Accuracy of the Sensorless Determined Rotor Position for Industrial Standard Drives in the Whole Speed Range

Manfred Schrödl Wolfgang Staffler Matthias Hofer
Institute of Electrical Drives and Machines
Vienna University of Technology
Vienna, Austria
Tel.: +43 / (1) – 58801-37212
Fax: +43 / (1) – 58801-37299
E-Mail: manfred.schroedl@tuwien.ac.at
wolfgang.staffler@tuwien.ac.at
matthias.hofer@tuwien.ac.at
URL: http://www.ieam.tuwien.ac.at

Keywords

Permanent Magnet Synchronous Machines, Sensorless Control, INFORM method, back EMF model, mechanical observer structure, probability density distribution, deterministic and stochastic errors

Abstract

This paper gives a view about a standardized implementation of a combined INFORM/EMF–model to cover the full speed range of sensorless permanent magnet synchronous motor drives. A special feedback loop returns the output information of the observer to the integrating voltage model. Thus, a stable operation with high robustness against parameter uncertainties and low frequency disturbances is achieved.

Introduction

For about 20 years, various attempts have been made to eliminate the sensor by using mathematical models based on electrical measurement quantities like phase or DC link currents and voltages. Several books (e.g. [1]) and survey papers (e.g. [2],[3],[4],[5],[6]) have been published, giving state of the art in sensorless control.
The combined field oriented control structure for sensorless control in the whole speed range uses following main effects:

- The back EMF (induced voltage) when the rotor rotates at a certain speed
- Saturation or geometric saliency at low speed (signal injection, INFORM method)

Obviously, at zero speed, no back EMF occurs in the PSM. Hence, at low speed a saliency-based model must be used. However, in this case, saliency must me measurable, which may be a problem, especially in surface-mounted magnet motors. For reliable industrial use, a quantitative qualification procedure is suggested, ensuring reliable operation at arbitrary speed and load conditions. The following steps are necessary for the quality test:

- define a reliable and frequently tested sensorless field-oriented control scheme.
- Calculation of the probability of a critical situation of estimated angular position.

The Basic Structure and the Combined INFORM/EMF-Model

The control scheme is characterized by a mechanical observer with output quantities angular speed and angular position (and – optionally - load torque) (Fig. 1). The measurement inputs (measuring indirectly the rotor position in EMF case and double the rotor position in INFORM case) into the

observer is the INFORM input used at low speed and the EMF input at high speed. However, the EMF model is always active and stabilized by the INFORM measurement at low speed. A more detailed scheme of the (linear 4th order-) structure is shown in [7]. As explained in [7], this linear structure enables calculation of a stable pole placement by classical control theory rules. The mechanical observer provides an estimated rotor position, which coincides with the PM flux position. By using the constant magnitude of the real PM flux ($|\underline{\psi}_M|=1$), the observer yields estimates of the stator-oriented components of the PM flux. They are compared with those obtained by the voltage model. The difference in both components is fed back to the integrator inputs via a certain gain K_ψ. Thus, the drifts of the integrators are limited because the radius of the PM flux curve in the complex plane is forced to the PM magnitude. However, at zero speed, the angular position obtained by this feedback process is not defined. This is the reason for the limited operating range of this type of EMF model. This problem is solved by introducing INFORM measurement sequences, which stabilize the whole system at low frequency including standstill.

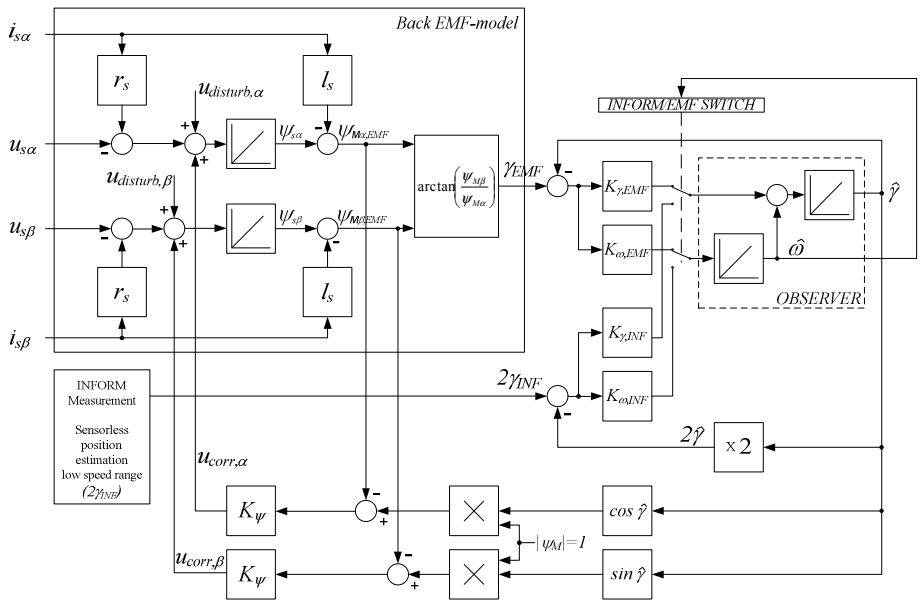


Fig. 1: Combined INFORM/EMF observer structure in a stator-oriented reference frame

The dynamic properties of the system are defined by the observer coefficients $K_{\gamma EMF}$, $K_{\omega EMF}$, $K_{\gamma INF}$, $K_{\omega INF}$ and EMF feedback coefficient K_ψ. There is an interesting coherence between characteristic INFORM curve and estimated permanent magnet flux space phasor: Both curves are circles in a complex plane whose arguments are either the rotor position (EMF model) or double the rotor position (INFORM model). Both "measured" rotor positions yield non-ideal results which are noisy. This noise can well be described by statistical methods. Looking at the probability density distribution of the angular deviation, it can approximated by a Gaussian distribution with mean value and standard deviation. A quantitative examination of the most likely failure mechanism in the sensorless position detection is given, resulting in necessary statistical parameters of the sensorless drive.

A criterion for calculating the probability of the occurrence of a relevant INFORM-based problem of operation is the probability of a so-called "180° error" [8]. It arises when the observer changes its position estimation by 180°, resulting in a second possible solution of the system „INFORM-measurement plus observer", because the INFORM method yields double the angular position.

The problem begins when the expression in brackets of the INFORM feedback term.

$$K_{\gamma,INF} \cdot (2 \cdot \gamma_{INF} - 2 \cdot \hat{\gamma}), \tag{1}$$

which can be seen from the signal flow in Fig. 1 gets a value of 180° [9]. In this case, the observer moves from the correct solution γ_{INF} to the second solution

$$\frac{1}{2}[2\gamma_{INF} + 360^\circ] \quad \text{or} \quad [\gamma_{INF} + 180^\circ], \tag{2}$$

respectively of the INFORM angular position. As a result, the estimated state "rotor position" gets a 180° - error and will remain in this wrong state. The consequence is that the produced torque has negative direction. In an industrial application, it is important to give a quantitative prediction for this critical situation. In the following, it is shown how to calculate the probability of this "180°- error" based on a defined test cycle depending on the application. The angular deviation

$$[y_{INFORM}(k+1) - 2\gamma_m{}^*(k+1)] \tag{3}$$

of the INFORM feedback expression is divided into the INFORM measurement error

$$\frac{1}{2}[y_{INF}(k+1) - 2\hat{\gamma}(k+1)] \tag{4}$$

and the prediction error

$$[\hat{\gamma}^*(k+1) - \hat{\gamma}(k+1)]. \tag{5}$$

As already mentioned, the INFORM measuring process can be described well by its load-dependent standard deviation σ. For probability calculation, the worst case $\sigma_{max} = \sigma(|i_{Sq,max}|)$ should be used. This stochastic parameter is characteristical for a motor-inverter-system and does not depend on the application. Furthermore, it is independent of the INFORM repetition rate. To get a statement about the failure of the sensorless position estimation the probability F_{crit} of this event is calculated by integrating the probability density function of the INFORM error (the area of the Gaussian probability density curve from positive angular deviation γ_{crit} to $+\infty$):

$$F_{crit} = \int_{\gamma_{crit}}^{\infty} P(\gamma)d\gamma = 1 - \int_{-\infty}^{\gamma_{crit}} P(\gamma)d\gamma, \tag{6}$$

with

$$\gamma_{crit} = 90^o - |\Delta\gamma_{load\,\max}|. \tag{7}$$

This integral expression cannot be solved directly. However, an asymptotic approximation exists, describing the angular deviation in multiples x of the standard deviation σ:

$$F_{crit}(x \cdot \sigma) \approx \frac{1}{x \cdot \sqrt{2\pi}} \cdot e^{-\frac{x^2}{2}} \tag{8}$$

INFORM Quality Measurements at the 5 kW Industrial PM Machine

No-load measurements

The no-load measurements give a good overview about the speed-dependence of the INFORM measurement quality. As can be seen from Fig. 2, the mean value shows a slight more or less linear deviation from the correct value depending on speed with a change rate of about 3 electrical degrees per rated speed. The standard deviation is about 4 electrical degrees in the regarded speed range.

Load measurements

Deterministic Error

The first necessary measurement is to detect the load dependence of the INFORM angle. This is a systematic deviation which is practically parameter-independent (especially no temperature influence) and also speed-independent and can hence be considered in the INFORM evaluation as a pure load-dependent correction function (normally, a straight line is sufficient). The load dependence of the systematic deviation of INFORM angle and also its indepencence from speed is given in the Fig. 3. Hence, a correction function with 40 degrees per rated current (straight line) can be used (Fig. 3).

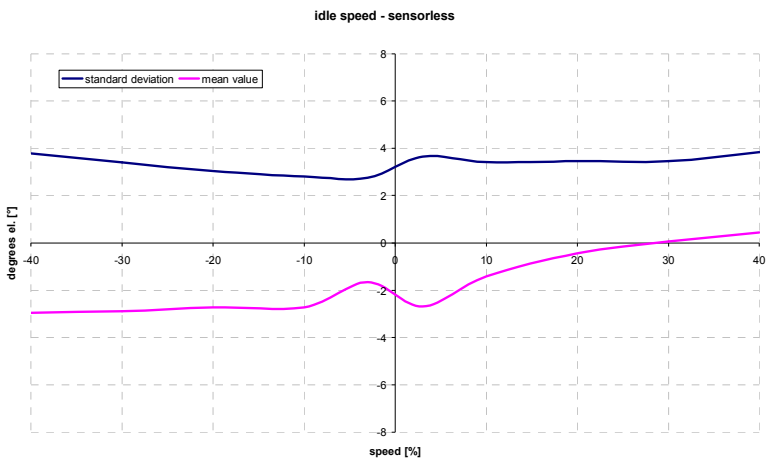


Fig. 2: Standard deviation and mean value depending on the speed of the tested motor – sensorless operation, no-load

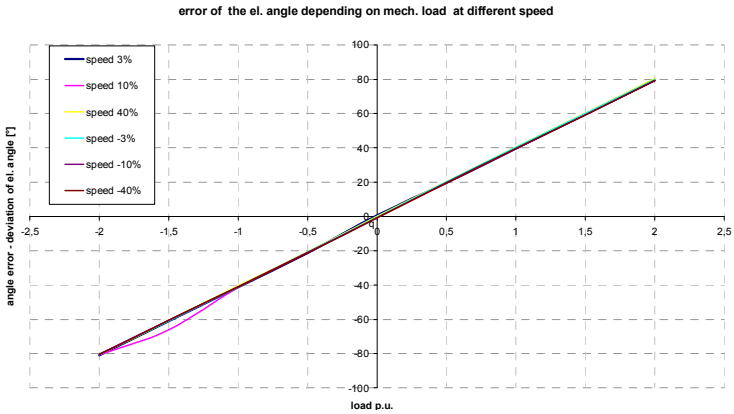


Fig. 3: Systematic deviation of INFORM angle depending on the load

Stochastic error

After correction of the deterministic deviations, a stochastic error remains, which is approximated by a Gaussian distribution (Fig. 5). The results of these standard deviation measurements are shown in Fig. 4. The standard deviation of the angular error in full operating range is better than 5 electrical degrees, which is sufficient for series production.

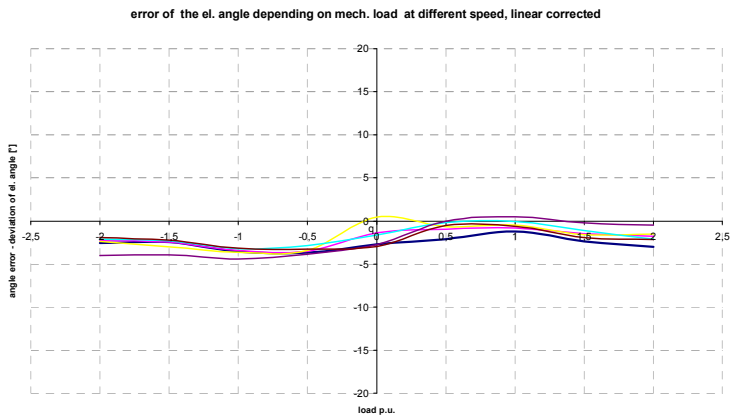
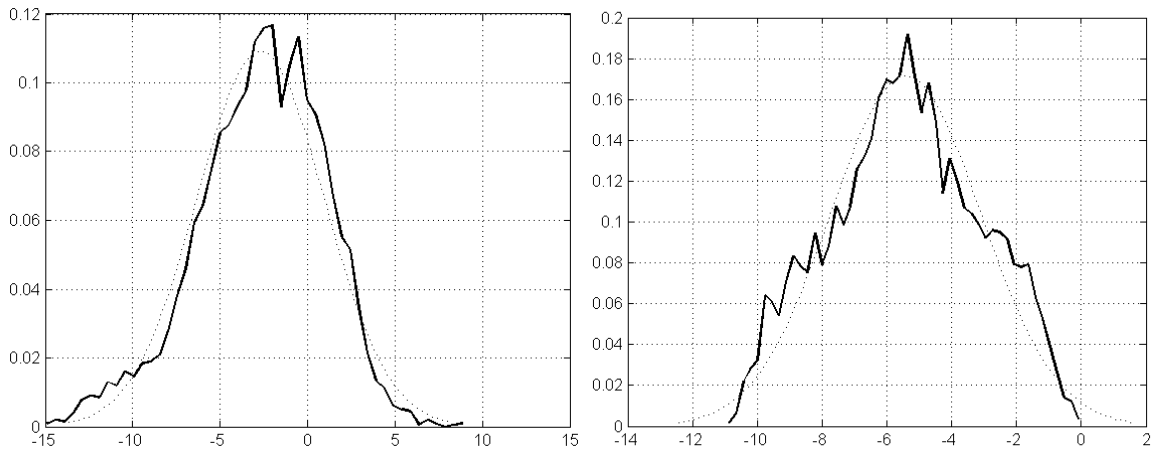


Fig. 4: Systematic deviation of INFORM angle depending on the load – a correction function is used, sensorless operation



mean value =-2,69° el. , standard deviation = 3,65° el. mean value =-5,42° el. , standard deviation = 2,33°

Fig. 5: a) Statistical distribution of the angular position error at 3% rated speed – low speed
b) Statistical distribution of the rotor angular position error at 40% rated speed (ω_m=0,4) – high speed

A good quality criterion about the sensorless properties especially including transient operation is given by a load step from minimum to maximum load and vice versa. The results are given in the following Fig. 6.

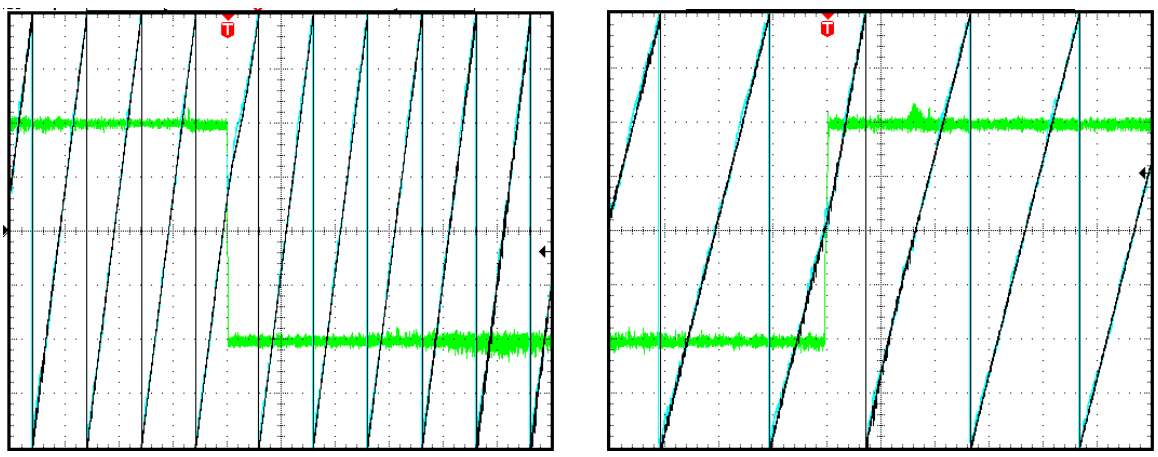


Fig. 6: Load-step from iq=2 to iq=-2 (maximum to minimum) and vice versa at rated speed of 10%
Ch1: angle of position encoder
Ch2: sensorless position
Ch4: load (I_{qmax}=2)

Sensorless Operation, Measurement Results in the Full Speed Range

After having tested the INFORM range, showing good static and transient quality in sensorless mode, the full speed range including the change between INFORM and EMF models is tested. A severe test is to change speed from positive rated speed to negative rated speed allowing full torque production at low speed (double the rated torque). Fig. 7 shows such a speed change. The reference position obtained by the mechanical position encoder gives information about the quality of the estimated sensorless angular position. As mentioned above the estimated rotor angular position yields non-ideal results and deviates from the mechanical angular position encoder. The calculated rotor position contains an additional noise which results especially from the current measurement and measurement inaccuracies.

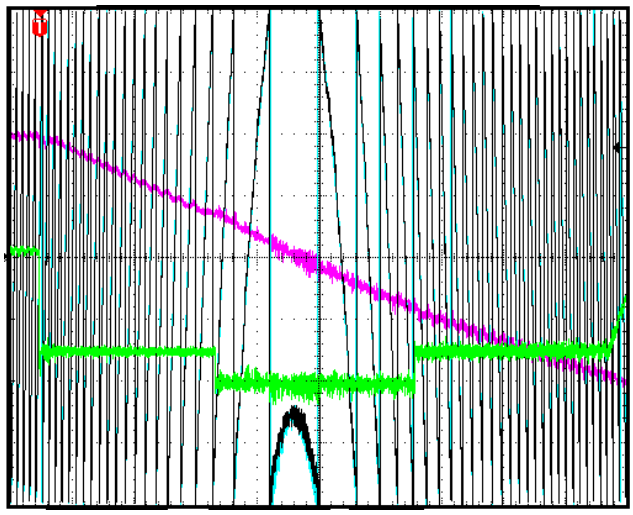


Fig. 7: Sensorless step from rated speed (*w=1.0)* to negative rated speed (w = -1,0) with maximum load of ($|i_{qmax}|$=1,5 at higher speed – using EMF-model and $|i_{qmax}|$=2 at low speed – using INFORM-measurement).
CH1(black): sensorless position (INFORM at low speed / EMF-model at higher speed)
CH2(blue): reference position from the mechanical position encoder
CH3(red): sensorless speed
CH4(green): iq_{meas}, measured load

Conclusion

A standardized control scheme based on a simple mechanical observer structure with INFORM- and EMF- measurement entrance has been be presented. The back EMF model is active during the whole operating range and is stabilized by the observer feedback loop. This model can be evaluated with respect to INFORM and EMF properties. The INFORM quality is measured by statistical parameters in the whole operating range. As an example, the procedure is implemented on an industrial PM motor drive (5 kW).

References

[1] Rajashekara, K., Kawamura, A., Matsuse, K. (editors); "Sensorless Control of AC Motor Drives" (Selected reprints), IEEE Press, New York, 1996. ISBN 0-7803-1046-2.
[2] Johnson, J.P., Ehsani, M., Güzelgünler, Y.; "Review of Sensorless Methods for Brushless DC", IEEE-IAS meeting 1999, pp. 143-150.
[3] Staebler, M.; "Sensorless control algorithms for AC motors – Overview and DSP implementation", Proc. PCIM 2000, Vol. "Intelligent Motion", Nuremberg, Germany, 2000, pp. 105-111.
[4] Schroedl M.; "Detection of the Rotor Position of a Permanent Magnet Synchronous Machine at Standstill", International Conference on Electrical Machines, ICEM, Italy, 1988
[5] Sepe R.B., Lang J.H.; "Realtime observer-based (adaptive-control of a permanent-magnet synchronous motor without mechanical sensor", IEEE Trans. Ind. Appl., Vol. 28, No.6, 1992
[6] Corley M; Lorenz R.; "Rotor position and velocity estimation for permanent magnet synchronous machines at standstill and high speed", IEEE IAS Conf. Proc. 1996, S.36-41.
[7] Schroedl M., Hofer M., Staffler W.; "Combining INFORM method, Voltage model and mechanical observer for sensorless control of PM Synchronous Motors in the whole speed range including standstill", PCIM, Nuremberg, Germany, 2006.
[8] Schrödl M.; "Sensorless Control of AC machines", Habilitationsschrift, VDI-Fortschrittsberichte Nr. 117, Reihe 21 (1992).
[9] Schrödl M; "Statistic Properties of the INFORM – Method in Highly Dynamic Sensorless PM Motor Control Applications Down to Standstill", European Power Electronics and Drives (EPE Journal), Vol. 13, Nr. 3 (Juni-July-August 2003), S. 22-29.
[10] Ferreira C.O., Kennel R.; "Encoderless Control of Industrial Servo Drives", EPE-PEMC, Portoroz-Solvenia, 2006.