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Rasmussen, Henrik

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Sensorless Speed Control including zero speed of Non Salient PM Synchronous Drives

H. Rasmussen

Aalborg University, Aalborg, Denmark

e-mail: hr@control.aau.dk

Abstract— This paper presents a position sensorless drive of non salient pole PM synchronous motors for all speeds including zero speed. Using adaptive Lyapunov design a new approach for the design of an observer is developed. The resulting scheme leads to a nonlinear full order observer for the motor states including the rotor speed. Assuming motor parameters known the design achieves stability with guaranteed region of attraction even at zero speed. The control method is made robust at zero and low speed by changing the direct vector current 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.

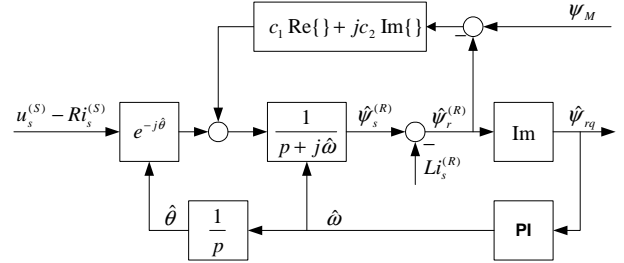


Fig. 1. Rotor angle observer

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 | stator resistances |
| L | stator inductance |
| ω | synchronous angular frequency |
| ω_{mech} | rotor speed |
| p | time derivative operator d/dt |
| Z_p | number of pole pair |
| θ | rotor position |

I. INTRODUCTION

The permanent magnet synchronous motor (PMSM) offers high power density implying reduced size and less material to transport. PM motors cannot be operated in open loop due to the highly unstable behavior of the motor dynamics. This means that PM motors needs a measurement of the rotor position in order to control the motor in a robust way. 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.

In more than ten years there has 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 [4]. In this paper 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 normally determined by an open loop or closed loop observer see [5] or by voltage injection methods exciting saliency or saturation effects in the motor see [2], [6], [7]. In [1] sensorless salient-pole PM synchronous motor drive in

all speed ranges are obtained by switching between a back-emf (BEMF) method in the medium and high speed range and an injection method in the low and zero speed range.

For a non salient PM synchronous motor the injection methods described are not valid and no BEMF is presented at zero speed. This is normally handled by a start-up procedure operating the motor in open loop 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 method based on Lyapunov stability will be presented operating from zero speed without changing the control structure. The idea of the method chosen is to force direct current into the machine in the faulty position the observer estimates at low speed; this will force the rotor position to the incorrectly estimated position, and the difference between the real position and the estimated position will be reduced.

The method is implemented and verified experimentally on a 800 W motor. The results demonstrate that the method works successfully from zero to full speed. The method is able to produce estimates of position and speed with a precision good enough to replace a shaft sensor.

II. OBSERVER DESIGN

A. Voltage equations

In the rotor oriented coordinate system $e^{j\theta}$ the voltage equation for the motor is

$$u_s^{(R)} = Ri_s^{(R)} + (p + j\omega)Li_s^{(R)} + j\omega\psi_M$$

with $\omega = p\theta$

In the coordinate system $e^{j\hat{\theta}}$ of the estimated rotor angle

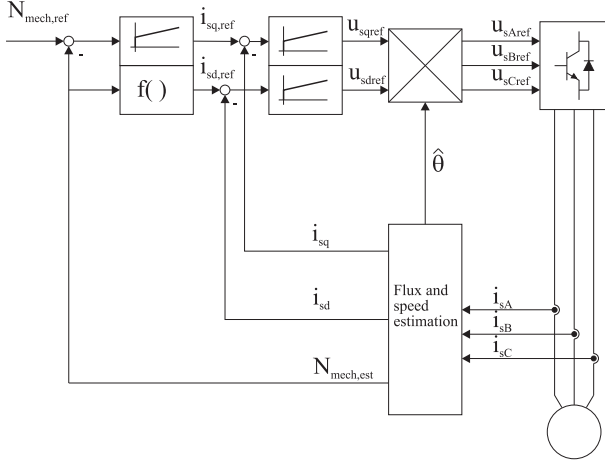


Fig. 2. Rotor Field Oriented Control

$\hat{\theta}$ the voltage equation is

$$u_s^{(\hat{R})} = Ri_s^{(\hat{R})} + (p + j\hat{\omega})Li_s^{(\hat{R})} + (p + j\hat{\omega})\psi_M e^{j(\theta - \hat{\theta})}$$

with $\hat{\omega} = p\hat{\theta}$

Omitting (\hat{R}) in the following and introducing $\tilde{\theta} = \hat{\theta} - \theta$ gives

$$u_s = Ri_s + (p + j\hat{\omega})Li_s + j\hat{\omega}\psi_M + (\omega \sin \tilde{\theta} + j(\omega \cos \tilde{\theta} - \hat{\omega}))\psi_M$$

B. Observer candidate

From this equation the stator flux linkage is given by

$$\psi_M + Li_s = \frac{1}{p + j\hat{\omega}} \left\{ u - Ri_s - (\omega \sin \tilde{\theta} + j(\omega \cos \tilde{\theta} - \hat{\omega}))\psi_M \right\}$$

Because the term $\left\{ \omega \sin \tilde{\theta} + j(\omega \cos \tilde{\theta} - \hat{\omega}) \right\} \psi_M$ is unknown a feedback observer may be given the form

$$\hat{\psi}_r + Li_s = \frac{1}{p + j\hat{\omega}} \{ u_s - Ri_s + v \}$$

where equations for v and $\hat{\omega}$ have to be calculated.

From the above equations the error dynamics are given by

$$p(\hat{\psi}_r - \psi_M) = -j\hat{\omega}(\hat{\psi}_r - \psi_M) + v + (\omega \sin \tilde{\theta} + j(\omega \cos \tilde{\theta} - \hat{\omega}))\psi_M$$

Stabilizing with $v = -c_1(\hat{\psi}_{rd} - \psi_M) - c_2\hat{\psi}_{rq}$ and taking the real and imaginary part of the equation gives

$$\begin{aligned} p(\hat{\psi}_{rd} - \psi_M) &= -c_1(\hat{\psi}_{rd} - \psi_M) + \hat{\omega}\hat{\psi}_{rq} + \omega \sin \tilde{\theta}\psi_M \\ p\hat{\psi}_{rq} &= -c_2\hat{\psi}_{rq} - \hat{\omega}(\hat{\psi}_{rd} - \psi_M) - (\hat{\omega} - \omega \cos \tilde{\theta})\psi_M \end{aligned}$$

$$\begin{aligned} p(\hat{\psi}_{rd} - \psi_M) &= -c_1(\hat{\psi}_{rd} - \psi_M) + \hat{\omega}\hat{\psi}_{rq} - \omega\hat{\psi}_{rq} \\ p\hat{\psi}_{rq} &= -c_2\hat{\psi}_{rq} - \hat{\omega}(\hat{\psi}_{rd} - \psi_M) - (\hat{\omega} - \omega)\psi_M + \omega(\hat{\psi}_{rd} - \psi_M) \end{aligned}$$

Insertion of $\tilde{\omega} = \hat{\omega} - \omega$ in the equations now gives

$$\begin{aligned} p(\hat{\psi}_{rd} - \psi_M) &= -c_1(\hat{\psi}_{rd} - \psi_M) + \tilde{\omega}\hat{\psi}_{rq} \\ p\hat{\psi}_{rq} &= -c_2\hat{\psi}_{rq} - \tilde{\omega}(\hat{\psi}_{rd} - \psi_M) - \tilde{\omega}\psi_M \end{aligned} \quad (1)$$

C. Lyapunov analysis

Stability of the error equations may be obtained by using a Lyapunov function candidate

$$P = \frac{1}{2} \left\{ (\hat{\psi}_{rd} - \psi_M)^2 + (\hat{\psi}_{rq})^2 + \frac{1}{\gamma}\tilde{\omega}^2 \right\}$$

The time derivative of this function is

$$\frac{dP}{dt} = -c_1(\hat{\psi}_{rd} - \psi_M)^2 - c_2(\hat{\psi}_{rq})^2 + \tilde{\omega}(-\psi_M\hat{\psi}_{rq} + \frac{1}{\gamma}\frac{d\tilde{\omega}}{dt})$$

Choosing $\frac{d\tilde{\omega}}{dt} = \gamma\psi_M\hat{\psi}_{rq}$ then gives

$$\frac{dP}{dt} = -c_1(\hat{\psi}_{rd} - \psi_M)^2 - c_2(\hat{\psi}_{rq})^2$$

For $c_1 > 0$ and $c_2 > 0$ the Lyapunov function candidate is shown to be a Lyapunov function and the following convergence is obtained

$$\hat{\psi}_r = \hat{\psi}_{rd} + j\hat{\psi}_{rq} \rightarrow \psi_M$$

Because we have $\hat{\psi}_{rq} = -\psi_M \sin \tilde{\theta}$ it is also shown that $\hat{\theta} \rightarrow \theta$.

Now we only have to examine the adaptation condition

$$\frac{d\tilde{\omega}}{dt} = \gamma\psi_M\hat{\psi}_{rq}$$

If ω is assumed constant the adaptation condition becomes

$$\frac{d\hat{\omega}}{dt} = \gamma\psi_M\hat{\psi}_{rq}$$

The assumption of constant ω means in practice that the variation of ω has to be slow compared to the adaptation time constant, which depends of γ .

The above equations then give the following observer

$$\begin{aligned} \hat{\psi}_r &= \hat{\psi}_s - Li_s \\ \frac{d}{dt}\hat{\psi}_s &= u_s - Ri_s - c_1(\hat{\psi}_{rd} - \psi_M) - j c_2\hat{\psi}_{rq} - j\hat{\omega}\hat{\psi}_s \\ \frac{d}{dt}\hat{\omega} &= \gamma\psi_M\hat{\psi}_{rq} \\ \frac{d}{dt}\hat{\theta} &= \hat{\omega} \end{aligned}$$

For known values of the initial rotor position, (R, L, ψ_M) , no offset due to drift and perfect dead time compensation the observer converges to the correct rotor angle. Because this is not to be expected in practice a robustness analysis has to be performed.

D. PI adjustment

The adjustment of $\tilde{\omega}$ given by the Lyapunov method is an integral controller

$$\tilde{\omega}(t) = \gamma\psi_M \int_{-\infty}^t \hat{\psi}_{rq}(\tau) d\tau$$

It may be expected that a quicker adaptation can be achieved by using a PI controller

$$\tilde{\omega}(t) = \gamma_1 \hat{\psi}_{rq}(t) + \gamma_2 \int_{-\infty}^t \hat{\psi}_{rq}(\tau) d\tau$$

Since a system with the transfer function

$$H(s) = \gamma_1 + \frac{\gamma_2}{s}$$

is output strictly passive for positive γ_1 and γ_2 it follows from the passivity theorem [8], that PI adjustment is stable if a transfer function from $-\tilde{\omega}$ to $\hat{\psi}_{rq}$ is strictly positive real. From equ.(1) a transfer function is found

$$\hat{\psi}_{rq} = -\frac{p + c_1}{p^2 + (c_1 + c_2)p + c_1 c_2 + \tilde{\omega}^2} \psi_M \tilde{\omega} = -G(p) \psi_M \tilde{\omega}$$

$G(s)$ is for $c_1 > 0$ and $c_2 > 0$ shown to be SPR because: The function has no poles in the right half-plane, It has no poles and zeroes on the imaginary axis and

$$\text{Re}\{G(j\omega)\} = \frac{c_1(c_1 c_2 + \tilde{\omega}^2) + c_2 \omega^2}{\|(-\omega^2 + j\omega(c_1 + c_2) + c_1 c_2 + \tilde{\omega}^2)\|} > 0$$

With the above assumption of constant ω the equations for the observer are given by

$$\begin{aligned} \hat{\psi}_r &= \hat{\psi}_s - L i_s \\ \hat{\psi}_s &= \int^t (u_s - R i_s - c_1(\hat{\psi}_{rd} - \psi_M) \\ &\quad - j c_2 \hat{\psi}_{rq} - j \hat{\omega} \hat{\psi}_s) d\tau \\ \hat{\omega} &= \gamma_1 \hat{\psi}_{rq} + \gamma_2 \int^t \hat{\psi}_{rq} d\tau \\ \hat{\theta} &= \int^t \hat{\omega} d\tau \end{aligned}$$

These equations are shown in fig. 1

E. Robustness

Because the Lyapunov analysis has shown stability, the robustness is analyzed in steady state with $\hat{\omega} = \omega$. Let us assume that uncompensated dead time compensation and error in R gives and voltage error δu . The observer equations then gives

$$0 = \delta u + j\omega \psi_M - c_1(\hat{\psi}_{rd} - \psi_M) - j c_2 \hat{\psi}_{rq} - j\omega \hat{\psi}_r$$

For $\|\omega\| \gg c_1$ and $\|\omega\| \gg c_2$ the real and imaginary part of this equation gives

$$\begin{aligned} \hat{\psi}_{rd} - \psi_M &\approx \delta u_q / \omega \\ \hat{\psi}_{rq} &\approx -\delta u_d / \omega \end{aligned}$$

leading to

$$\sin(\hat{\theta} - \theta) \approx \frac{\delta u_d}{\omega \psi_M}$$

Because these inequalities calls for small values of (c_1, c_2) and the dynamics of the observer calls for (c_1, c_2) as big as possible, the practical choice is a compromise between fast observer dynamics and small steady state estimation error. Experiments and simulations show that best performance is obtained for $c_2 \ll c_1$.

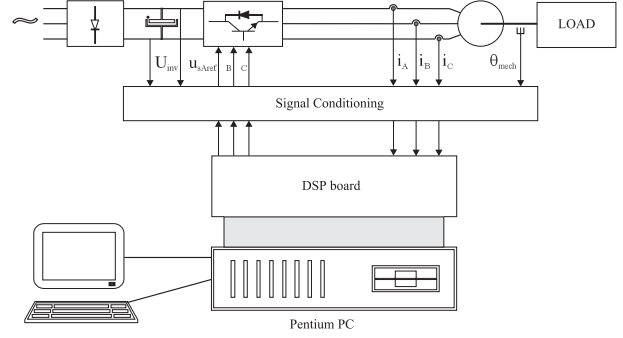


Fig. 3. Laboratory setup

F. Zero and very low speed control

Fig.2 shows the rotor field oriented control system. At zero and very 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

$$i_{sd,ref} = i_{ref0} e^{-|\hat{\omega}_r|/\omega_0} \quad (2)$$

with i_{ref0} determined by the maximal load torque expected at zero speed and ω_0 small due to the fact that estimation error of the rotor angle is only significant at low speed.

III. EXPERIMENTS

A. Laboratory setup

The laboratory setup shown in Fig.3 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

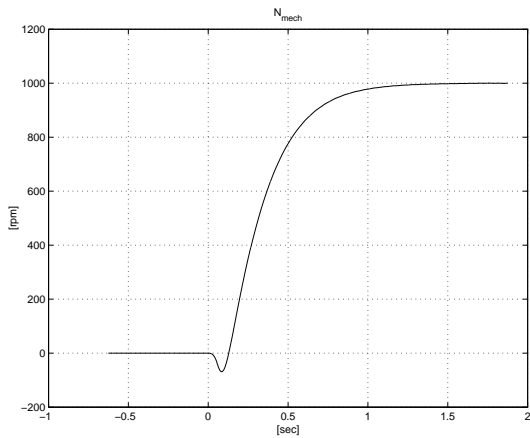
| | R | L | ψ_M | Z_p | N_{mech} |
|------|-----|-------|----------|-------|------------|
| Nom. | 4.0 | 0.013 | 0.3 | 3 | 1500 |

B. Initial startup

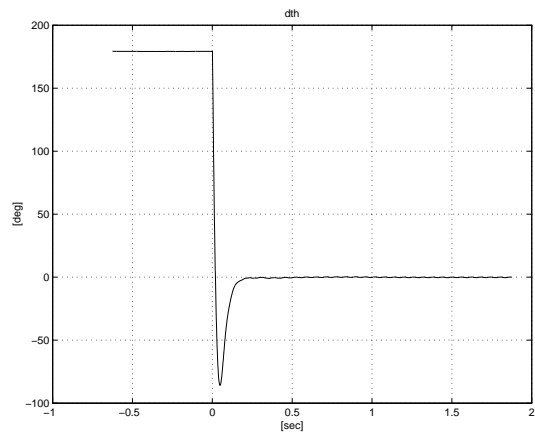
Fig.4.a and Fig.4.b show the start-up response with the rotor angle initialized to the worst condition, which is to be opposite to the initial value given the estimate of the rotor position. The initial negative speed in Fig.4.a is due to the fact that the estimation error of the rotor angle $\hat{\theta} - \theta > 90$ degrees. This situation only occurs the very first time the control system is started. Next time the reference is set to zero speed the angle is estimated with a small estimation error due to the $i_{sd,ref}$ value different from zero.

C. Rotor speed step responses

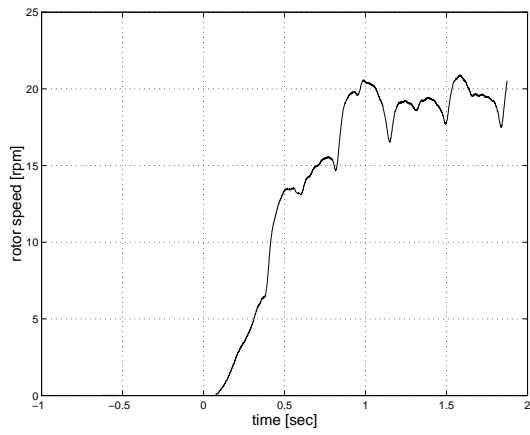
Fig.4.c shows a step response for a very low speed. The scale of the speed axis has to be noticed showing that the variation of the rotor speed is less than $5rpm$.



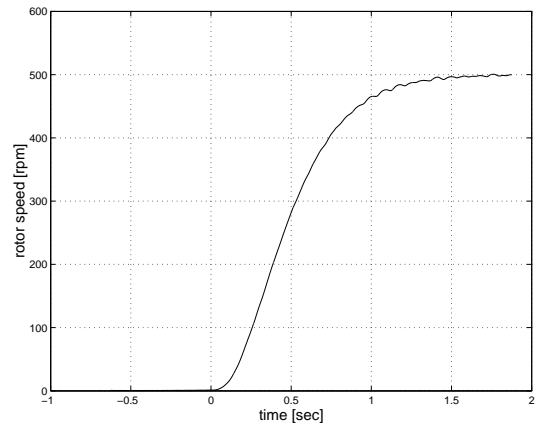
a) First Rotor speed step response with rotor angle initialized to an 180 degree error at startup



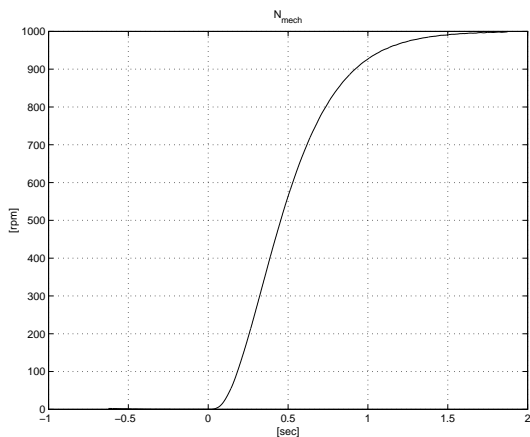
b) Convergence of the estimated rotor angle with rotor angle initialized to an 180 degree error at startup



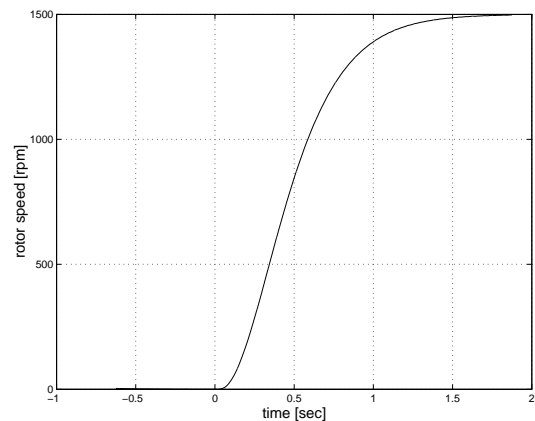
c) Very low rotor speed step response 0 – 20rpm



d) Low rotor speed step response 0 – 500rpm

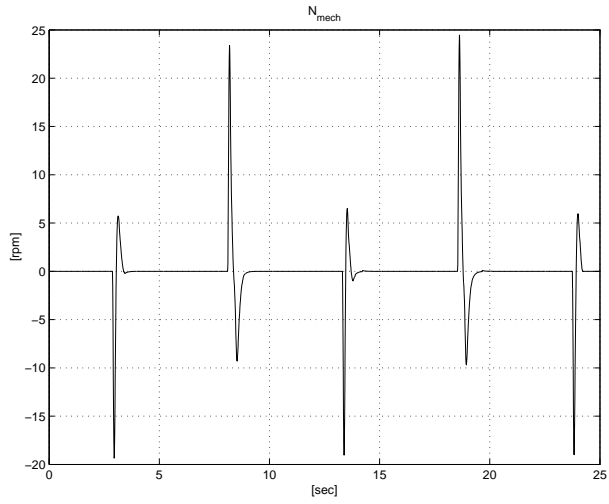


e) Rotor speed step response 0 – 1000rpm

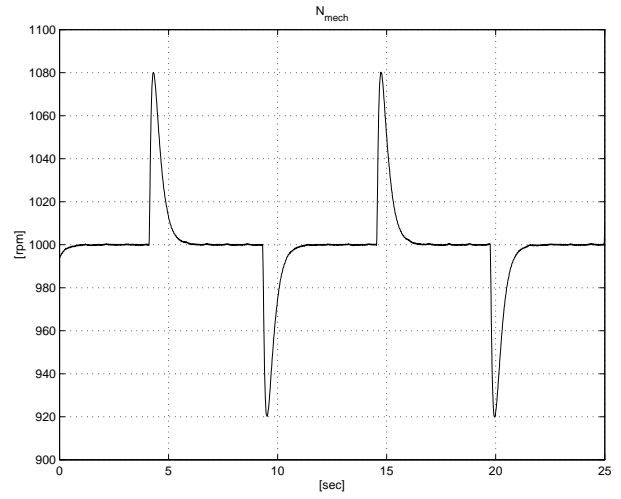


f) High rotor speed step response 0 – 1500rpm

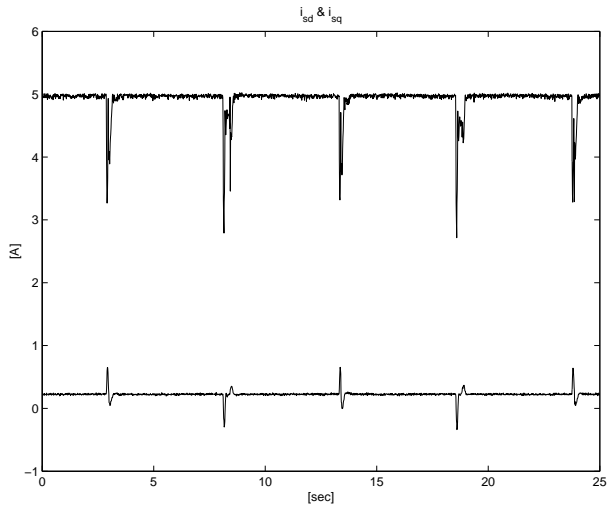
Fig. 4. Experiments



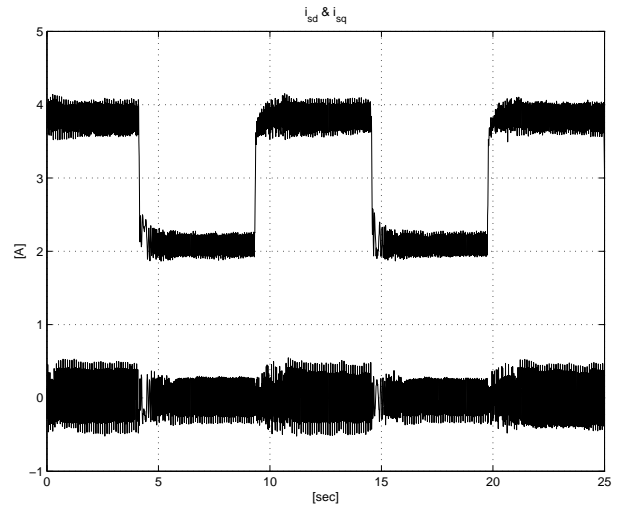
a) Rotor speed N_{mech}



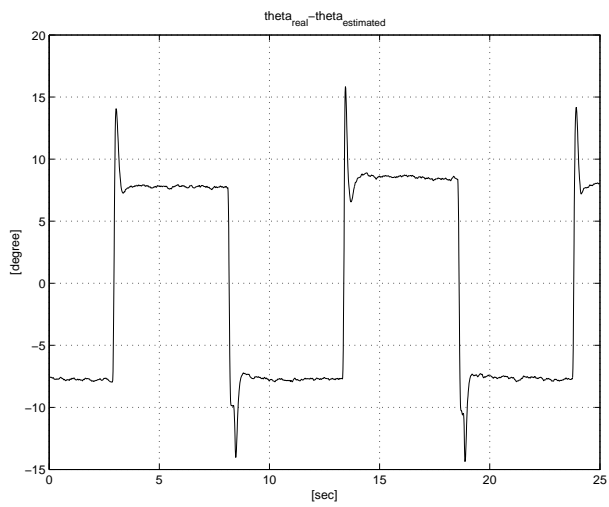
b) Rotor speed N_{mech}



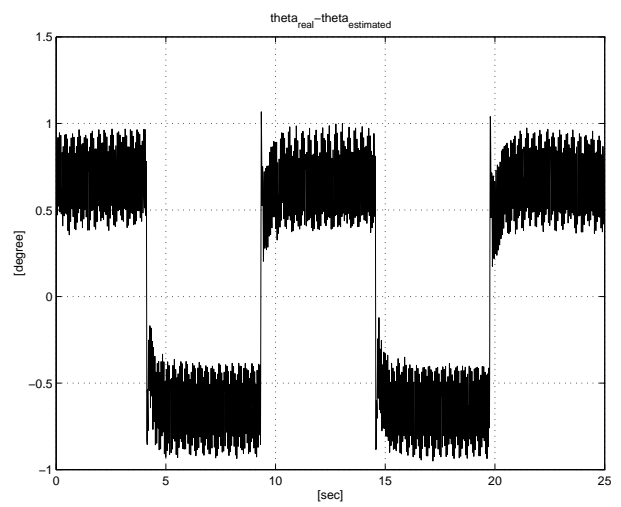
c) i_{sd} and i_{sq}



d) i_{sd} and i_{sq}



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



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

Fig. 5. Torque step at rotor speed $0rpm$ (a,c,e) and $1000rpm$ (b,d,f)

Fig.4.d, 4.e and 4.f shows step response for $0 - 500rpm$, $0 - 1000rpm$ and $0 - 1500rpm$ respectively. The curve form of the responses are as expected and the sound of the motor also indicate field orientation during the transients.

D. Load step response

Fig.5 show the response of step in the load torque both at $0rpm$ and at $1000rpm$.

Fig.5.a and b show the speed variation for step in the load torque. Even at zero speed reference the speed is equal to zero in steady state.

Fig.5.c and d show the i_{sd} and i_{sq} current. Fig.5.d shows the normal response at $1000rpm$ where $i_{sd} = 0$ and i_{sq} is the torque producing current. Fig.5.c shows the i_{sd} and i_{sq} at zero speed. The i_{sd} is given a reference value equal to $5A$ and when the load torque tries to turn the rotor axis the angle between this current in the estimated rotor angle and the real rotor angle produces a torque equal to the load torque and the speed is kept equal to zero as seen from fig.5.a

Fig.5.e and f show the error between the estimated and real rotor angle. The error at zero speed depends on $i_{sd,ref}$ due to the fact that we have $m_e = 3/2 Z_p \psi_M i_{sd} \sin(\theta)$. Fig.5.f shows the error at high speed and the scale of the axis has to be noticed.

IV. CONCLUSION

A new observer for the rotor angle is presented. Stability of the observer is proven by the Lyapunov method and robustness is analyzed in steady state. 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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