New self sensing scheme based on INFORM, heterodyning and Luenberger observer

Sigurd Ovrebo, Student member IEEE, Roy Nilsen
Norwegian University of Science and Technology, 7491 Trondheim, Norway

Abstract—Self sensing techniques for AC machines has been a research topic for almost two decades. Two promising methods are found in injection of high frequency carrier [1-8] and the INFORM method [9-13]. Booth schemes are based on utilization of saliency in order to make position estimate. The excitation and signal processing for these methods differs. A new scheme based on the INFORM measurements a tracking observer found in [1-6] is presented. The new scheme gives the modified INFORM method a close to zero phase lag in rotor position estimate. The new scheme is implemented and evaluated with a 32 kW IPMSM.

Index Terms—self sensing, sensorless control, PMSM, INFORM

I. INTRODUCTION

Sensorless control of electric machines has been a research topic for more than two decades. The objective for this work is to eliminate the need for a position sensor by using the machine as the position sensor. The position sensor and cable connection has been a source of failure for motor control applications. For small drives the sensor contributes considerable to the overall cost. Sensorless control is divided into two speed regions; a high speed region and a low speed region. In the high speed region the back EMF can be used for the rotor position estimate. In the low and zero speed region he back EMF becomes too small for position estimation. In this region second order effects in the machine are often use in order to make a position estimate. Two excitation methods successfully extract rotor position information; injection of high frequency sinusoidal signal (HFCI-High Frequency Carrier Injection) and the INFORM (INdirect Flux detection by On-line Reactance Measurement) method. The methods use the same phenomena; the saliency present in the machine. In this paper a new scheme based on INFORM excitation [13] and a tracking observer [1-6] is presented.

Nomenclature:

\( f_c \) - carrier signal frequency in per unit
\( u_{sc} \) - carrier signal voltage, rotor ref frame in per unit
\( X_s' \) - stator inductance matrix, rotor ref frame in per unit
\( I_{sc}' \) - stator carrier current, rotor ref frame in per unit
\( \omega_n \) - reference speed
\( \theta \) - rotor position
\( n \) - rotor speed in per unit

II. THE EXISTING SCHEMES

A. Injection of High Frequency Carrier Signal (HFCI)
The scheme based on injection of a balanced three-phase high frequency carrier voltage [1-8] adds a voltage component to the fundamental excitation.

The current response from the carrier voltage is filtered off with a synchronous filter. The high frequency response can be described as:

\[
0_c' = j \cdot n \cdot x_s' \cdot i_{sc}' + x_s' \cdot \frac{di_{sc}'}{\omega_n} \cdot \frac{dt}{dt} \quad (1)
\]

The current can be expressed as

\[
I_{sc}' = i_{sc} e^{j(\omega_n f_c - \omega_n t)} \quad (2)
\]

In steady state (1) can be written as

\[
u_{sc}' = j \cdot f_c \cdot x_s' \cdot i_{sc}' \quad (3)
\]

![Fig.1. High Frequency injection of balanced three-phase voltage](image-url)
\[
\mathbf{j} = \begin{bmatrix}
0 & -1 \\
1 & 0
\end{bmatrix}
\] (4)

The inverse matrix if the inductance is introduced when stator current is derived from (3)
\[
\dot{\mathbf{i}}_{sc}^r = \frac{1}{f_c} \mathbf{j}^{-1} \cdot \mathbf{u}_{sc}^r
\] (5)

Transforming (5) into stationary reference frame gives one positive and one negative rotating term in the current response [2].
\[
\begin{align*}
L_{sc}^x &= \begin{bmatrix}
i_{scx} \\
i_{scb}
\end{bmatrix} = i_{sp} \cdot \begin{bmatrix}
\cos(\omega_n t) \\
\sin(\omega_n t)
\end{bmatrix} + i_{cn} \cdot \begin{bmatrix}
\cos(-\omega_n t + 2\theta) \\
\sin(-\omega_n t + 2\theta)
\end{bmatrix} \\
\omega_c &= \omega_n \cdot f_c \\
i_{sp} &= \frac{u_{scx}}{f_c} \sum x \cdot \frac{x^2 - (\Delta x)^2}{\sum x^2} \\
i_{cn} &= \frac{u_{scx}}{f_c} \Delta x \cdot \frac{x^2 - (\Delta x)^2}{\sum x^2} \\
\sum x &= x_q + x_d \\
\Delta x &= x_q - x_d
\end{align*}
\] (6-11)

For an IPMSM (Interior Permanent Magnet Synchronous Machine) with a single saliency the current response is elliptic (\(\alpha vs. \beta\) plot). The major axis of the ellipse gives the double rotor position. There are several ways of extracting the rotor position from the high frequency current response [1-8]. The saliency in an IPMSM is mainly due to rotor geometry and stator teeth saturation. These saliencies are in the same regions of the machine and can be observed as a single saliency.

### B. Tracking Observer

In [1-6] the positive high frequency and fundamental current are filtered off, leaving only the negative rotating component of the high frequency current. This current forms a vector rotating with double the rotor frequency. A heterodyning term is used to give an error signal into a Luenberger style observer that tracks the position. This scheme is called a tracking observer. The speed is estimated as an internal state.

\[
\begin{align*}
\frac{d\dot{\mathbf{i}}_{sc}^r}{dt} &= \frac{\omega_n}{\sum x^2 - (\Delta x)^2} \cdot \left(\sum x \cdot \Delta x \cdot e^{-/2\theta}\right) \cdot \mathbf{u}_{sc}^r
\end{align*}
\] (13)

During the measurements for \(b\) and \(c\) phase the position dependent term in (13) gets a offset in accordance to (17) and (18). The constants \(y_0\) and \(\Delta y\) are defined as:
\[
y_0 = \frac{\sum x}{\sum x^2 - \Delta x^2}
\] (14)

The feed forward term \(m_i\) in the physical model gives the observer zero phase lag position estimate [14].

### C. INFORM method

The INFORM method [9-13] uses the derivatives of the stator current to form a position dependent expression. For comparison, the expressions are presented in an alternative notation compared to [9] and [10]. The back EMF is removed from the stator voltage equation as in the measurements, and the resistive voltage drop is neglected. The derivative of the stator current can be described by introducing the inverse of the inductance matrix from (1) and representing the equation in stator stationary reference frame.

\[
\begin{bmatrix}
\dot{x}_s^x \\
\dot{x}_s^y
\end{bmatrix} = \begin{bmatrix}
\sum x & 1 \\
0 & 1
\end{bmatrix} \begin{bmatrix}
x_s^x \\
x_s^y
\end{bmatrix} + \begin{bmatrix}
\Delta x & -\Delta x \\
-\Delta x & \Delta x
\end{bmatrix} \begin{bmatrix}
\cos 2\theta & -\sin 2\theta \\
-\sin 2\theta & \cos 2\theta
\end{bmatrix} \begin{bmatrix}
\mathbf{u}_s \\
\mathbf{u}_s^x
\end{bmatrix}
\] (12)

During the three measurements series the stator reference frame is oriented in the respective phase directions. (12) can be simplified as only \(u_{sc}^x = u_{s}\) (\(u_{sc}^y = 0\)). The stator current derivative in phase \(a\) then becomes (voltage vector is applied in phase \(a\) direction):

\[
\frac{d\dot{i}_s^a}{dt} = \frac{\omega_n}{\sum x^2 - (\Delta x)^2} \cdot \left(\sum x \cdot \Delta x \cdot e^{-/2\theta}\right) \cdot \mathbf{u}_{sa}^r
\] (13)

During the measurements for \(b\) and \(c\) phase the position dependent term in (13) gets a offset in accordance to (17) and (18). The constants \(y_0\) and \(\Delta y\) are defined as:

\[
y_0 = \frac{\sum x}{\sum x^2 - \Delta x^2}
\] (14)
\[ \Delta y = \Delta x \left( \sum x \right)^{-2} - (\Delta x)^{-2} \]  

(15)

If a fixed time \( \Delta t \) is used for the INFORM measurements the delta currents are:

\[ \Delta i_{r1} = \omega_n \cdot \Delta t \cdot u_\phi \left[ y_0 - \Delta y \cdot \cos(2\theta) \right] \]  

(16)

\[ \Delta i_{r2} = \omega_n \cdot \Delta t \cdot u_\phi \left[ y_0 - \Delta y \cdot \cos(2\theta - 4\pi / 3) \right] \]  

(17)

\[ \Delta i_{r3} = \omega_n \cdot \Delta t \cdot u_\phi \left[ y_0 - \Delta y \cdot \cos(2\theta - 2\pi / 3) \right] \]  

(18)

In [6] two expressions for the double rotor position are presented. Both expressions are independent of machine parameters.

Using only the real part of the currents:

\[ \zeta_{RE} = \Delta i_{r1} + \Delta i_{r2} \cdot e^{\frac{2\pi}{3}} + \Delta i_{r3} \cdot e^{\frac{2\pi}{3}} \]  

(19)

Using the imaginary parts of the currents:

\[ \zeta_{IM} = (-\Delta i_{r1} + \Delta i_{r2} - \Delta i_{r3} + \Delta i_{r2}) + j\sqrt{3} (\Delta i_{r1} - \Delta i_{r2} + \Delta i_{r2} - \Delta i_{r3}) \]  

(20)

\( \zeta_{RE} \) and \( \zeta_{IM} \) are rotating vectors forming a circle, where the vector describes the double rotor position. In [9] the argument of \( \zeta_{RE} \) and \( \zeta_{IM} \) are used as correction terms in a Kalman filter.

D. INFORM method integrated in PWM

In [9] the INFORM measurements was performed in three different ways. The criterion for excitation was the commanded voltage vector. At very low commanded voltage a series of vector voltages was included in the zero vectors (fig.3). At higher commanded voltage the INFORM samples were performed from the natural variation in the space vector. When the commanded voltage vector was close to the basis vectors a third transient excitation was given.

Control signals for the upper switches in the converter legs are shown in fig. 3. The transient excitation given is an excitation in the a-phase direction. The small pulses in intervals t1-t2 and t4-t5 are made to reduce the current vector deviation during the measurements.

III. NEW SCHEME

The new scheme is based on INFORM excitation found in [13] where the transient excitation is integrated in the zero vector. In contrast to the basic INFORM method the new scheme make a position estimation based on one measuring sequence and an offset. Transient excitation is only used in phase a direction. The saliency tracking methods found in [1-6] are used to obtain speed and position estimates.

The basic idea for estimation of the position based on one measuring sequence is: the online estimation of direct and quadrature axis inductance are already made in order to optimize the torque per amp trajectory [14]. In the standard derivation of the position, two measurements must be performed. In order to get a good position estimate the change of position between two measurements must be compensated for. In the new scheme this is not necessary. Instead, the almost constant offset term is used and the position can be obtained with only one transient excitation sequence.

In the higher speed region the back EMF should be used for the position and speed estimation. The scheme presented in this paper will only be used for very low and zero speed. In the low speed region the stator voltage is small due to the small back EMF. The excitation in fig.3 is used for this speed region. The transient excitation is applied in every switching period in order to give the scheme maximum bandwidth. This is merely performed in order to compare the scheme with the HFCI (High Frequency Carrier Injection) based methods. In an industrial application the transient excitation could be used in intervals of the switching period.
The current is sampled at time instances \( t_2, t_3 \) and \( t_4 \) in Fig. 3. The delta currents are formed as (same for all three phases):

\[
\begin{align*}
\Delta i_{sa,1} &= i_{sa}(t4) - 2 \cdot i_{sa}(t3) + i_{sa}(t2) \\
\Delta i_{sb,1} &= i_{sb}(t4) - 2 \cdot i_{sb}(t3) + i_{sb}(t2) \\
\Delta i_{sc,1} &= i_{sc}(t4) - 2 \cdot i_{sc}(t3) + i_{sc}(t2)
\end{align*}
\]  

(21)

(22)

(23)

The three delta values in (21), (22) and (23) are combined in order to get the imaginary and real part of the \( \frac{di_s}{dt} \) trajectory.

\[
\begin{align*}
\text{Re}(\Delta i_s) &= \Delta i_{sa,1} - 0.5 \cdot (\Delta i_{sa,1} + \Delta i_{sb,1}) \\
\text{Im}(\Delta i_s) &= \frac{\sqrt{3}}{2} (\Delta i_{ha} - \Delta i_{c1}) \\
\xi &= (\text{Re}(\Delta i_s) - \text{offset}) + j \cdot \text{Im}(\Delta i_s)
\end{align*}
\]  

(24)

(25)

(26)

Fig. 4 shows \( \frac{di_s}{dt} \) trajectory in the complex plane. The trajectory forms a circle located on the real axis with an offset determined of the constant part of the inverse inductance terms. The pulse width of the transient excitation is held constant and the current changes are used to estimate the position.

The complex vector is normalized before entering the heterodyning process. This makes the tuning of the observer easier as the amplitude of the \( \xi \) does not have any impact on the roots of the observer. Normalizing can only be used if the machine has single saliency.

\[
c_{out} = \frac{\text{Re}(\xi)}{\sqrt{\text{Re}(\xi)^2 + \text{Im}(\xi)^2}}
\]  

(27)

In Fig. 5 an outline of the new scheme is presented. The scheme offers almost zero phase lag estimation of the rotor position for the INFORM based excitation. For a custom made drive the normalizing term should be removed. If the DC-link voltage changes or different type machines are used the normalized term minimize the commissioning of the drive.

Fig. 5. New scheme

\[
c_{\alpha} = \frac{\text{Im}(\xi)}{\sqrt{\text{Re}(\xi)^2 + \text{Im}(\xi)^2}}
\]  

(28)

IV. EXPERIMENTAL WORK

The setup used in the paper consists of a 32 kW IPMSM, a TMS320c2812 Texas instruments fixed point DSP with 12 bit AD converter. The machine data are given in Table 1. The DSP is still an early version and the ADC does not have the features promised from the supplier. The ADC has approximately 9 bit effective resolution and the conversion time had to be increased in order to get the ADC to function properly.

In Fig. 6 the trajectory of \( \frac{di_s}{dt} \) is presented. A single saliency is clearly present.

Fig. 6. \( \frac{di_s}{dt} \) trajectory in complex plane, \( n=0.1 \) pu
The tracking capability of the scheme is presented in fig.7. The reference speed is altered from 250 to -250 rpm.

The offset in the position estimate is a result of the initialization of the position sensor. The initialization is performed as one basic INFORM measurement [9] in all three phase directions. Since the initial estimate is only performed once the offset can be in the error band of the method. The error band is approximately +/- 5 electrical degrees

In [8] and [6] the impact of transient operation is discussed. Fig.8 shows the complex vector \( \vec{c} \) during a 500 rpm step in the speed command. There are several sources for distortion of the complex vector \( \vec{c} \). In the experimental setup there are no antialiasing filters on the current measurements. During the transient operation there is additional noise on the current measurements. A possible improvement would be over sampling of the delta currents in order to filter the sampled currents.

The tracking of the rotor position has not failed at any transient condition on the lab, even a full 1 pu step in the speed is tracked without problems.

The speed term from the tracking observer had considerably noise content. A second order Butterworth filter, with a cut off frequency at 50 Hz, was used to filter out the noise. Fig. 9 shows a bandwidth test for the setup. A 25Hz alternating reference was feed into the q-axis current regulator. The accuracy of the speed estimation in fig.9 is approximately +/- 3 % of rated speed.

The reason for the relative low bandwidth lies in the shape of the complex vector \( \vec{c} \). In fig. 10 there are offsets and gain errors that will have impact on the estimated speed. There is also a term varying with one theta, this is apparent in fig. 10 indicated by the dotted line W.

Quality improvement of the complex vector \( \vec{c} \) is a subject for future work.
A speed estimate based on the position output from the observer was implemented. The speed estimation was updated with the same time interval as the speed regulator. The speed estimate was only based on the change in position over 4 ms. This gives a 250 Hz update of the speed estimate. Fig.11 show the bandwidth of this implementation. The bandwidth was doubled compared to the observer based estimate. The speed estimate accuracy in fig.11 is approximately +/- 2.5 % of rated speed.

V. CONCLUSIONS

A new scheme with INFORM based excitation [13] and tracking observer [1-6] is presented. The transient excitation is integrated in the PWM pattern. The scheme is supposed to be combined with a high speed algorithm based on back EMF. The operating range for the new scheme will only be in the low and zero speed region. In the low speed range the transient excitation will be applied in intervals of the switching period.

The new scheme offers (in the actual setup with no load):

- Double rotor position estimate from one transient excitation sequence (given that the inductance is estimated online)
- Position estimate with approximately +/- 5 electrical degrees accuracy
- Close to zero phase lag on the position estimate [14]
- 50 Hz bandwidth on speed estimation and approximately +/- 2.5 % accuracy referred to rated speed.
- Easier implementation compared to the standard INFORM method [11]
- Possibilities for multiple saliency tracking [2]

REFERENCES

