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Sensorless field oriented control of a PM motor including zero speed

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Abstract— **This paper presents a simple control method for controlling permanent magnet synchronous motors (PMSM) in a wide speed range without a shaft sensor. The method estimates the stator flux by integration of the measured BEMF signal. To compensate for the offset in the BEMF the offset is estimated. The control method is made robust at zero and low speed by changing the direct vector current component to a value different from zero. In order to verify the applicability of the method the controller has been implemented and tested on a 800 W motor.**

NOMENCLATURE

a	complex spatial operator $e^{j2\pi/3}$
$i_{sA,B,C}$	stator phase currents A,B and C
$u_{sA,B,C}$	stator phase voltages A,B and C
i_s	stator current complex space vector
u_s	stator voltages complex space vector
ψ_s	stator flux
ψ_r	rotor flux
R_s	stator resistances
L_s	stator inductance
ω	rotor speed
p	time derivative operator d/dt
Z_p	number of pole pair

I. INTRODUCTION

The induction motor has in the past been the most deployed motor type on the industrial market but has in resent years been or will be penetrated by brush less PM motors. The reason for this has to be found in the increasing demand for operating systems as energy efficient as possible and the fact that PM motors have higher power density implying less material to transport. However, PM motors needs a measurement of the rotor position in order to control the motor in a robust way. PM motors cannot be operated in open loop due to the highly unstable behavior of the motor dynamics. The traditional method to determine the rotor position is to use an encoder or resolver, but these components are expensive and will add additional cost to the motor so it will not be competitive to the induction motor. In more than ten years there have been an extensive research in finding reliable position sensorless methods to estimate the rotor position from the applied voltages and the consumed currents. The most significant papers of the research up to 1996 can be found in the reference [3]. There are basically two types of brushless PM motors, namely the BLDC type and the PMSM type. In the BLDC type the rotor position is determined by BEMF sensing in 60 degrees tri-state intervals. However in this article focus will be on PMSM type of motor due to the fact that the results are mend for low noise emission applications like pumps for domestic use. In PMSM solutions the rotor position is nor-
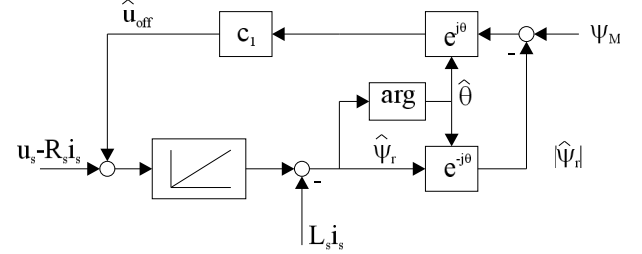

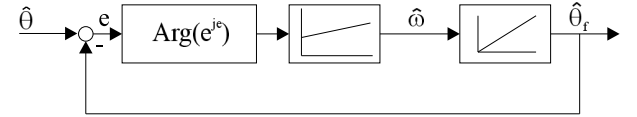Fig. 1 – *Rotor angle observer*

Fig. 2 – *Speed estimator*

mally determined by an open loop or closed loop observer see [4] or by voltage injection methods exciting saliency or saturation effects in the motor see [1] ,[6] and [7] . An open loop observer that estimates the rotor position from an integration of the BEMF signal will in the paper be extended in order to perform more robust estimation with respect to bias and inverter non-linearity's. A similar observer type have in [2] been reported for flux estimation in induction motor drives.

At start up no BEMF is presented, which means that the position of the rotor is unknown and cannot be used for control. Normally the start-up procedure operates the motor in open loop voltage control up to a given minimum speed where BEMF is reliable, and after this point a jump to observer based field-oriented control takes place. This jump can be noise full and can give extreme speed transients and pull out can in severe situations occur. In this paper a new bumpless method will be presented that operates from zero speed without changing the control structure. Different methods for performing bumpless transfer has been reported in literature and an extensive survey of different methods can be found in [5]. The idea in the method chosen is to force direct current into the machine in the faulty position the observer estimates; this will force the rotor position to the incorrect estimated position, and the difference between the real position and the estimated position will be reduced. In this situation the control strategy is the strongest, but as the motor speed increases the direct current is faded out, and will vanish when the aforementioned minimum speed has been
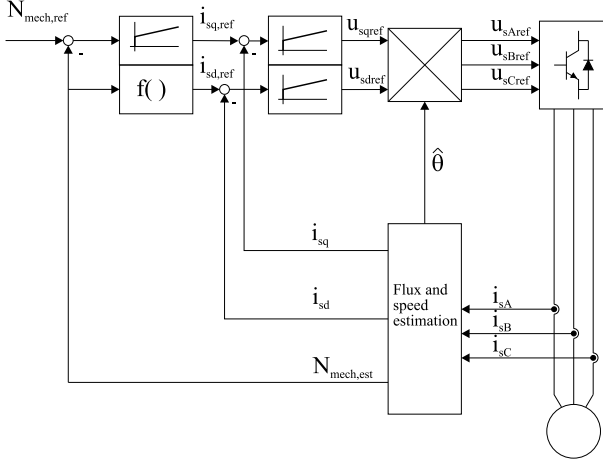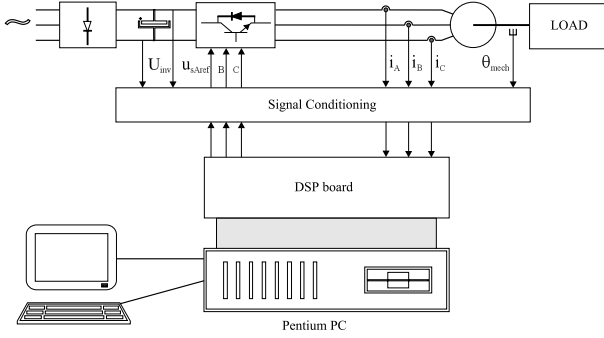
Fig. 3 – *Rotor Field Oriented Control*

Fig. 4 – *Laboratory setup*

reached. After the minimum speed has been reached the motor has become the strongest and the control system will now follow the motor.

II. PM MOTOR MODEL

The observer is based on the traditional PM motor model in a stator fixed reference frame, and a complex representation. Using complex space phasors for voltage and currents

$$
\begin{aligned}
i_s &= \tfrac{2}{3}(i_{sA} + a i_{sB} + a^2 i_{sC}) \\
u_s &= \tfrac{2}{3}(u_{sA} + a u_{sB} + a^2 u_{sC})
\end{aligned}
\tag{1}
$$

the dynamics for the motor is given by the following stator voltage equation and flux linkage equation

$$
\begin{aligned}
\frac{d\psi_s}{dt} &= u_s - R_s i_s \\
\psi_s &= L_s i_s + \psi_r \\
\psi_r &= \psi_M e^{j\theta}
\end{aligned}
\tag{2}
$$

where θ is the rotor angle. The electrical rotor speed is expressed from the mechanical rotor speed as

$$
\frac{d\theta}{dt} = \omega = Z_p \omega_{mech}
\tag{3}
$$

III. ROTOR FLUX OBSERVER DESIGN

The estimation of ψ_r given in (2) requires an open integration of the voltage equation and the unavoidable offsets contained in the inputs then make the output drift away. If the offsets are modelled as $\hat{u}_{off}$ the estimator for the rotor flux $\hat{\psi}_r$ is

$$
\begin{aligned}
\frac{d\hat{\psi}_s}{dt} &= = u_s - R_s i_s + \hat{u}_{off} \\
\hat{\psi}_r &= \psi_{Mref} \, e^{j\hat{\theta}}
\end{aligned}
\tag{4}
$$

where $\hat{u}_{off}$ has to be designed in a way leading to a flux estimate with constant amplitude $\left|\hat{\psi}_r\right|$. This is obtained for

$$
\begin{aligned}
\hat{\theta} &= \arg(\hat{\psi}_r) \\
\hat{u}_{off} &= c_1(\psi_{M,ref} - |\hat{\psi}_r|)e^{j\hat{\theta}}
\end{aligned}
\tag{5}
$$

giving an estimate of the rotor flux vector rotating close to a circular trajectory, as shown in the stability analysis. For known magnitude of the permanent magnet $\psi_{M,ref} = \psi_M$ the observer may be seen as an rotor field angle observer. A signal flow graph of the observer is shown in fig. 1. An estimate of the rotor speed may be obtained by

$$
\begin{aligned}
\frac{d\hat{\theta}_f}{dt} &= \hat{\omega} \\
\hat{\omega} &= K_p(1 - \tfrac{1}{T_i p}) \arg e^{j(\hat{\theta} - \hat{\theta}_f)}
\end{aligned}
\tag{6}
$$

with a signal flow graph shown in fig. 2.
The algorithm for the estimator then becomes

$$
\begin{aligned}
\frac{d\hat{\psi}_s}{dt} &= u_s - R_s i_s + c_1(\psi_{M,ref} - |\hat{\psi}_r|)e^{j\hat{\theta}} \\
\hat{\psi}_r &= \hat{\psi}_s - L_s i_s \\
\hat{\theta} &= \arg(\hat{\psi}_r) \\
\hat{\omega} &= K_p(1 - \tfrac{1}{T_i p}) \arg e^{j(\hat{\theta} - \hat{\theta}_f)} \\
\frac{d\hat{\theta}_f}{dt} &= \hat{\omega}
\end{aligned}
\tag{7}
$$

Fig. 3 shows the rotor field oriented control system. At zero and low speed the reference value for i_{sd} is given a value different from zero. If the rotor angle is estimated correctly a value for $i_{sd} \neq 0$ gives no torque. If the rotor angle is estimated with an error the rotor is forced in the direction of $\hat{\theta}$ used in the controller. This new principle means that no manual mode at zero and low speed is necessary, closed loop control is obtained for all values of the speed reference. The function for $i_{sd,ref}$ is

$$
i_{sd,ref} = i_{ref0} e^{-|\hat{\omega}_r|/\omega_0}
\tag{8}
$$

with (i_{ref0}, ω_0) experimentally determined.

IV. STABILITY ANALYSIS

From the more dense represented system model

$$
\begin{aligned}
\frac{d}{dt}(\psi_r + L_s i_s) &= u_s - R_s i_s \\
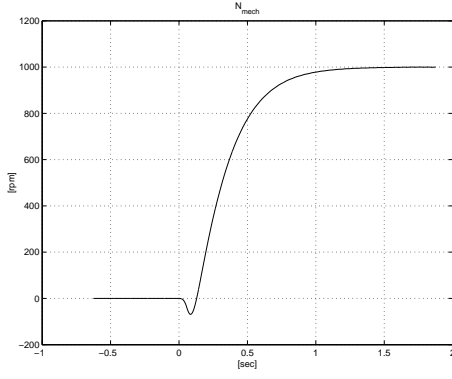\psi_r &= \psi_M e^{j\theta}
\end{aligned}
\tag{9}
$$

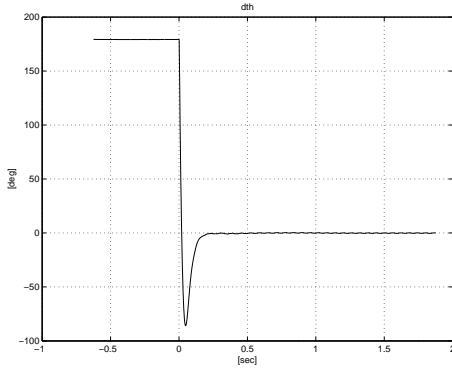Fig. 5 – *First Rotor speed step response with rotor angle initialized to an* 180 *degree error at startup*

Fig. 6 – *Convergense of the estimated rotor angle with rotor angle initialized to an* 180 *degree error at startup*

Fig. 7 – *Normal Rotor speed step response* $0 - 1000rpm$
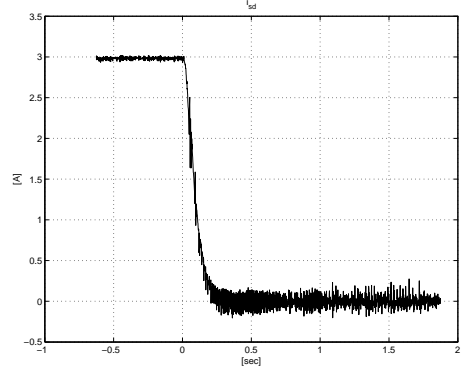
Fig. 8 – i_{sd} *response for* $i_{sd,ref}$ *function enabled*

and the estimator

$$
\begin{aligned}
\frac{d}{dt}(\hat{\psi}_r + L_s i_s) &= u_s - R_s i_s + c_1(\psi_{M,ref} - \hat{\psi}_M)e^{j\hat{\theta}} \\
\hat{\psi}_r &= \hat{\psi}_M e^{j\hat{\theta}}
\end{aligned}
\tag{10}
$$

we get the error model

$$
\frac{d}{dt}(\hat{\psi}_M e^{j\hat{\theta}} - \psi_M e^{j\theta}) = c_1(\psi_{M,ref} - \hat{\psi}_M)e^{j\hat{\theta}}
\tag{11}
$$

If this error model is transformed to a coordinate system rotating in the direction of the estimated rotor angle $\hat{\theta}$ we get

$$
(p + j\hat{\omega})(\hat{\psi}_M - \psi_M e^{-j\tilde{\theta}}) = c_1(\psi_{M,ref} - \hat{\psi}_M)
\tag{12}
$$

where $\hat{\omega} = \frac{d\hat{\theta}}{dt}$ and $\tilde{\theta} = \hat{\theta} - \theta$

Using the error variable $\tilde{\psi}_M = \hat{\psi}_M - \psi_M$ we get

$$
(p + j\hat{\omega})(\tilde{\psi}_M - \psi_M(1 - e^{-j\tilde{\theta}})) + c_1\tilde{\psi}_M = c_1(\psi_{M,ref} - \psi_M)
\tag{13}
$$

If it is assumed that $|\tilde{\theta}| \ll 1$ and we are using the scaled variables

$$
\begin{aligned}
\tilde{x}_M &= \tilde{\psi}_M/\psi_M \\
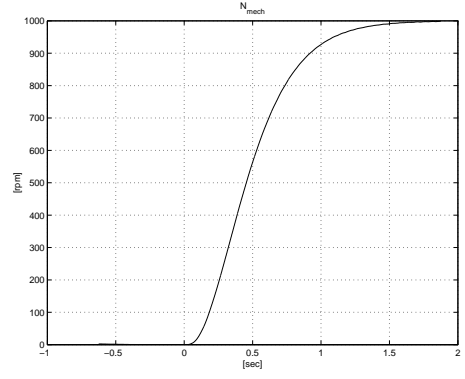\delta_M &= (\psi_{M,ref} - \psi_M)/\psi_M
\end{aligned}
\tag{14}
$$

the error model is reduced to

$$
(p + j\hat{\omega})(\tilde{x}_M + j\tilde{\theta}) + c_1\tilde{x}_M = c_1\delta_M
\tag{15}
$$

Taking real and imaginary parts gives,

$$
\begin{aligned}
p\tilde{x}_M + c_1\tilde{x}_M - \hat{\omega}\tilde{\theta} &= c_1\delta_M \\
p\tilde{\theta} + \hat{\omega}\tilde{x}_M &= 0
\end{aligned}
\tag{16}
$$

keeping in mind that the variables $\tilde{x}_M$ and δ_M are scalars. The solution

$$
\begin{aligned}
\tilde{x}_M &= \frac{c_1 p}{p^2 + c_1 p + \hat{\omega}^2}\delta_M \\
\tilde{\theta} &= \frac{-c_1\hat{\omega}}{p^2 + c_1 p + \hat{\omega}^2}\delta_M
\end{aligned}
\tag{17}
$$

is seen to be stable for $c_1 > 0$ and $\hat{\omega} \neq 0$. The constant c_1 can be used to design an robust observer in the desired speed range for the application. It is also seen that the steady state errors in the rotating coordinate system is

$$
\begin{aligned}
\tilde{x}_{M,ss} &= 0 \\
\tilde{\theta}_{ss} &= -\frac{c_1}{\hat{\omega}}\delta_M
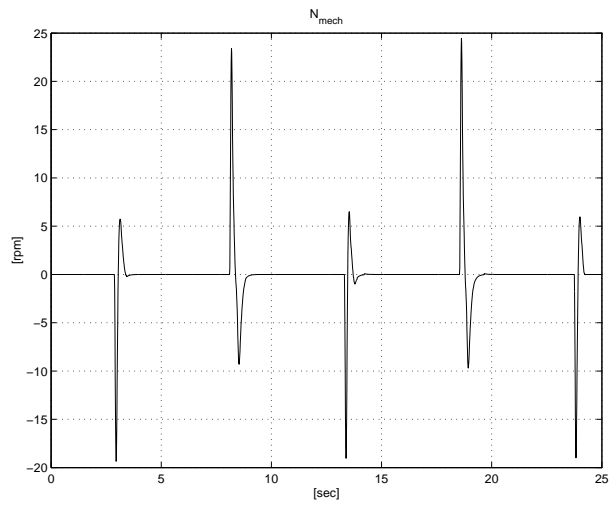\end{aligned}
\tag{18}
$$

For known rotor field we can use $\psi_{M,ref} = \psi_M$ in the observer. This gives $\delta_M = 0$ and zero steady state estimation error of the rotor angle. Further more it can be seen that the
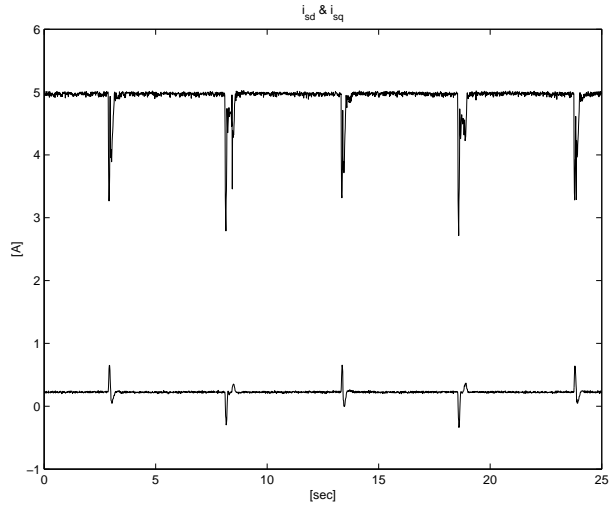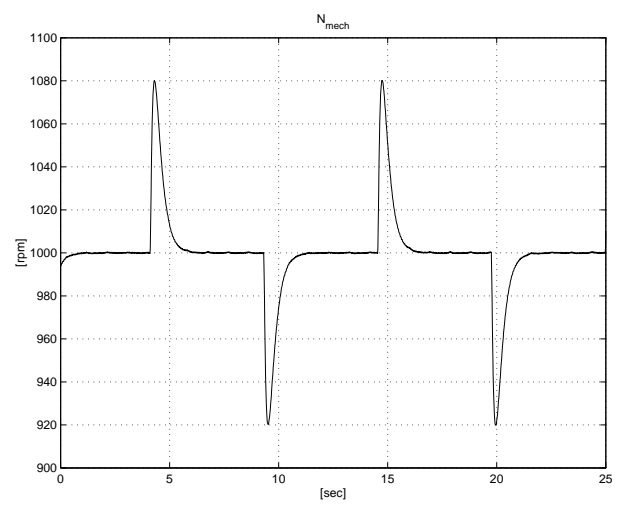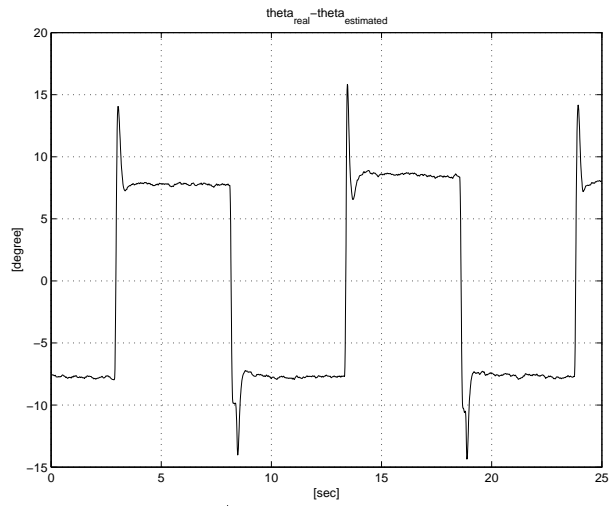
a) i_{sd} and i_{sq}
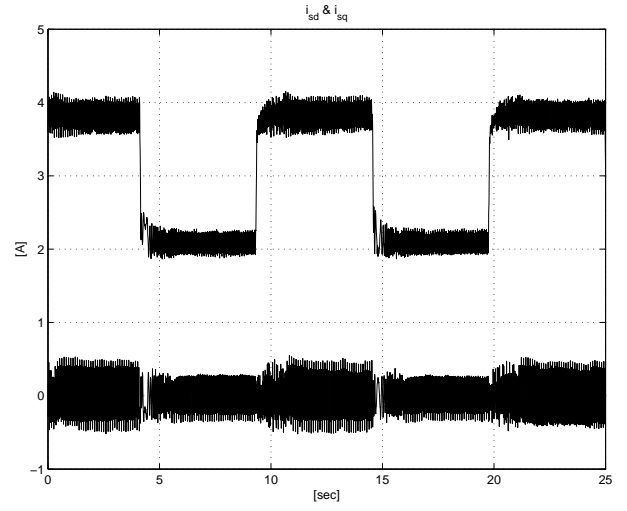
b) i_{sd} and i_{sq}
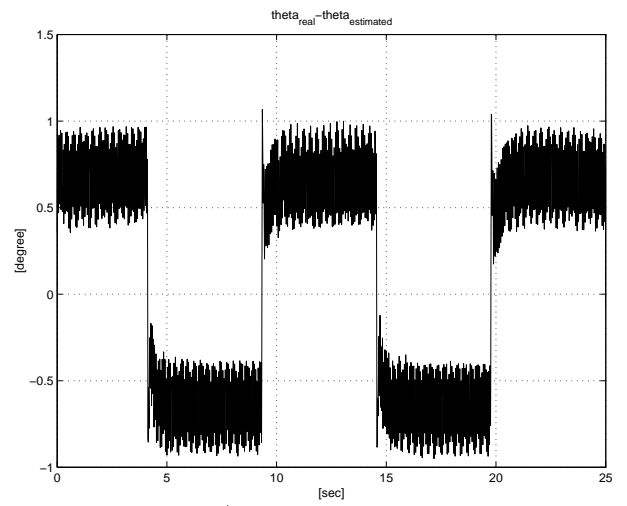
c) *Rotor speed N_{mech}*

d) *Rotor speed N_{mech}*

e) *Estimation error $\hat{\theta} - \theta$ in degrees*

f) *Estimation error $\hat{\theta} - \theta$ in degrees*

Fig. 9 – Torque step at rotor speed $0rpm$ (a,c,e) and $1000rpm$ (b,d,f)

choice of c_1 is a balance between damping and bias, meaning that a low value will result in pure damping and low bias and visa versa.

V. Experiments

The laboratory setup shown in Fig. 4 is based on Real Time Workshop, Simulink and DSpace. The drive system is via a signal conditioner connected to a DSP board in the computer. The control software is Simulink blocks written in C. The nominal motor parameters are

	R_s	L_s	ψ_M	Z_p	N_{mech}
Nom.	4.0	0.013	0.3	3	1500

Fig. 5 and Fig. 6 show the start-up response with the rotor angle initialized to be opposite to the induced i_{sd} current. The initial negative speed in Fig. 5 is due to the fact that the estimation error of the rotor $\hat{\theta} - \theta > 90$ degrees. Fig. 6 show that the estimation error tends to a small value and a normal stepresponse is obtained. Fig 7 show a normal step response obtained after convergense of the estimate of the rotor angle. Fig 8 shows the i_{sd} current. At high speed the $i_{sd,ref}$ function goes to zero as given by (8). Fig. 9 show the response of step in the load torque both at 0-speed and at 1000 rpm.

VI. Conclusion

Various papers concerning methods for starting PMSM without position sensors have been presented. Most methods have a special mode for start-up and operations at low speeds. The proposed method operates in the same mode from zero speed to maximum speed, which simplifies the control algorithm and eliminates the lag of robustness when a controller shifts modes. The method makes it possible to start from zero speed in closed loop and produce a constant torque at very low speeds by changing the direct vector current component as a function of the speed. The method is implemented and verified experimentally on a 800 W motor. The results demonstrate that the method work successfully over a wide speed range. The method is able to produce estimates of position and speed with a precision good enough to replace a shaft sensor.

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