Control Strategies Enabling High Frequecy Injections for PMSM Position Estimation

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***Abstract*—The aim of this paper is to present two different control approaches with injection of high frequency signals for estimation of rotor position and speed of a permanent magnet synchronous motor (PMSM) due its anisotropy. There are selected and modified two methods, a sliding mode control and a direct torque control which are not usually used for injecting high frequency signals because they do not use a PWM modulator. Therefore the injection of the high frequency signal and its backward demodulation is a quite challenging task. Another drawback of used control algorithms is the necessity of short sampling period; the main control algorithm including the injection and the demodulation (position estimation) can not be computationally demanding. It is proved by simulations and experiments that both algorithms enable injecting of the high frequency signal. All experiments were carried out on a laboratory prototype of the drive with rated power of 250 W.**

***Index Terms*—hf injections, direct torque control, permanent magnet synchronous motor, sliding mode control**

I. Introduction

PMSM drives require a position or speed sensor for its proper function. However, in most applications, the position encoder or resolver presents several disadvantages as reliability, construction demands or price. To overcome these facts, sensorless strategies for PMSM adjustable drives have been proposed in recent years.

Sensorless techniques can be divided into two main areas, (i) methods using the fundamental properties or model of the machine and (ii) methods exploiting subsidiary features often called anisotropy based models. The first area of rotor position estimation method can be based on the back EMF estimation. Methods based on the back EMF are relatively simple but do not work well in low speed regions since the back EMF is small in comparison with noise appearing in the drive control system. Its advantage is relatively low computational cost [1]. The accuracy of the method can be improved by improvement of the back EMF equations by a model of the state evolution what results in a state space model which can be evaluated by a stochastic filter, often by the Extended Kalman filter [2], [3], [4].

Methods based on high-frequency signal injections can be more efficient at lower and zero speed than any other sensorless estimation schemes mentioned above. These methods have capability to provide accurate position and speed estimation without a need of motor parameters information. This is due to the presence of anisotropy and/or saliency in the machine. The saliency is defined as the inductance difference between direct-inductance L_d and quadrature-inductance L_q and it is due to either the asymmetric structure of the machine or the flux induced magnetic saturation due to the fundamental excitation [5]. It is shown in the literature that sensorless techniques from both areas which at first look seen as incompatible could be used in one approach. A state space model representation of the machine is completed by another observation equation that includes phase lock loop [16].

Injection based methods could be divided in several groups: (i) rotating injections, (ii) pulsating injections, (iii) injection of testing pulses. The pulsating hf injections are usually used in control algorithms based on flux oriented control because these algorithms use a PWM modulator [6], [7]. The PWM modulator enables a quite simple injections of a high frequency signal in the converter output voltage. More difficult is a solution without a modulator, e.g. in a direct torque control, a sliding mode control or a finite control set model predictive control. These control structures are often associated with rotating injections or injections of testing pulses [8], [9].

In this paper, a sliding mode control and direct torque control schemes will be modified and employed for hf rotating injections in order to enable the estimation of position in permanent magnet synchronous drives. The SMC brings several advantages in electric drives, e.g. it enables fast torque and stator flux response, simple control structure very similar to a DTC one, and efficient operation due the short sampling period.

The direct torque control (DTC) brings several advantages in electric drives, e.g. it enables fast response in both torque and stator flux, simple control structure and efficient operation due a short sampling period. On the other hand, it brings several disadvantages, e.g. the switching frequency is not constant in one stator period, it changes with speed, load torque, and depends strongly on bandwidth of the flux and torque hysteresis controllers [10], [11]. Moreover, DTC does not use current and voltage PI controllers what yields a faster torque response and lower parameter dependence. Unfortunately, the DTC algorithm needs to work with very short sampling period in range of tens of microseconds.

The main advantages of the direct sliding mode

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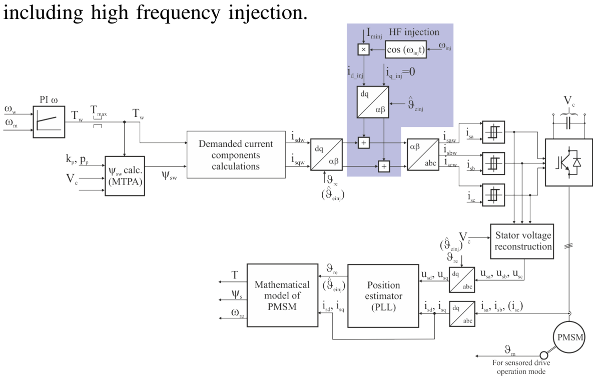


Fig. 1. The modified structure of direct torque control algorithm including high frequency injection.

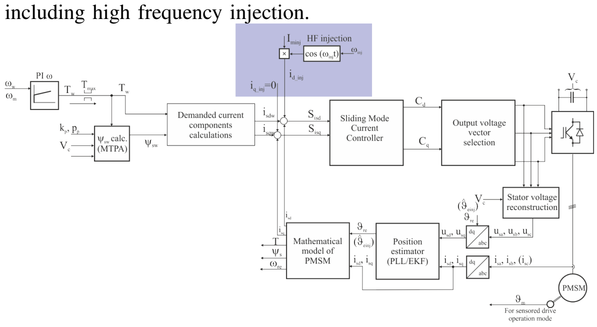


Fig. 2. The modified structure of sliding mode control algorithm including high frequency injection.

control (SMC) is a simple control structure in its basic configuration and very good torque dynamic response [14], [15]. Sliding mode control, which is used in this research for machine control, is associated with variable structure systems. Such systems were first studied in [12], [13]. The disadvantages of the SMC is similar to the DTC ones, particularly the short sampling period and high variable switching frequency.

II. Direct Torque Control Enabling High Frequency Injections

From the point of view of pulsating injections, it is very challenging task to configure the DTC system to enable the injections of high frequency signal in a given axis, usually the d-axis of the rotating coordinate system (axis of the permanent magnet flux orientation). Therefore a modified structure of the DTC is proposed. The control scheme is displayed in Fig.1. The structure differs from the standard DTC in the demanded current component calculations. The demanded components of stator current i_{sdw} and i_{sqw} in the rotating coordinate system dq are calculated from the demanded torque T_w and demanded flux ψ_{sw} in block "Demanded current components calculation". This block replaces the hysteresis comparator of the torque and flux and a table of demanded output voltage vector which is used in a standard DTC approach [11].

The injection algorithm is designed for injections into the d-axis of the coordinate system, therefore the injected current $i_{d\,inj}$ is added to the d-axis current component i_{sdw}. The injected current is injected with constant angular frequency ω_{inj} with frequency $f_{inj} = 1000$ Hz and amplitude I_{minj}. The modified current components are then transformed in the phase current demanded values i_{saw}, i_{sbw}, i_{scw}. These are led to the hysteresis current comparators, compared to the measured phase currents i_a, i_b, i_c. Switching combinations are selected depending on the relation between the measured and demanded phase currents. The current hysteresis comparators ensure fast dynamic response comparable with the standard DTC.

III. Sliding Mode Control Enabling High Frequency Injections

The scheme of the proposed control algorithm can be seen in Fig. 2. This control allows the high frequency signals injections in to the stator current components in the rotating reference frame similarly to the modified DTC without significant modifications of the control structure.

The sliding mode control employed in this research controls the stator current vector of a PMSM in the rotating reference frame (d, q). The aim of the sliding mode is to control the d and q component of the stator current vector, two switching functions are therefore defined S_{isd} and S_{isq}:

$$S_{isd} = i_{isdw} - i_{isd} \quad (1)$$

$$S_{isq} = i_{isqw} - i_{isq} \quad (2)$$

where i_{isdw} and i_{isqw} are the reference stator current vectors along the d and q axes, respectively. These switching functions define two sliding surfaces: $S_{isd} = 0$ and $S_{isq} = 0$. The voltage vector is then chosen depending on the sign of the switching functions and on their respective derivatives. Two sign comparators are used to determine the logical state of the variables C_d and C_q. The switching table for the voltage selection is addressed using the logical variables C_d and C_q, along with the number of the sector with the position ϑ_{re}. The output voltage selection block then generates the switching states S_a, S_b and S_c to be applied to the three-phase inverter [14], [15].

The injection of the high frequency current component into the rotation reference frame is performed with constant injecting injection frequency $f_{inj} = 1000$ Hz and with amplitude I_{minj}, current i_{qinj} is set to zero [16], [17].

IV. Rotor Position and Speed Estimation

A widely used mathematical model in rotating reference frame linked to a rotor flux linkage vector is employed [11]. The mathematical model of the PMSM assumes that the inductance remains the same around the machine. This assumption is not truth considering the real configuration of the machine. The difference of inductances in direct and quadrature axis can reach 5% for a surface mounted PMSM. This anisotropy can be used for estimation algorithms based on high frequency injections. The pulsating hf injections are used in the proposed position estimator of the drive.

In general, high frequency signal injection methods are divided into 3 steps: signal injection, demodulation process, position and/or speed estimation. The injected high-frequency components are considered to be sufficiently higher than the rotor speed and much lower than the inverter switching frequency. Only the performances at low speed are studied, it is assumed that d and q axis carrier current in the estimated rotor frame are equal to the commands and the speed EMF terms are negligible.

A. Phase Locked Loop estimator

The configuration is shown in Fig. 3. The implementation of the Phase Locked Loop (PLL) structured observer in high frequency signal injection schemes requires tuning of PI controller to lock on the rotor position. Measured stator currents are transformed in a fictional rotating frame $\hat{R}$. Then the currents are filtered with a bandpass filter to avoid unwanted components of the current. The current components are transformed using a signum function and led into PI controller with zero demanded value. The PI controller set the output in the way the difference of its input to be equal to zero. The output of the PI controller then corresponds with the electric rotor speed which represents one of the estimator output. By integration of the PI controller output the electrical rotor position $\hat{\vartheta_{einj}}$ is obtained. For better results of speed $\hat{\omega_{re}}$ estimation, it is recommended to calculate it using the difference of the estimated position in a time period. The estimated value $\hat{\vartheta_{einj}}$ is led back as a feedback into the transformation block which creates a loop of a PLL.

V. Simulation results

In order to verify the right function of the proposed algorithms the simulation model of the drive was designed. The model was written in C language, to simplify implementation of the proposed control algorithms with the injections and position estimator into a microprocessor controller. The proposed control algorithms with position and speed estimators was studied on a small scale laboratory drive with rated power of 250 W. Smaller drives brings serious problems because of physical parameters; particularly low inductance leads to high current ripple, very low inertia makes the speed control difficult. The machine parameters are: stator resistance $R_s = 0.14\ \Omega$, stator inductance $L_s = 0.00025$ H , permanent magnets flux $\psi_{pm} = 0.0226$ Wb, moment of inertia $J = 0.000072$ kgm^2, polepairs $p_p = 3$. The dc-link voltage was set to V_c =30 V. Although the motor parameters are not propitious for the control algorithm, it can be seen a very good behavior of the proposed estimator in the simulated system.

Fig. 3. PLL based position and speed estimator.

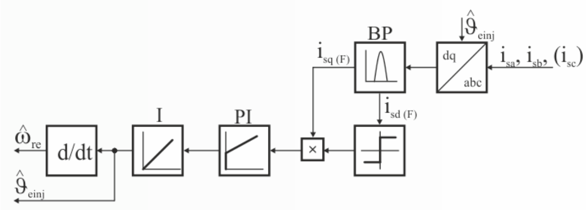


Fig. 4. Current i_{sd} with high frequency component in DTC.

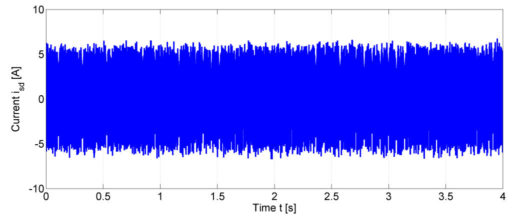
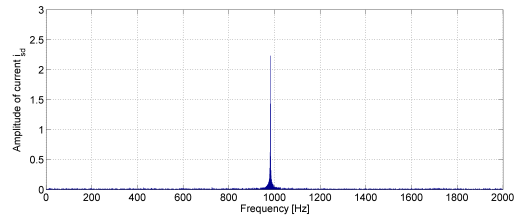


Fig. 5. Current i_{sd} frequency spectrum in DTC.



First evaluation of the algorithm was performed with measured rotor position, prediction PLL based estimator was in this case connected in open loop to verify the correct observer design. The simulation results are shown in Fig.4-7.The simulation is performed for start of the drive $\omega_{re} = 2\,rad.s^1$. It is shown that current component i_{sd} for both control structures contain the hf component. It is very important for accurate estimation.

VI. Experimental evidence

Experimental evidence of the control algorithm with proposed position and speed estimator based on EKF was performed on a small scale laboratory drive with rated power of 250 W with the same parameters as the drive used in simulations. The sampling period for the DTC and SMC algorithms calculations was set to 50 μs. The quality of DTC algorithm can be seen from Fig. 8 where the measured and estimated position and a phase stator current are shown under no-load condition of the motor. The result of the SMC with a loaded

Fig. 6. Current i_{sd} with high frequency component in SMC.

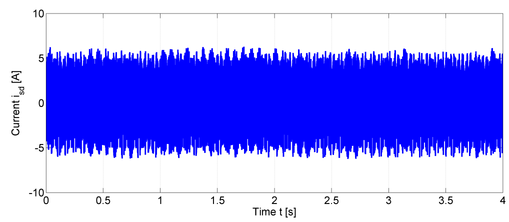


Fig. 7. Current i_{sd} frequency spectrum in SMC.

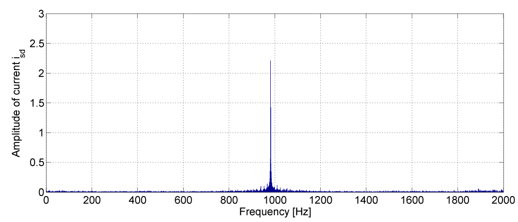


Fig. 8. Measured (green) and estimated (blue) position and stator current (magenta) in DTC, $f_{re} = 1.5Hz$, unloaded machine.

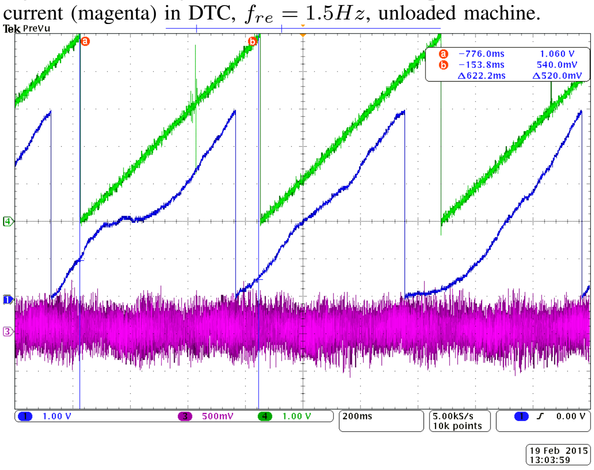
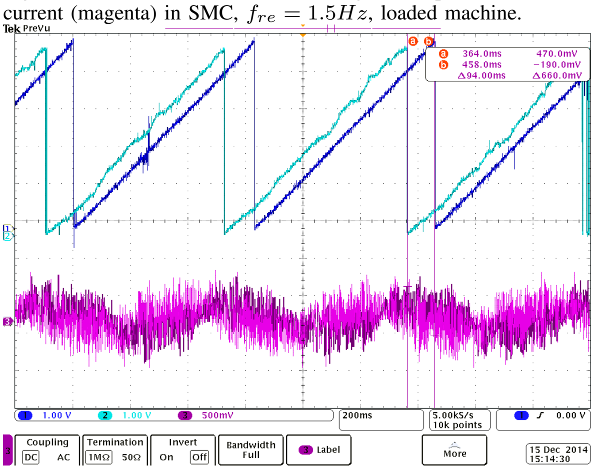


Fig. 9. Measured (blue) and estimated (light blue) position and stator current (magenta) in SMC, $f_{re} = 1.5Hz$, loaded machine.



machine can be seen from Fig. 9. It can be seen that the measured and estimated positions are with similar waveforms, the estimation error is around 0.87 rad. The accuracy of the estimation strongly depends on the gain settings in the PLL PI controllers, it must be set as an compromise between required dynamics and accuracy but it is not the main goal of this paper. It must be noted that the electrical frequency is quite high for the estimation using PLL, it is recommended to use this kind of estimator up to $1Hz$ of electrical frequency.

VII. Conclusion

There were described two different strategies of PMSM control, the direct torque control and the sliding mode control. The strategies were modified to enable injections of high frequency signal in the output voltage. The modified algorithms inject the high frequency signals using the demanded stator current vector components which the current high frequency component is added to. To evaluate the proper function of the injection part of the control algorithm, a simple PLL based position estimator utilizing the machine anisotropy was implemented to the control structure. This estimator is very simple to implement but does not work well in higher speeds (approximately over frequency of 1 Hz).

The proper function of both proposed control structures were verified by several simulations and experiments on a laboratory prototype with rated power of 250 W.

VIII. Acknowledgment

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