Adaptive observer and high frequency signal injection

This chapter presents a speed and position estimation method for sensorless control of Permanent Magnet Synchronous motors. The approach combines a speed adaptive flux observer with a high frequency signal injection technique at low speed and stand still. Simulation results show that this is an advanced observer which works for Surface Mounted Permanent Magnet Motors, featuring robustness, stability and capability of rejecting load torque transient, including good response under stepwise change conditions in the reference speed.

7.1 Adaptive observer

In an adaptive observer, the rotor speed and position estimation is based on the estimation error between two different models, a reference model and an adaptive model.
The estimated variable can be the stator flux or the stator current. The adaptive observer designed in this chapter is made of a flux model (reference model) and a voltage model (used as adaptive model).
The principle of the adaptive observer is to construct an error term from the two models and use this in an adaptation mechanism. In the following, the stator flux is the estimated variable of the two models. The two models are compared to extract the error term (which is used to estimate the rotor speed). The estimate of the rotor speed is used to adjust the adaptive model.

7.1.1 Reference model

The reference model can be derived by expressing the estimated stator flux of the motor as a function dependant of the current components. This can be done based on equation (2) presented in chapter two, (see machine model).

$$\begin{aligned} \hat{\lambda}_{d\_i} &= \hat{L}_d i_d + \hat{\lambda}_m \\ \hat{\lambda}_{q\_i} &= \hat{L}_q i_q \end{aligned} \tag{31}$$

Where the sign $\wedge$ stands for the estimated quantities of the machine in the estimated rotor dq reference frame.

7.1.2 Adaptive model

Consider equation (18) representing the machine voltage equations in the estimated rotor dq reference frame, (see previous chapter).

$$V_d = \hat{R}_s i_d + \frac{d\hat{\lambda}_d}{dt} - \hat{\omega}_m \hat{\lambda}_q$$
$$V_q = \hat{R}_s i_q + \frac{d\hat{\lambda}_q}{dt} + \hat{\omega}_m \hat{\lambda}_d \tag{32}$$

Equation (32) can be solved for the flux components variation and used to formulate the adaptive model of the observer in the estimated rotor dq reference frame as depicted in the following equation [1].

$$\frac{d\hat{\lambda}_{d\_u}}{dt} = V_d - \hat{R}_s \hat{i}_d + \hat{\omega}_m \hat{\lambda}_{q\_u} + k\tilde{i}_d$$
$$\frac{d\hat{\lambda}_{q\_u}}{dt} = V_q - \hat{R}_s \hat{i}_q - \hat{\omega}_m \hat{\lambda}_{d\_u} + k\tilde{i}_q \tag{33}$$

Where k is a gain parameter to be selected accordingly.

$\hat{i}_d$ and $\hat{i}_q$ are the estimates for the stator current components and can be described as follow:

$$\hat{i}_d = \frac{\hat{\lambda}_{d\_u} - \hat{\lambda}_m}{\hat{L}_d}$$
$$\hat{i}_q = \frac{\hat{\lambda}_{q\_u}}{\hat{L}_q} \tag{34}$$

With $\hat{\lambda}_m$ the estimated permanent magnet flux.

$\tilde{i}_d$ and $\tilde{i}_q$ are the components of the current error, which can be expressed as in the following equation.

$$\tilde{i}_d = i_d - \hat{i}_d$$
$$\tilde{i}_q = i_q - \hat{i}_q \qquad (35)$$

7.1.3 Error term

Various alternatives for obtaining an error term from the two derived models are available. In the following, the error term is defined as:

$$F_\zeta = \hat{\lambda}_{q\_u} - \hat{\lambda}_{q\_i} \qquad (36)$$

Where $\hat{\lambda}_{q\_u}$ can be obtained from the q-axis term of equation (33).

7.1.4 Estimated speed and rotor position

The estimated speed of the machine can be obtained by processing the derived error term in a PI speed adaptation [1]:

$$\hat{\omega}_m = k_p F_\zeta + k_i \int F_\zeta dt \qquad (37)$$

With k_p and k_i the proportional and integral gain of the PI regulator respectively.
The estimated rotor position can then be obtained by integrating the estimated speed.

7.2 High frequency signal injection

An alternating voltage fluctuating at the angular frequency $\omega_i = 2\pi f_i$ (with f_i the injected high frequency) is used for the high frequency signal injection model applied in this chapter.
The injected voltage signal can be described as in the following equation (see previous chapter):

$$u_i(t) = \hat{u}_{\max} \cos \omega_i t \qquad (38)$$

Where $\hat{u}_{\max}$ and f_i are to be set to the proper values depending on the project specifications and the requirements involved. In this project, the required value of $\hat{u}_{\max}$ and f_i were obtained by experimental simulation. The signal $u_i(t)$ is superimposed on the d-axis component of the voltage in the estimated rotor reference frame, and an alternating high frequency current response (which is function dependant of the rotor position estimation error), is detected in the q-direction of the estimated rotor reference frame.
The demodulation principle is shown in the figure below.

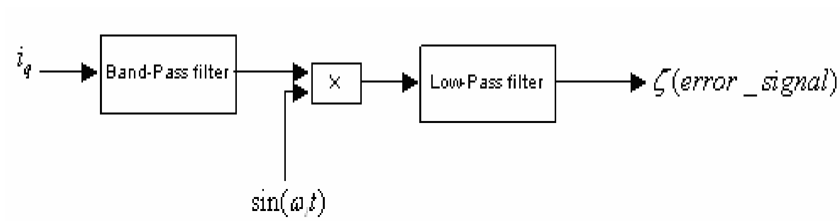


Figure 7.1: *Demodulation principle of the error signal contained in the q-axis current component.*

The q-axis current component of the measured current is band-pass filtered and forced to oscillate (alternatively) at the injected high frequency, then low-pass filtered to extract its fundamental component (error signal), which is function dependent of the error in the estimated rotor position. The equation describing the error signal, taken on an ideal basis is presented below.

$$\zeta = \frac{\hat{u}_{\max}}{\omega_i}\left[\frac{L_{q-}L_d}{4L_qL_d}\right]\sin(2\tilde{\theta}_m) \quad (39)$$

Where $\tilde{\theta}_m = \theta_m - \hat{\theta}_m$, is the estimated error of the rotor position.

It can be seen from equation (39) that ideally, if there is no error in the estimated rotor position ($\tilde{\theta}_m = 0$), the error signal will be zero ($\zeta = 0$). This goes for all types of Permanent Magnet machine, assuming that they all own a little saliency, (providing that $L_d \neq L_q$).
The filters used in figure 7.1 are discrete filters, designed using Filter Design and Analysis (FDA) tools from Simulink

7.3 Combined observer

The combination of the adaptive observer and the high frequency signal injection approach is illustrated in the figure below.

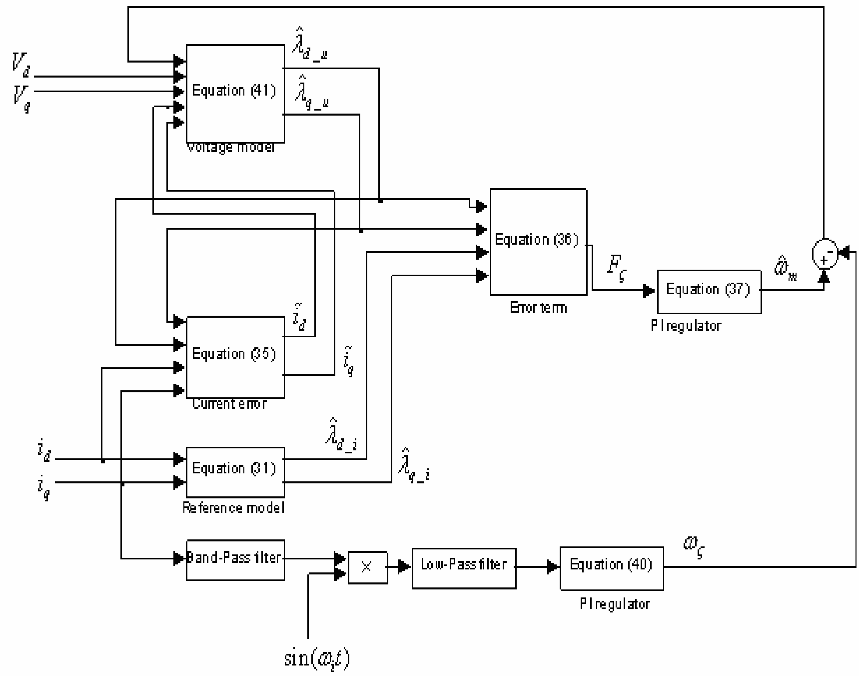


Figure 7.2: *Combined adaptive observer and signal injection model.*

V_d, V_q, i_d and i_q can be obtained by transforming the measured machine variables from the stationary reference frame to the rotor dq reference frame.

As mentioned previously, the error signal demodulated from the q-axis current component should be zero ($\zeta = 0$), during steady state, providing no error in the estimate rotor position. To meet this requirement, a PI-regulator is used to drive the error signal to zero during steady state, thereby obtaining a correction term described by the following equation:

$$\omega_\zeta = k_p\zeta + k_i\int \zeta dt \qquad (40)$$

Where k_p and k_i are the proportional and integral gains of the PI regulator.

The key point is to use the error signal of the signal injection method to adjust the adaptive model of equation (33). Therefore the correction term (previous equation), is subtracted from the estimated speed as shown in figure 7.2. This leads to a rearrangement of the adaptive model described in equation (33):

$$\frac{d\hat{\lambda}_{d\_u}}{dt} = V_d - \hat{R}_s\hat{i}_d + (\hat{\omega}_m - \omega_\zeta)\hat{\lambda}_{q\_u} + k\tilde{i}_d$$

(41)

$$\frac{d\hat{\lambda}_{q\_u}}{dt} = V_q - \hat{R}_s\hat{i}_q - (\hat{\omega}_m - \omega_\zeta)\hat{\lambda}_{d\_u} + k\tilde{i}_q$$

7.4 Control system

The block diagram of the control system comprising the cascaded connection of the speed and current control loops is shown in the figure below. The position control could be achieved with the aid of a Proportional controller, used as the outermost control loop in the control system.

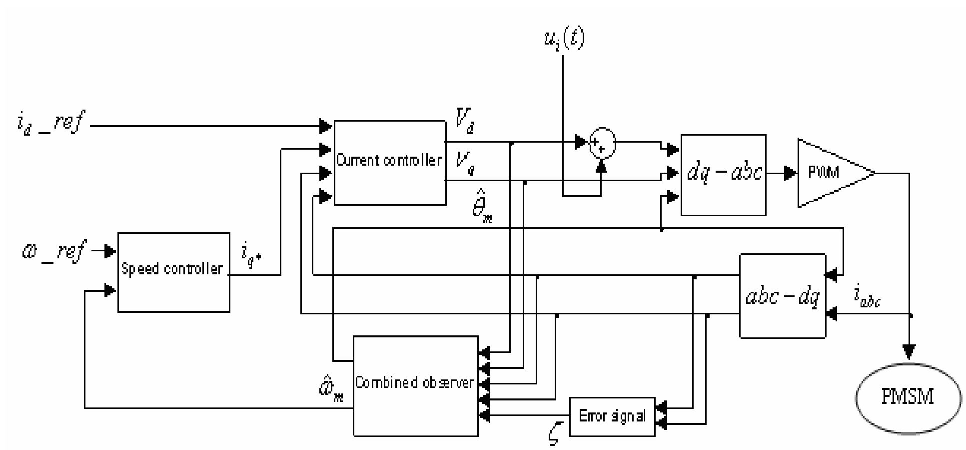


Figure 7.3: *Control system of the sensorless scheme with the proposed algorithm*

7.5 Simulation results

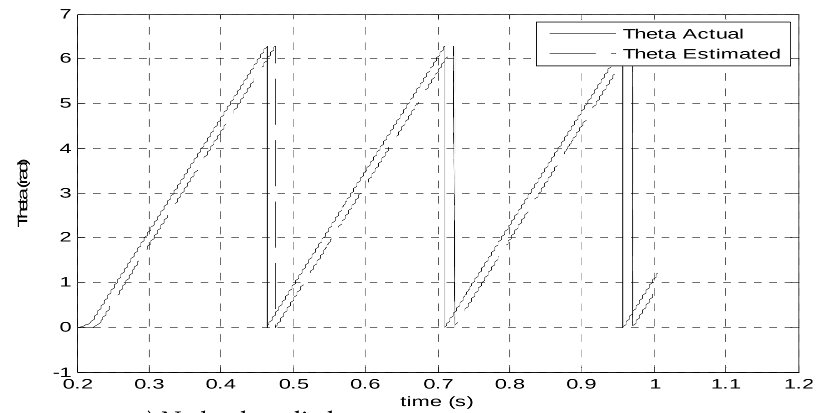
The proposed observer was investigated by mean of simulations, done in Simulink. A 0.4 KW Surface Mounted Permanent Magnet Motor model was developed and used. Inverter non linearity was not considered in the model. The motor parameters are given in table 7.1. A reference speed approximately 1.6 % of the rated speed was adopted, for convenient case of study at low speed range.

Table 7.1: *Motor parameters.*

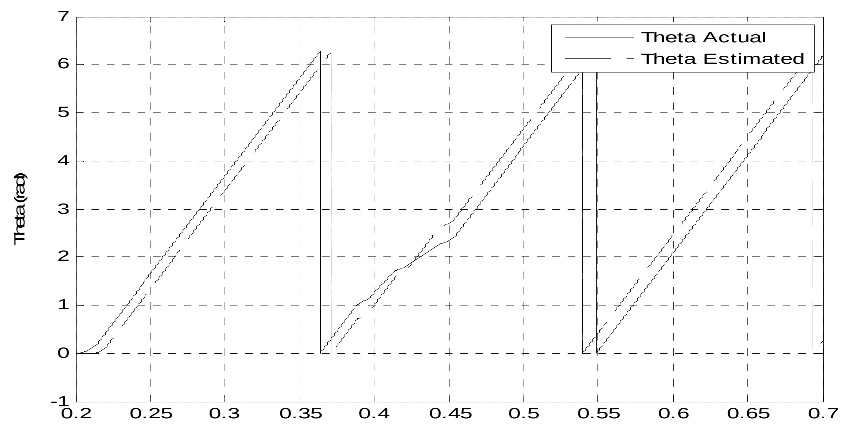
Nominal power	0.4 KW
Nominal voltage	380 V
Nominal current	2 A
Nominal torque	1.3 Nm
Number of pole pairs	2
Stator resistance	10.4 Ω
Direct axis inductance	0.043 H
Quadrature axis inductance	0.043 H
Total moment of inertia	0.94 $Kg.Cm^2$
Nominal speed	6000 rpm

Simulations results performed at different operating conditions of the machine are shown in the figure below.

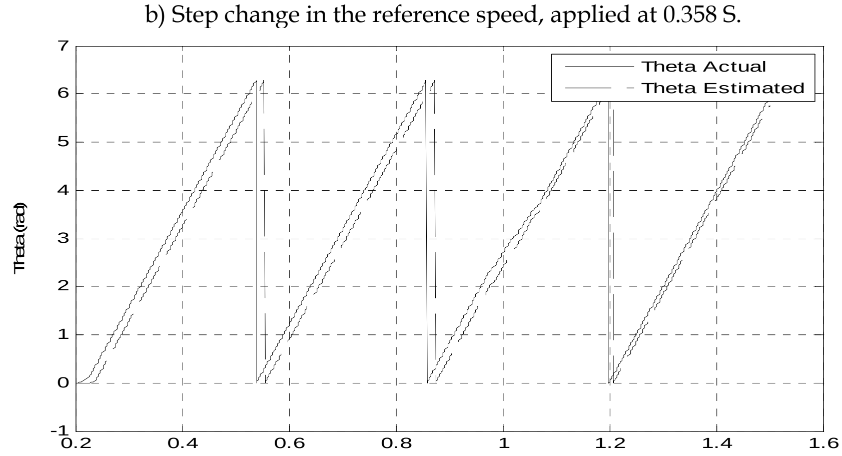
Figure 7.4: *simulation results of the proposed algorithm at different operating conditions.*



a) No load applied



b) Step change in the reference speed, applied at 0.358 S.



c) Step change in the load, applied at 0.97 S (approximately).

At no load (see fig 7.4 a), the algorithm based on adaptive observer combined with high frequency signal injection was proved to be effective. It can be seen from the simulation results that no delay is consumed by the observer to find the rotor position from stand still, (this shows the robustness of the observer).

Figure 7.4 b shows the simulation result with a step change in the reference speed, applied at 0.358 S approximately. It can be seen from this figure that the change applied in the reference speed introduces distortions in the rotor position estimation. However, the adaptive observer does not lose the rotor position, which shows the capability of the observer to cope with disturbances in the reference speed.

In figure 7.4 c, a step change in the load was applied at 0.97 S (approximately). The effect of load change can be clearly seen on the figure (after t= 1 S). It is important to notice that the observer follows the impact of the disturbance on the actual rotor position, thereby providing accurate position estimation still. This aspect proves the ability of the algorithm to reject load torque transients.

7.6 Partial conclusion

Chapters six and seven present two different techniques to estimate the rotor position and speed of a Surface Mounted Permanent Magnet Motor. The simulation results performed for the same machine show the limitations and the features of these algorithms.
The approach based on modified voltage model achieves good results, but suffers from some limitations under disturbance in the reference speed and the load torque, (see pages 30-31).
As opposed to the estimation scheme based on modified voltage model, the approach based on adaptive observer features robustness, stability and capability of rejecting load torque transient, under step change condition in the reference speed and the load torque.
Therefore, the adaptive observer will be the selected approach for the implementation in DSPACE.

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