Sensorless speed control of permanent magnet synchronous machines for low speed and standstill

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Abstract: The subject of this paper is a method for sensorless speed control of permanent magnet synchronous motors (PMSM), which is suitable for low speed including standstill. The control scheme is a cascaded structure with a speed control in the outer loop and a rotor oriented current control in the inner loop.

The estimation of the rotor position is based on the on-line identification of the stator inductance, which is a function of the rotor position.

For the speed control a scheme is used, which combines a differentiator and a Luenberger observer.

1 Introduction

Permanent magnet synchronous machines with rotor orientated control are state of the art for low and medium power drive applications with high demands on dynamic behavior [Vas94]. The control concept consists of a cascaded scheme with a torque control in the subsidiary loop and a speed control in the superposed loop. For this, the feedback of the current (for the torque control) and the knowledge of the rotor position (for the transformation in rotor orientated co-ordinates) as well as knowledge about the motor speed (for the speed control) are necessary.

If we speak about „sensorless control“ in the meaning of renunciation of mechanical sensors, the rotor position and rotor speed have to be estimated. An overview about different techniques is given in [Vas98].

Operating at low speed is a well-known problem. Because of the low voltages in this operating range the estimation of rotor position and rotor speed is hardly influenced by measurement errors, inverter dead times and the forward voltage drops of the inverter.

Some common disadvantages of known sensorless control schemes are, that they are not suitable for industrial applications in the meaning of renunciation of a stator voltage measurement, strong restrictions to the computation power, or they do not work at low-speeds. The method presented in the following overcomes these restrictions.

2 Torque Control

For torque control in rotor oriented reference frame information about the rotor position, which corresponds to the transformation angle, is needed. In this approach the on-line identification of the stator inductance is utilized to get this information.

The inductance distribution over the circumference is influenced in a high degree by magnetic saturation caused by the rotor´s permanent magnets as well as the stator current [Kie00].

For a typical servo drive with PMSM, the inductances of the direct axis L_{Sd} and the quadrature axis L_{sq} vary about 20%. Experimental results for a typical PMSM are shown in Fig. 1. It can be seen that the inductance distribution can be described by a sinusoidal function, whose period equals to half of one electrical turn.

This saliency is used for rotor position detection in the proposed scheme.

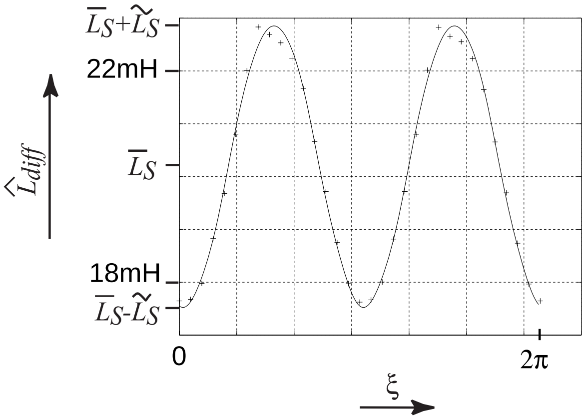

Fig. 1. Inductance distribution over one electrical turn.

In this scheme the inductance is estimated by a correlation method. A sinusoidal test signal with a frequency ω, usually higher than the bandwidth of the current control loop, is injected. The impedance Z_ξ is determined from the stator currents $i_{S\xi}$ and voltages $u_{S\xi}$ by evaluation of the equation:

$$\hat{Z}_\xi(j\omega) = \frac{\int_0^{\frac{2\pi}{\omega}n} u_{S\xi}(t)e^{-j\omega t}dt}{\int_0^{\frac{2\pi}{\omega}n} i_{S\xi}(t)e^{-j\omega t}dt} \qquad (1)$$

By this, the differential inductance L_ξ, which is the ratio of the differential stator flux linkage and the differential magnetization current, can be identified from the imaginary part of the impedance Z_ξ. To achieve better results, several periods of the test signal, oscillating with an angular frequency ω, are evaluated. ξ describes a freely chosen direction in the d,q-plane.

Due to the orthogonality of the trigonometric functions, Equ.(1) ensures a pretty good estimation of the inductance even if the stator voltages and currents show minor distortions.

In the control scheme depicted in Fig. 2, the reference voltage is submitted directly to the modulator. Compared to a current reference injection, the implementation effort is about the same, but in the case of using an open loop voltage control, the current controller does not have to manage a reference-component, alternating with high frequency.

The stator inductance as a function of the electrical rotor position $L_S(\varepsilon_{RS})$ can be approximated by the sinusoidal function:

$$L_S(\varepsilon_{RS}) = \bar{L}_S + \tilde{L}_S \sin(2\varepsilon_{RS} + \varepsilon_{RS0}) \qquad (2)$$

For a direct determination of the rotor position $2\varepsilon_{RS}$ from Equ.(2), at least one measurement in addition to the a-priori-knowledge of the average inductance $\bar{L}_S$ and the amplitude of the alternating component $\tilde{L}_S$ is necessary. Both of these parameters are a function of the steady component of the stator current, which complicates the evaluation of the rotor position largely.

Therefore, this scheme uses another approach and estimates the stator inductances in at least three different directions ξ (e.g. the phase directions *a,b,c*). To reduce the time delay, resulting from three subsequent measurements, it is useful to perform the evaluation of the inductances L_ξ from only one measurement. For this the sinusodial superposed voltage in one explicit direction is replaced by a rotating voltage pointer, which affects sinusodial voltages in each direction. Because the injection of the superposed sinusoidal voltages should not effect the current control, these signal components have to be filtered out of the measured currents by a notchfilter as shown in Fig. 2.

The estimated inductivities in the three phase directions, L_{Sa}, L_{Sb} and L_{Sc}, can be transformed in the orthogonal stator oriented system, resulting in $L_{S\alpha}$ and $L_{S\beta}$. The zero_component (L_{S0}) is equal to the mean value of L_S.

The maximum of the distribution $L_S(\varepsilon_{RS})$ points into the direction of the q-axis and the minimum into the direction of the d-axis [Kie00]. Regarding this, the estimated rotor position can be evaluated by

$$\varepsilon_{RS} = \pm\frac{\pi}{2} + \arg(L_{S\alpha} + jL_{S\beta})\,. \qquad (3)$$

The absolute electrical rotor position can not be detected unambiguously by this scheme. Thus, the correct orientation is determined during start-up by a proper technique ([Bru97], [Kie01], [Öst96]). Once detected, the absolute rotor position can be tracked by using the assumption, that the change of the rotor position is less than $\pi/2$ between two estimation cycles. This condition is fulfilled in nearly all applications.

The following measurement results have been achieved on a servo drive system. The experimental set-up consists of a PMSM with three pole pairs and a rated current of 3.1A. It is fed by LUST's servo drive CDD3000 (rated current 4A), which is connected to a DSP by a synchronous

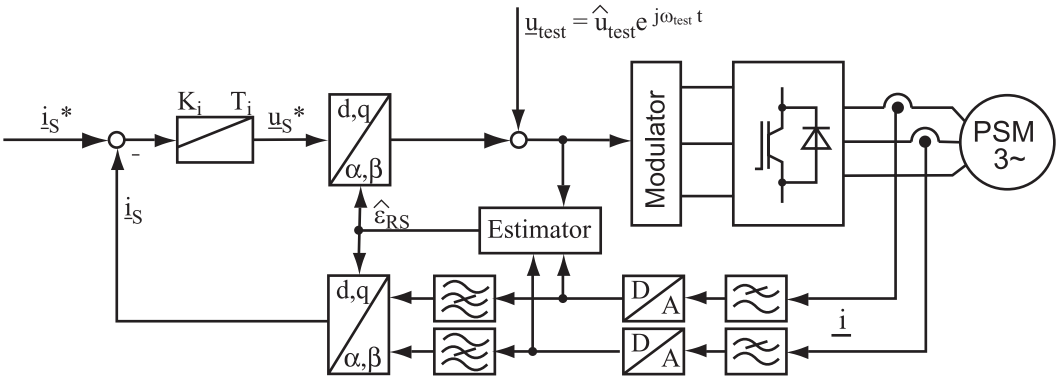

Fig. 2. *Control scheme for sensorless control including the test signal injection*

serial interface (SSI). An optical encoder is coupled to the shaft of the motor to validate the results.

In Fig. 3, the results of the inductivity estimation L_{Sa}, L_{Sb} and L_{Sc} and the resulting rotor position are shown.

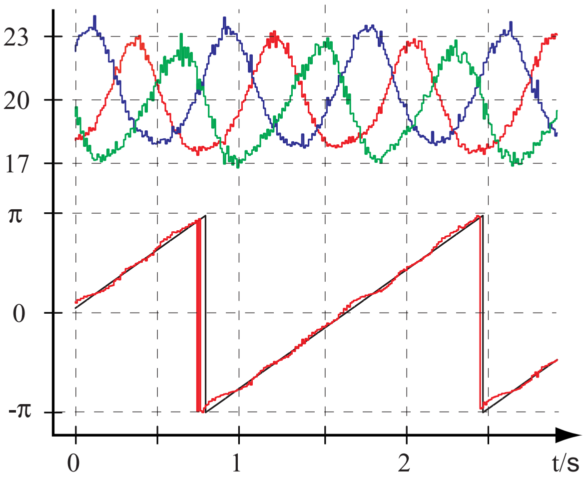

Fig. 3. *Inductivity estimation in the phase directions, measured and from saliencies evaluated rotor position*

During this measurement the optical encoder has been utilized. The speed reference is 0.2 Hz and the angle is estimated in open loop with a test signal frequency of 300 Hz.

Every two periods of the injected test signal, corresponding to 6.67 ms in this case, the inductance is determined in the three phase directions and a new value for the rotor position is available.

Even if the estimated rotor position in Fig. 3 is very close to the measured position, a pre-dominant 6th harmonic can be seen, which results from unconsidered saliencies.

3 Speed Control

It seems to be obviously, that the rotor speed can be derived by differentiating the estimated rotor position. But unfortunately this approach features one main drawback: *The sampling rate of speed calculation is very low, resulting in a poor dynamic behavior of the speed control.*

Nevertheless, the speed is estimated with stationary accuracy.

A more sophisticated solution to determine the rotor speed is to make use of an observer. In order to reduce the computation efforts, a third order Luenberger styled observer in the rotor oriented reference frame has been chosen (Fig. 4). According to the low speeds, the coupling terms between the d- and the q-direction in the rotor flux oriented model of the permanent magnet synchronous machine can be neglected and the result is the linear model:

$$\frac{d}{dt}\begin{bmatrix} i_{Sq} \\ \omega_{RS} \\ m_L \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_{Sq}} & -\frac{\Psi_P}{L_{Sq}} & 0 \\ \frac{3}{2}\frac{p^2\Psi_P}{J} & 0 & -\frac{p}{J} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{Sq} \\ \omega_{RS} \\ m_L \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{Sq}} \\ 0 \\ 0 \end{bmatrix} u^*_{Sq} \tag{4}$$

$$i_{Sq} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{Sq} \\ \omega_{RS} \\ m_L \end{bmatrix}$$

This system can be approximated by a time-discret model with the state vector $\hat{\underline{x}}_k$ and the estimated system matrix $\hat{A}$, input matrix $\hat{B}$ and the output matrix $\hat{C}$.

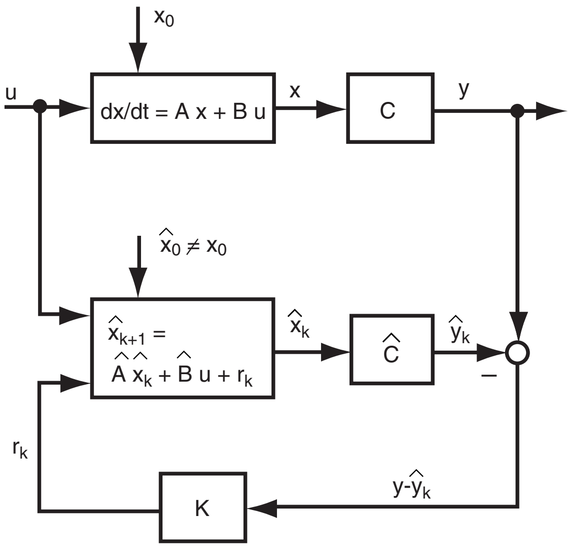

Fig. 4. Luenberger observer

Compared to the speed estimation from the saliencies, the observer equations can be calculated with very high sampling rates (e.g. 8 kHz). At the same noise level better dynamic behavior of the speed control is possible. But unfortunately, the stationary accuracy of the speed estimation is missed.

To combine the benefits of both estimation methods a modified scheme is used for speed control. As shown in Fig. 5, the input of the proportional block, which is important for the dynamic of the control, is fed by the observer speed, $\hat{\omega}_{obs}$. The integration block, suitable for stationary accuracy, is fed by the differentiator-based velocity $\hat{\omega}_{diff}$.

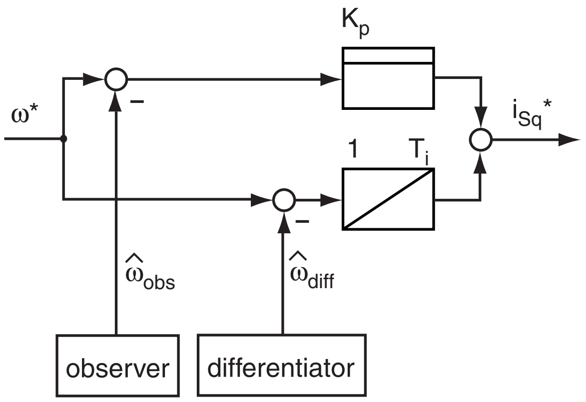

Fig. 5. Modified PI-controler

Experimental results obtained with this modified control scheme are shown in Fig. 6. The drive is in no-load operation. A stationary accuracy as well as a good dynamic behavior can be achieved in spite of the poor dynamic behavior of the speed signal obtained by differentiation. Remarkable is the fact, that at no-load the observer seems to deliver stationary accuracy for the speed, but this is not true at loaded conditions.

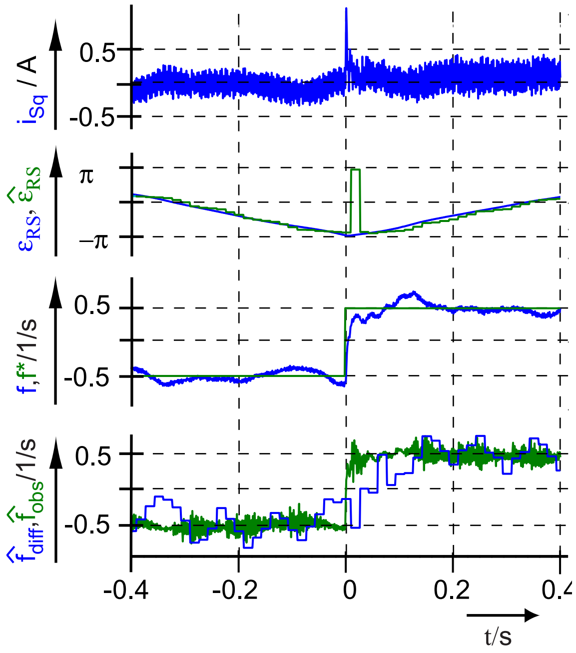

Fig. 6. Measurement of the real speed, rotor position and estimated rotor position with close loop sensorless speed control

4 Conclusions

In this paper a method for a sensorless speed control scheme for PMSM has been presented, which combines the evaluation of saturation saliencies and a Luenberger observer. The performance of this method has been demonstrated by experimental results.
The benefits of this scheme are:

- It demands only low computation power.
- It is suitable for low speed including standstill.
- No voltage measurement is necessary.

These characteristics recommend the control scheme for the utilization in commercial servo drives.

5 References

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