

ISEM²⁰¹³ 

International Symposium on Applied
Electromagnetics and Mechanics

Abstract Book of the 16th edition of the
**International Symposium on Applied
Electromagnetics and Mechanics**

International Conference

and of the 7th IWASPNDI Workshop

July 31st - August 2nd, 2013, Québec City (Canada)

Conference officially hosted by



**UNIVERSITÉ
LAVAL**

Conference organized by

*Canada Research Chair on Multipolar Infrared Vision Infrarouge Multipolaire (MIVIM)
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É. du CAO

*à la frontière des connaissances
at the cutting edge of knowledge*

Sensorless Field Oriented Control using back-EMF and flux observer for a surface mounted permanent magnet synchronous motor

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Abstract. This paper proposes a Sensorless Field Oriented Control for surface mounted permanent magnet synchronous motor combining two approaches for different rotor speed ranges. The active flux observer is applied at low speed and combined with a back-EMF observer at high speed. This combination allows for an improvement of the rotor position estimation for a large speed range and is therefore resulting in a higher stability of the sensorless control scheme when compared to the conventional back EMF method. The presented approach is discussed based on simulations.

Keywords: back-EMF, Flux observer, permanent magnet synchronous motor, sensorless speed control

1. Introduction

The sensorless control for the electrical machines has become an important part of research and is playing a particular role in industry because of its reliability and low cost. For high speed operation of the motor, e.g. back-EMF [1][2][10] is employed for the speed estimation. However, it is troublesome for sensorless control at low speed. Many approaches have already been successfully employed. One of the most used methods is high frequency signal injection [5][6-9].

In [7] at low speed, the rotor position is obtained from a predefined ramp function of the rotor speed, because the rotor position is the integral of the rotor speed. After the rotor ramps up with a constant q-current along this predefined ramp from standstill to a fixed high speed range, the approach for low speed is switched to the one for high speed range, e.g. field oriented control.

Besides, an active flux concept [3]-[4] provides the speed estimation for interior permanent magnet synchronous motor (IPMSM) at low speed without signal injection. This paper introduces a novel approach, which is based on back-EMF and active flux. In this approach, the back-EMF and active flux observer can be switched at a predefined speed level to achieve the sensor less control over the entire speed range. Additionally, a study of a reduced active flux approach is presented here, which is applied to a surface mounted permanent magnet synchronous motor (SMPMSM).

2. Position estimation by back-EMF observer

Fig. 1 shows the proposed sensorless speed control scheme of PMSM: the stator currents $(i_a, i_b, i_c)^T$ are measured and voltages $(u_\alpha, u_\beta)^T$ are calculated from the measured voltages $(u_a, u_b, u_c)^T$. Rotor speed ω and rotor position θ are estimated by the observer. The active flux and back-EMF are switched at a predefined speed. Due to the linear independence of the currents in dq coordinates, it is possible to control both current components separately.

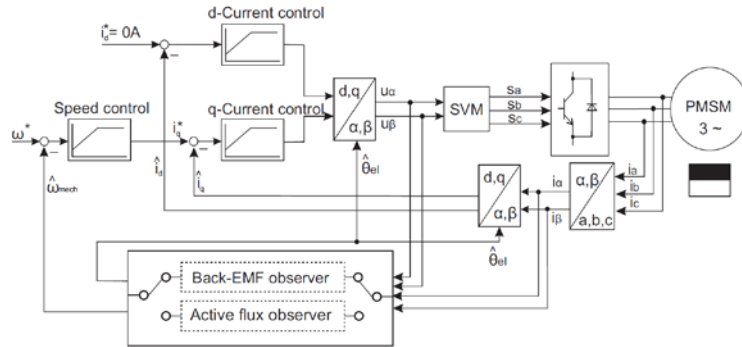


Fig. 1. Sensorless control scheme of PMSM.

2.1. Active flux observer

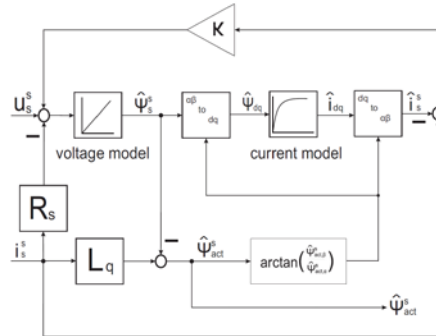


Fig. 2. Active flux observer.

The active flux observer model, which is consisting of a voltage model and a current model (Fig. 2), is suitable for rotor speed and rotor position estimation at low speed range. The stator current $i_s^s = (i_\alpha, i_\beta)^T$ and the stator voltage $u_s^s = (u_\alpha, u_\beta)^T$ in the α - β coordinate system are conversant and they represent the input signal of the observer. These quantities are converted from measured stator current $(i_a, i_b, i_c)^T$ and stator voltage $(u_a, u_b, u_c)^T$.

Active flux observer model using a fixed α - β coordinate system can be represented by [4]

$$\begin{pmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{pmatrix} = T^{-1}(\hat{\theta}) \begin{pmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{pmatrix} T(\hat{\theta}) \begin{pmatrix} \hat{\Psi}_\alpha \\ \hat{\Psi}_\beta \end{pmatrix} + \frac{\Psi_F}{L_d} \begin{pmatrix} \cos(\hat{\theta}) \\ -\sin(\hat{\theta}) \end{pmatrix}, \quad (1)$$

$$\frac{d}{dt} \begin{pmatrix} \widehat{\Psi}_\alpha \\ \widehat{\Psi}_\beta \end{pmatrix} = -R_s \cdot \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} + \begin{pmatrix} u_\alpha \\ u_\beta \end{pmatrix} + K \begin{pmatrix} i_\alpha - \widehat{i}_\alpha \\ i_\beta - \widehat{i}_\beta \end{pmatrix} \quad (2)$$

where

$$\begin{pmatrix} u_\alpha \\ u_\beta \end{pmatrix} = R_s \cdot \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} + \frac{d}{dt} \begin{pmatrix} \widehat{\Psi}_\alpha \\ \widehat{\Psi}_\beta \end{pmatrix} \quad (3)$$

is the voltage equation, $(i_\alpha, i_\beta)^T$ is calculated from $(i_a, i_b, i_c)^T$. The estimated current, voltage and flux are $(\widehat{u}_\alpha, \widehat{u}_\beta)^T, (\widehat{i}_\alpha, \widehat{i}_\beta)^T, (\widehat{\Psi}_\alpha, \widehat{\Psi}_\beta)^T$. The parameters R_s and $L_d = L_q$ are stator resistance and inductance. The current estimation error

$$e_i = \begin{pmatrix} \widehat{i}_\alpha \\ \widehat{i}_\beta \end{pmatrix} - \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} \quad (4)$$

is fed back to voltage model and weighted by constant K . The active flux is defined as

$$\begin{pmatrix} \widehat{\Psi}_{act,\alpha} \\ \widehat{\Psi}_{act,\beta} \end{pmatrix} = \begin{pmatrix} \widehat{\Psi}_\alpha \\ \widehat{\Psi}_\beta \end{pmatrix} - L_q \cdot \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix}. \quad (5)$$

Subsequently, the rotor position can be estimated applying

$$\widehat{\theta}_{el} = \arccos \left(\frac{\widehat{\Psi}_{act,\beta}}{\sqrt{\widehat{\Psi}_{act,\alpha}^2 + \widehat{\Psi}_{act,\beta}^2}} \right) + n \cdot \pi, \quad (6)$$

with $n = N_p$.

2.2. Observer stability analysis

The stability of the observer has already been proved in [11]. The estimated errors can be described as

$$\dot{i}_{s,e}^s = -C \cdot \Psi_{s,e}^s \quad (7)$$

with

$$C = T^{-1}(\widehat{\theta}) \begin{pmatrix} 1 & 0 \\ L_d & 1 \\ 0 & L_q \end{pmatrix} T(\widehat{\theta}). \quad (8)$$

The state error dynamics are given by

$$\frac{d}{dt} \Psi_{s,e}^s = -K \cdot i_{s,e}^s = -KC \cdot \Psi_{s,e}^s. \quad (9)$$

With $\Psi_{s,e}^s$, a Lyapunov candidate function and its derivative are defined as

$$V = \frac{1}{2} \Psi_{s,e}^s T \Psi_{s,e}^s > 0 \quad (10)$$

$$\dot{V} = \frac{d}{dt} V = \Psi_{s,e}^s T \frac{d}{dt} \Psi_{s,e}^s = -\Psi_{s,e}^s T KC \Psi_{s,e}^s. \quad (11)$$

With every positive eigenvalues of KC , \dot{V} is smaller than zero and the observer is stable.

2.3. Back-EMF using Luenberger observer

The Back-EMF method is applied at high speed operation. The observer model of the PM synchronous motor is presented in state space form. In a fixed α - β coordinate system it can be represented by

$$\underline{y} = \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \cdot \underline{x} \quad (12)$$

$$\dot{\underline{x}} = \frac{d}{dt} \begin{pmatrix} i_\alpha \\ i_\beta \\ u_{p\alpha} \\ u_{p\beta} \end{pmatrix} = \begin{pmatrix} -\frac{R_s}{L_s} & 0 & -\frac{1}{L_s} & 0 \\ 0 & -\frac{R_s}{L_s} & 0 & -\frac{1}{L_s} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cdot \underline{x} + \begin{pmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \cdot \underline{u}, \quad (13)$$

where $u_{p\alpha}, u_{p\beta}$ denotes the back-EMF and the state vector \underline{x} can be determined by Luenberger observer[1] with its observer gain \underline{L} . The rotor position reads as [2]

$$\hat{\theta}_{el} = \arccos\left(\frac{u_{p\beta}}{\sqrt{u_{p\alpha}^2 + u_{p\beta}^2}}\right) + n \cdot \pi. \quad (14)$$

The angular speed can be expressed by

$$\omega_{el} = \frac{d\hat{\theta}_{el}}{dt}. \quad (15)$$

Since the measurements are contaminated by stochastic signal noise, a low pass filter is employed.

3. Results

3.1. Specifications of the machine

The parameters of the permanent magnet synchronous machine are shown in Table 1. The main specifications of the machine are measured, e.g. standstill torque T_0 , stator resistance R_s , Stator inductance (quadrature axis) L_q and stator inductance (direct axis) L_d .

Table 1
Specifications of the permanent magnet synchronous machine

Parameters and constraints	Value
Number of pole pairs p	4
Maximum speed n_{max}	2000 [rpm]
Rated speed n_N	4500 [rpm]
Rated power P_N	10.3 [kW]
Rated phase to phase voltage U_N	380 [V]
Maximum permitted motor current I_{max}	75 [A]

Rated motor current I_N	21.2 [A]
Maximum torque T_{max}	67 [Nm]
Rated torque T_N	49.2 [Nm]
Mass moment of inertia J	$60 \cdot 10^{-3}$ [kg·m ²]
Stator resistance R_s	0.2 [Ω]
Stator inductance (quadrature axis) L_q	0.005 [H]
Stator inductance (direct axis) L_d	0.005 [H]
Excitation flux ψ_F	0.2735 [Vs]
Time constant (quadrature axis)	0.025 [H/ Ω]
$t_q = L_q/R$	
Time constant (direct axis) $t_d = L_d/R$	0.025 [H/ Ω]
Coefficient of friction μ	0

3.2. Control and estimation results

At high speed operation, an overshoot occurs due to the switch between the two approaches for rotor position estimation in Fig. 3a at ca. 0.05 second. The same effect is also seen in Fig. 3b with a reference value at 150 rad/s: back-EMF observer is activated instead of active flux observer at 30 rad/s.

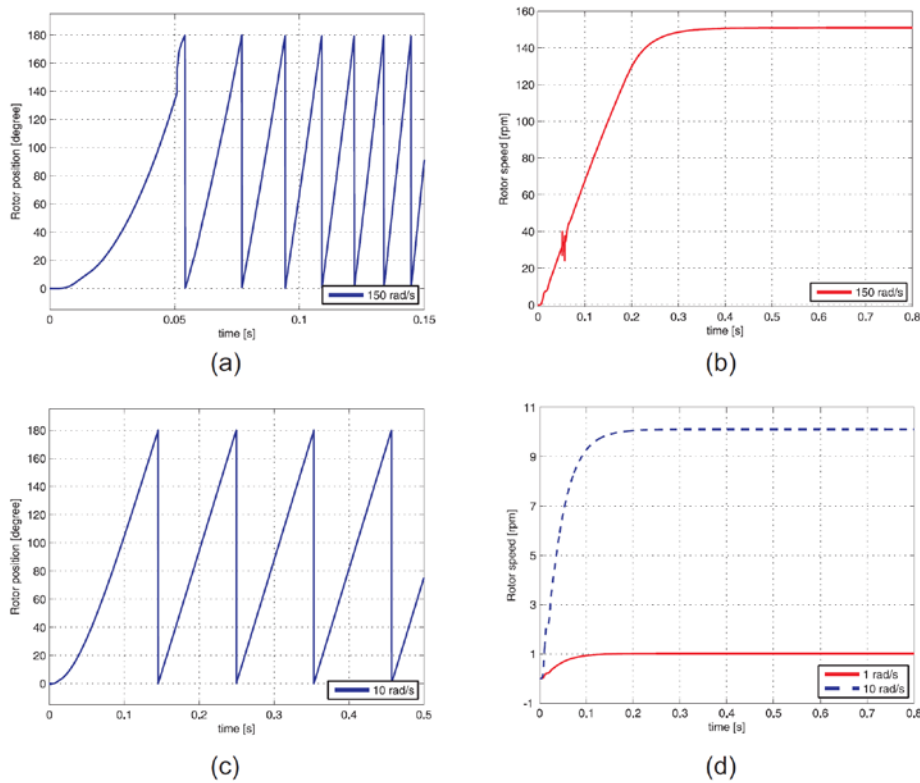


Figure 3: Position observer.

The performance of the sensorless controller at low speed are presented in Fig 3d: At low speed, only the active flux observer is employed. Hence, a switch is not necessary. The result from the arccos function of the position observer at low speed, which has zigzag trajectory between 0 and 180°, is plotted

in Fig. 3c for 10 rad/s. The current rotor position can be calculated using (9) and will be appropriated for the Park's transformation (Fig.1). The speed control results at low speed 1 rad/s and 10 rad/s are presented in Fig 3d, which show that active flux observer suits for the rotor speed and position estimation at low speed very well. The results show that the observer is asymptotically stable, which verifies the theoretical conclusion in the previous section.

4. Conclusions

It can be concluded from the results that the scheme discussed provides an accurate and robust position and speed estimation. In comparison to the conventional back-EMF method the presented combination allows for a higher accuracy, particularly in the low speed operation range. Furthermore, the active flux observer is suitable for position and speed estimation at low speed of SMPMSM with machine's non-saliency ($L_d=L_q$) as well.

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