position/speed estimation and closed-loop control of a Permanent Magnet Synchronous Machine (PMSM) used in the steer-by-wire implementation is proposed. The presence of a sensorless algorithm in the steer-by-wire application improves the safety and robustness of the application. The model presented as part of this research is intended to facilitate the design of the various Proportional (P) and Proportional Integral (PI) controllers used in practice in both the vector control algorithm of the PMSM and the sensorless observer. The model also allows the prediction of the steer-by-wire performance under different load conditions. Since model based sensorless control systems suffer during low speeds and low operational frequencies [4], a high frequency based sensorless system was implemented.

2 STEER-BY-WIRE SYSTEM

2.1 Steer-by-wire System Overview

The steer-by-wire system aims to eliminate some of the mechanical linkages within a traditional steering mechanism while still replicating the steering feel at the driver's end. The direct mechanical coupling is eliminated and replaced with two electrical drives with associated position and speed sensors such as encoders as shown in Figure 1. The two electrical drives are required for providing torque feedback at the handwheel (Machine M1) and replicating the position of the handwheel at the steered side (Machine M2).

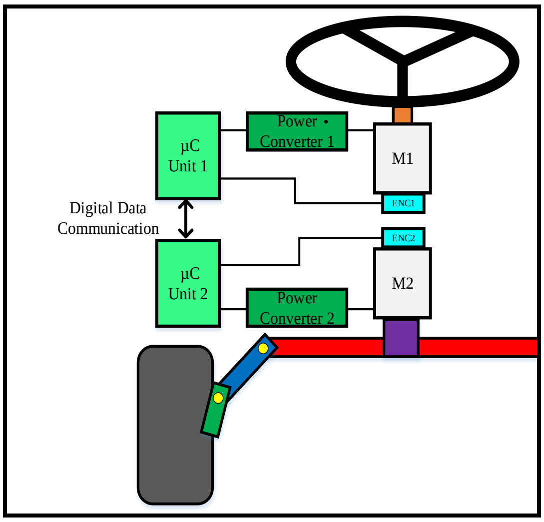

Figure 1: Steer-by-wire system.

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Most of the electrical drives used in steer-by-wire applications presented in literature are implemented using PMSMs as shown in Figure 2 [5, 6], due to a number of advantages associated with this machine such as: higher efficiency and higher power density compared to brushed DC drives, better heat dissipation characteristics compared to induction machine based drives, no commutator maintenance and higher maximum speed.

Figure 2: PMSM modelled in Simulink.

2.2 *Characteristics of Steer-by-Wire*

The numerous steer-by-wire systems proposed to date have shown considerable advantages over conventional steering arrangements. The absence of the steering column simplifies interior car design and therefore the handwheel can be placed at different parts of the vehicle since it does not have to be necessarily mounted on the dashboard. The removal of the physical link between the handwheel and the steered wheel arrangement also results in a lower probability that the impact produced by a frontal crash will cause the steering arrangement to invade the driver's space; hence reducing the occurrence of driver injuries. Since the steer-by-wire system requires a digital signal processor/microcontroller to control the drive it is also possible to adapt the steering dynamics according to the driver's comfort and preference.

One of the main challenges in by-wire applications in general is that of generating an authentic force feedback at the driver inputs. In steer-by-wire research considerable effort has been done in order to provide a torque feedback at the handwheel which has the same physiological effects on the driver [7-9]. The possible failure of the position / speed sensor has also resulted in researchers having to introduce mechanical systems and sensors to comply with automotive safety requirements.

3 SENSORED POSITION CONTROL OF THE PMSM

The steer-by-wire application requires the design of two control systems for the PMSMs present in the system. The machine which provides torque feedback at the handwheel must operate in current control mode while the machine which sets the position at the steered wheel side must operate in position control mode. In this research Rotor Flux Orientated Control of the PMSM is used and consists of cascaded control loops for position, speed and current. The parameters of the PMSMs considered for the steer-by-wire application required for the generation the MATLAB/Simulink model are listed in Table I.

The open-loop bandwidth of the electrical part of the PMSM model has a bandwidth of 65 Hz while the open-loop bandwidth of the mechanical part has a bandwidth of 0.016 Hz. The bandwidths were determined from the s-domain transfer functions for the respective models. The controllers in the cascaded position control system for the PMSM where tuned as listed in Table II. The gains chosen for the controllers were tuned in such a way that the PMSM exhibits a stable response when in sensorless control mode. The PI controllers in the system have a dual nature; they are used to provide an adequate response with minimum delay while filtering out any noise present due to the sensorless estimates.

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TABLE I. PMSM MODEL PARAMETERS

	Description	Value	Unit
L_d	D frame stator inductance	807.9	mH
L_q	Q frame stator inductance	641.1	mH
R	Stator Resistance	262	mΩ
J	Moment of Inertia	7.7×10^{-3}	kg m²
B	Coefficient of Friction	7.5×10^{-4}	Nms
p	Number of Pole Pairs	6	-

TABLE II. CONTROLLER GAINS

Loop	K_p	K_i	Closed-Loop Bandwidth [rad/s]	Damping Ratio
Current	0.55	365.13	753	0.84
Speed	1.92	113.14	82	0.707
Position	10	0	10	1

3 SENSORLESS POSITION CONTROL OF THE PMSM

3.1 Sensorless Position Control Overview

The use of model-based sensorless observers is widely reported in literature due to their applicability over a range of speeds; however most of these observers fail at low or zero speed conditions [10]. These methods rely on the estimate of the back-emf, which decreases significantly at low speeds, hence the resulting estimates are susceptible to sensor noise and variation in machine parameters. Since in steer-by-wire, position control at low speed is required, model-based observers are not suitable. Hence sensorless algorithms which are based on tracking machine saliencies must be used in order to obtain accurate rotor position/speed estimates.

Tracking of saliencies is typically done through the injection of additional signals during operation of the electrical machine. The methods for signal injection are subdivided into transient and continuous injection methods. In this research a continuous high frequency (HF) signal injection method is used. HF-based methods in literature have been shown to obtain a rotor position estimate by superimposing a continuous high frequency carrier on the voltage fed onto the PMSM for the purpose of saliency tracking [11, 12].

3.2 High Frequency Injection Saliency Tracking

In the MATLAB/Simulink model presented in this article sensorless control is based on injecting a high frequency component in the stationary αβ-frame. These components are added to the reference fundamental frequency stator voltages in the synchronous dq-frame transformed into the αβ stationary as shown in Figure 3. The three phase currents i_a, i_b and i_c contain components of both the fundamental frequency and the injected HF. For the purposes of saliency tracking the low frequency current component is filtered out with a fourth order band-pass filter and transformed to the αβ frame. For an injection frequency ω_i of 2 kHz a fourth order band-pass filter with double poles at 1 kHz and 3.3 kHz respectively was designed and included in the model. The output of this filter after transformation is denoted as $i_{i\alpha\beta}$ and is the isolated current component due to the HF injection on the stator windings. The heterodyning approach is then used on $i_{\alpha\beta}$ to obtain an error term which can be used in a phased-locked loop (PLL) to obtain the speed and position estimates as shown in Figure 4.

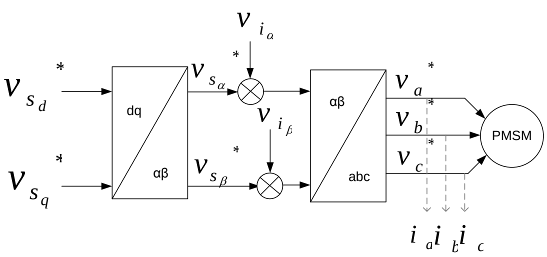

Figure 3: High Frequency Injection in the αβ stationary frame.

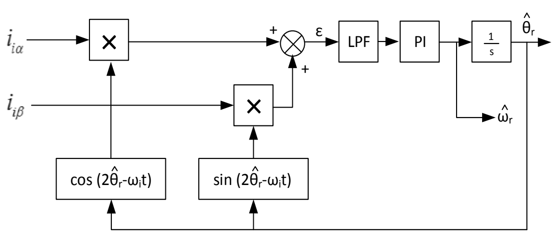

Figure 4: PLL rotor position/speed estimator

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4 CLOSED-LOOP POSITION/SPEED TRACKING SIMULATION RESULTS

The main aim of the PMSMs in the steer-by-wire system is to track position references at low speed. The Simulink/MATLAB model developed as part of this research has inputs which allow for testing of this tracking capability for different position references and different load conditions.

In the simulation results presented in this article a full-load of 5 Nm is applied at the output of the PMSM. A change in reference position from 0.1 rad to 1.1 rad is applied at 0.5 s and filtered through a first order low-pass filter with a bandwidth of 25 Hz. The test was carried out while operating in sensorless control. The actual/estimated shaft speed is shown in Figure 5. The actual/estimated shaft position is shown in Figure 6. The three phase stators currents and the dq frame stator currents are shown in Figures 7 – 8.

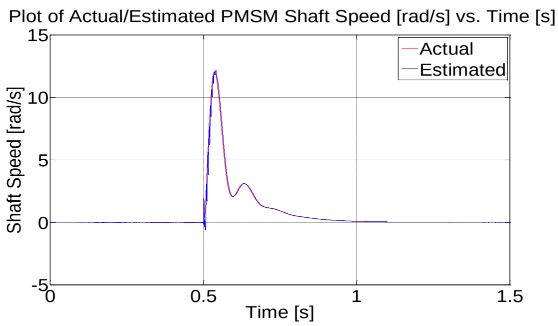

Figure 5: Plot of Actual/Estimated PMSM Shaft Speed

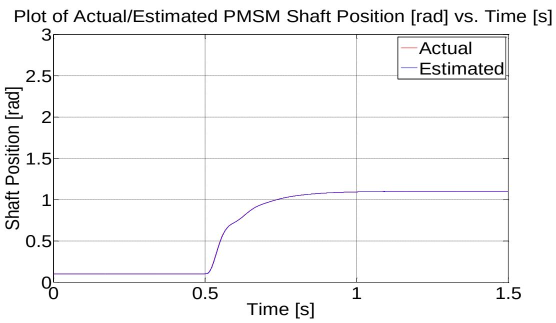

Figure 6: Plot of Actual/Estimated PMSM Shaft Position

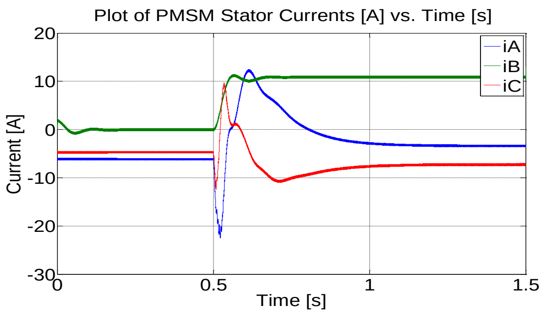

Figure 7: Plot of PMSM Stator Currents

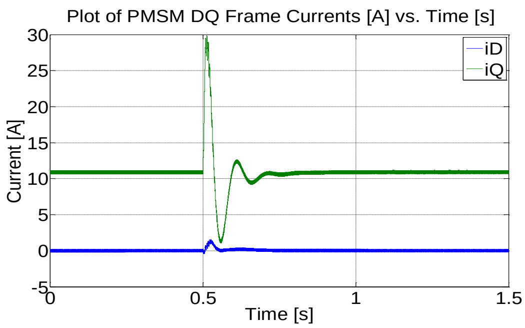

Figure 8: Plot of PMSM Stator DQ Frame Currents

5 CONCLUSIONS

In the simulation results presented the tracking of the rotor position/speed for a change in reference position at full load conditions was shown. The sensorless observer presented and simulated in this article tracks both speed and position with minimum error. During the operation shown in Section 4 the system was operating in sensorless control, that is the estimated speed and position where being both observed and used for control purposes. In this mode the error in the estimates was negligible for the purposes of vector control.

The change in the position reference given in simulation is of 1 rad and reaches steady state in approximately 39 ms. This translates into a steering rate of change of 1458 degrees/s which is well above the average human steering capability observed as part of this same research.

Hence the model presented and designed in this paper shows the validity of using a HF injection based saliency detection method to estimate the speed and position in sensorless steer-by-wire PMSMs. The inclusion of such algorithms could result in improved functional safety in the steer-by-wire application by providing an alternative means of measurement for shaft positon/speed.

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