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SPEED ESTIMATOR WITH ADAPTATIVE FUZZY FILTER

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Abstract: A novel sensor-less system for induction motors is designed. This novel design is based on an adaptative fuzzy system, which is obtained by mixing open-loop estimator response with steady-state estimator. This open-loop estimator is improved by means of using an adaptative fuzzy controlled filter that selects the optimised cut frequency. The results validate the entire work in not only transient and steady state but also in the start-up. *Copyright © 2002 IFAC*

Keywords: Fuzzy, filter, speed, control, motor, estimator, observer.

1. INTRODUCCION

The plant that is studied is an induction motor (IM) and the rotor speed is the searched variable of this system. There are several classifications about these methods to find this speed (Rajashekara et al. 1996). We can choose between **steady-state plant models** and **transient plant models**. The first one is more adequate for simple controls, that is, controls that are not too sensitive about the knowledge of the flux position. The others are used in Field Orientated Controls (FOC) or in other kind of IM control (Dion et al. 1994). We can make another classification between methods. The first methods use **properties that are not ideal** in the IM like Holtz 2000. These properties have effects over the measured variables. The others use **general equations of the plant** (Vas 1998, Lin and Chen 1999, Shin et al. 2000, Akatsu and Kawamura 2000, Jezernik 2000, Tusini et al. 2000) in order to solve the trouble. The proposed system is a solution by the second way. The methods that use general equations can be classified in three groups, depending on the kind of solutions of these equations. The first group are the **open-loop estimators**. They use integrators, derivators and plant's parameters to find the speed (Vas 1998, Shin et al. 2000, Akatsu and Kawamura 2000, Jezernik 2000). They are called open-loop estimators because they do not use any kind of closed loops in order to solve the equations. In the group that use **observers** (Vas 1998, Lin and Chen 1999, Tusini et al. 2000), speed value is found using this kind of structure of control algorithm This kind of structure contains inside a closed loop over the observed magnitude, even this closed loop can be a Kalman's filter matrix. The last one is got from applying a **MRA System** (Vas 1998). This method gives the speed error from two internal models; one of them is based only on the measured values whilst the other uses some measured values and estimated values. If a regulator closes the loop over the error value from the two models the estimated speed can be found. Some MRAS use artificial intelligence in order to close the loop (Vas 1998).

The mainly troubles are:

- Sensibility against variations of the plant parameters (Lin and Chen 1999, Akatsu and Kawamura 2000, Jezernik 2000)
- Problems with the integration of internal variables (Shin et al. 2000)
- Difficulty to implement the systems with too computational charge
- Mathematical Noise in the estimated process

In this work is proposed to implement a filter with a variable cut frequency. The value of this frequency depends on the point of work of the plant. Further the output of this new estimator is the ponderated average between two different estimators. The ponderated average depends on the working point of the plant.

2. SPEED ESTIMATORS

2.1 Steady-state estimator "SS"

The estimators that work with a steady-state model are not good enough to be used in a high performance control systems. They can be applied in any system that a high accuracy is not needed or a great volume of computations calculations cannot be supported. They need low cost equipment but give a low performance. The problems of this kind of estimators increase when they have to work in the extremes of the work zone of the plant.

These steady-state estimators are based in the vector transformation theory over the plant model [Annex I], which is shown in Vas (1998).
If the frequency of the voltage that is applied is known, ω_1 we can find the approximated angle of the stator flux in steady-state.

$$\theta(t) = \int \omega_1(t)dt \tag{1}$$

This can be possible if a vector modulator is used. This modulator must be able to apply the instantaneous value of the desired voltage, that is, it must work with voltage and angle.

$$u_{sAref} = \left|\overline{u}_{sref}\right| \cos(\theta);$$
$$u_{sBref} = \left|\overline{u}_{sref}\right| \cos(\theta - 2\pi/3);$$
$$u_{sCref} = \left|\overline{u}_{sref}\right| \cos(\theta + 2\pi/3) \tag{2}$$

Thus the same angle can be used to solve the Park's transformation over the stator currents (3).

$$\begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix} = \begin{bmatrix} \cos\theta) & \cos\theta-2\pi/3) & \cos\theta+2\pi/3) \\ -\sin\theta) & -\sin\theta-2\pi/3) & -\sin\theta+2\pi/3) \end{bmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \tag{3}$$

Two currents are found. These currents, in steady-state, represent torque and flux, i_{sq} & i_{sd} respectively (4).

$$i_{sq} = k_1 * \Gamma_{mptor} \tag{4}$$

We can consider that, in steady-state, the sliding value is proportional to the torque (5).

$$\omega_{sl} = k_2 * i_{sq} \tag{5}$$

The speed value will be the frequency applied (synchronous pulse rate) minus the slide value (6).

$$\omega_r = \omega_1 - \omega_{sl} \tag{6}$$

The results of this estimator are shown in Figure 1.

2.2 Open-loop estimator "OL"

At the first, transient estimators seem better to be used in systems with quick dynamics such as induction motors [Annex I]. However when the model, that is discussed in Vas (1998) (7), is tested these problems can be found:

- Sensibility of the integration method: With a different method of integration (similar to a filter) can be found better results (Shin et al. 2000).
- A great account of derivators and divisions are used that cause errors in critical points (too little currents, etc.)
- These methods depend directly on a great number of plant's parameters. The solution can be found by implementing a plant's parameter estimator.

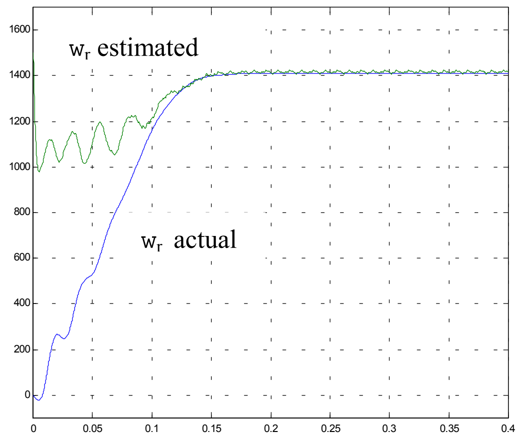

Figure 1. Steady-State Estimator
Estimated Speed during the start-up

$$\omega_r = \left[-\frac{d\Psi_{rd}}{dt} - \frac{\Psi_{rd}}{T_r} + \frac{L_m}{T_r} i_{sD} \right] \Big/ \Psi_{rq} \tag{7}$$

The result of this estimator is shown in Figure 2.

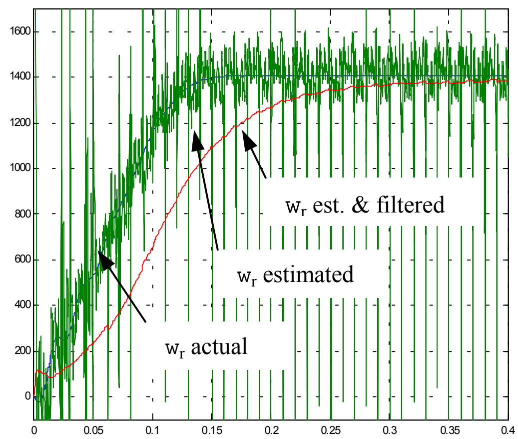

Figure 2. Open-Loop Estimator
Estimated and filtered Speed during the start-up

The mainly problem of this kind of estimators is that they to have to introduce derivators and/or divisions in the calculation process. The easiest solution is to implement a filter in the output. However this solution implicates an evident delay in the output signal.

The steady-state model, without filter, offers the most careful speed but in the transient work zone the estimated speed in very different from the actual

speed. The open-loop estimator has a lot of associated noise over the estimated speed, however in the transient work zone the estimated speed follows the actual speed. Therefore a filter is needed to use this output. The filter should not delay the response during the transient. But, in the steady-state, this filter should be bigger than in the transient to obtain a better performance without noise. Therefore the filter has to change the cut frequency at real time. This change must be dependent on the work point. That is, the cut frequency of the filter must be a kind of function of the level of steady-state of the plant under control.
The same system that is able to know the level of steady-state will be able to make a ponderated average between the estimated values of both estimators.

3. DESIGN OF A SYSTEM WITH PONDERATED AVERAGE OUTPUT

A steady-state estimator can estimate a more careful speed, even without output filter, while the system reaches a higher level of steady-state. Moreover the steady-state estimator is quicker than the filtered open-loop estimator. Therefore, in order to improve the system response, a system that makes a ponderated average between the responses of both estimators is proposed. This system will change the ratio of the ponderated average depend on the level of steady-state of the plant. The i_{sq} which is mainly constant during the steady-state becomes variable during the transients. Therefore the level of steady-state of the plant under control can be found from derivation of the i_{sq}. If a fuzzy system, that determines this level, can be implemented the ponderated average can be also obtained.

The ponderated average equation will be:

$$\omega_r = R\left(\omega_{r\_Steady-State-Estim}\right) + \left(1 - R\right)\left(\omega_{r\_Open-Loop-Est}\right) \quad (8)$$

The application of the above equation is not enough to find careful results; there are two further different problems.
a) Estimated speed from an open-loop estimator has to be filtered by an intelligent filter because it contains a lot of noise.
b) The behaviour of whole the system depends on the own estimated speed besides variations of i_{sq} Therefore the system's inputs will be di_{sq}/dt and the estimated speed ω_r. Figure 3.

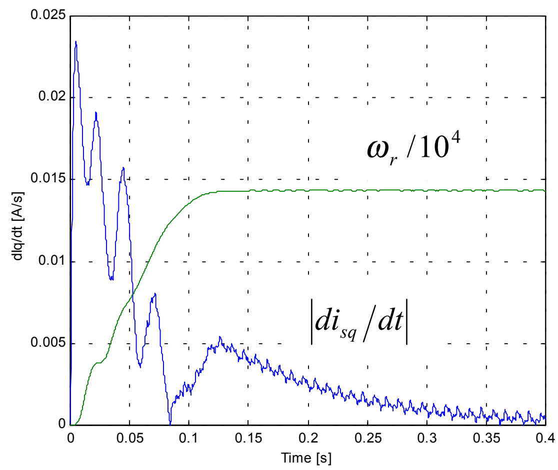

Figure 3. $\left|di_{sq}/dt\right|$; ω_r

The implemented system is shown in Figure 4.

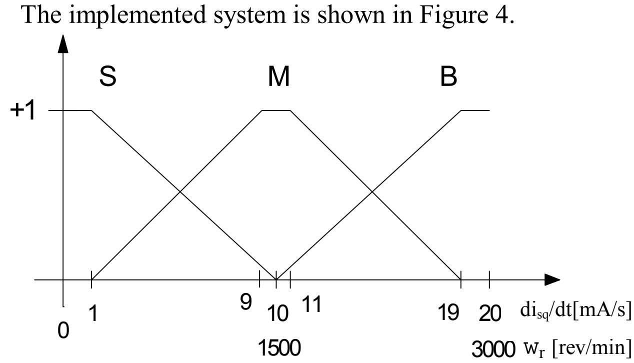

Figure 5. Input Fuzzy membership functions

1) The shape of the input functions will be trapezoidal functions. Figure 5.
2) The shape of the output functions will be Singleton. Figure 6.
3) The rules table will be Table 1
4) The inference method will be min, max
5) The defuzzyfication is made by centroid method

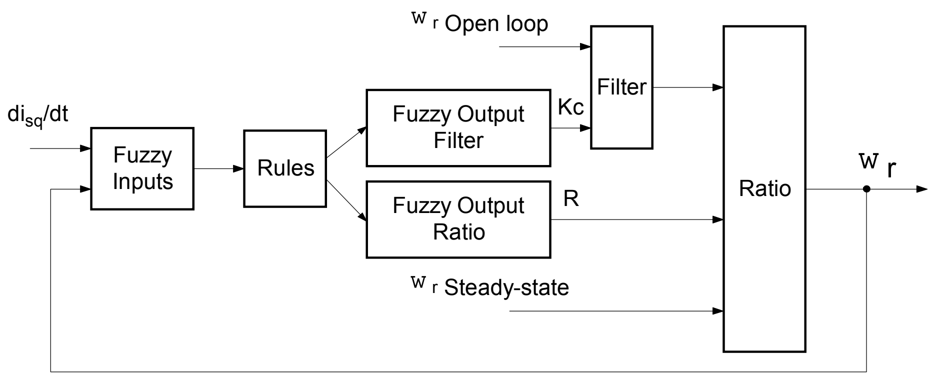

Figure 4. Experimental set up

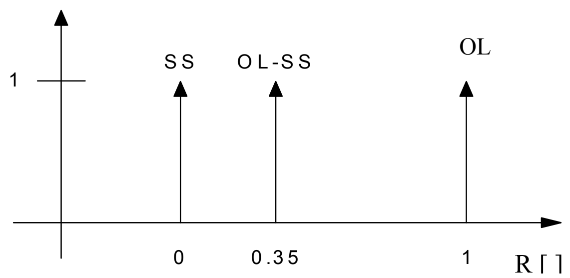

Figure 6 Input membership functions Ratio (R)

Table 1. Inference Table

If dIq/dt S and ω_r S then Ratio **(R)** SS

If dIq/dt M and ω_r S then Ratio **(R)** OL-SS

If dIq/dt B and ω_r S then **Ratio (R)** OL-SS

If dIq/dt S and ω_r M then **Ratio (R)** SS

If dIq/dt M and ω_r M then **Ratio (R)** OL-SS

If dIq/dt B and ω_r M then **Ratio (R)** OL

If dIq/dt S and ω_r B then **Ratio (R)** SS

If dIq/dt M and ω_r B then **Ratio (R)** OL-SS

If dIq/dt B and ω_r B then **Ratio (R)** OL

4. DESIGN OF AN ADAPTATIVE FILTER

If we want to obtain the estimated speed, from an open-loop estimator, the implementation of (7) is not enough because there are associated problems of noise, Figure 2. Therefore a filter is needed before to introduce this signal in the system that makes the ponderated average. The filtered level must be neither too soft (it wouldn't refuse the noise), especially in steady-state, nor too hard (it might introduce an important delay), especially during the transients. The filter must be adaptative.

The filter structure is shown in (9)

$$\frac{U_o}{U_i} = \frac{K_c z}{z + (K_c - 1))} \quad (9)$$

or in this kind of equations

$$U_o(k) = K_c[U_i(k) - U_o(k-1)] + U_o(k-1) \quad (10)$$

$$K_c = T_s \omega_c \quad (11)$$

The knowledge about the plant determines the filter level that is needed every interval of the current derivation. The lower the current i_{sq}, the lower the cut frequency. Obviously the relation between the filtered level and the derivated current value is not lineal, so fuzzy system has been chose to be implemented. The filtered level that is needed depends on the same inputs than the ponderated average, so the same inputs can be used now. But evidently the rules and the output membership will be different.

The system's characteristics are:

1) The shape of input functions will be trapezoidal functions. Figure 5.
2) The shape of output functions will be Singleton. Figure 7.
3) The rule table will be Table 2
4) The inference method will be min, max
5) The defuzzyfication is made by centroid method.

Table 2. Inference Table

If dIq/dt S then **Filter (Kc)** FG
If dIq/dt M then **Filter (Kc)** FM

If dIq/dt B and ω_r S then **Filter (Kc)** FM

If dIq/dt B and ω_r M then **Filter (Kc)** FS

If dIq/dt B and ω_r B then **Filter (Kc)** FS

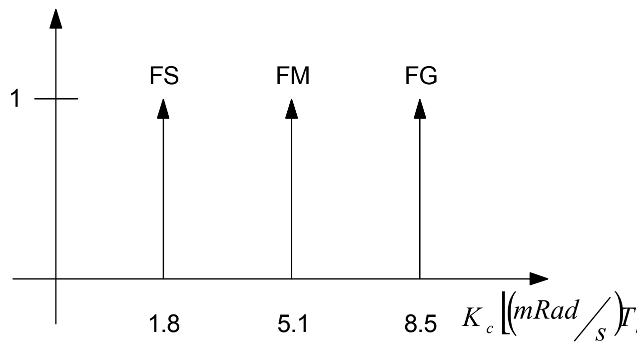

Figure 7.Out.membership func. Kc (Filter)

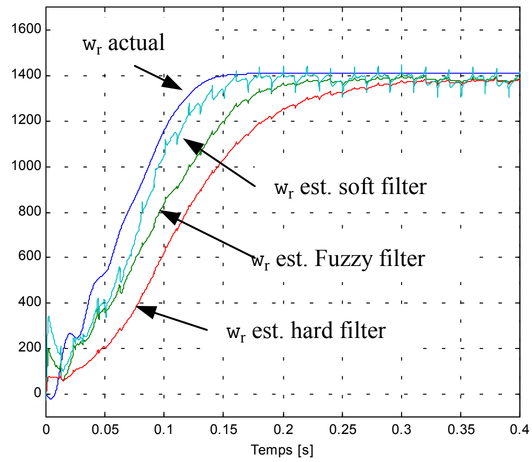

Figure 8 Fuzzy filter response
on the Open Loop Estimator

In the figure 8 we can see three waves under the actual speed. We can see a bad filtered response although is very near to the actual speed (soft filter constant). The lowest response is good filtered signal but too delayed (hard filter constant). The response that is between both waves is the adaptative filtered response. The system chooses the best cut frequency and the response is always good filtered and not too much delayed.

The system reaching the aims can be seen. The behaviour during the transient is widely improved respect the hard filter. The response in the steady-state is as well as the best response (hard filter) but quicker. The good performance using this system in FOC is not demonstrated yet.

5. RESULTS

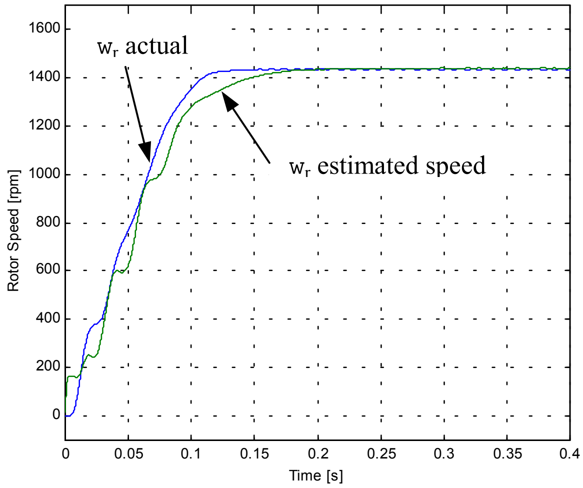

Figure 9. Actual and estimated speed during the start-up (220V / 50 Hz)

Figures 1 and 8 show, separately, the responses of both estimators that have been used to make the ponderated average. The response of the steady-state estimator is not good during almost all the transient. That is, between 0.1 and 0.15 seconds although the motor is in the transient the steady-state response is better than the filtered open-loop estimator. Therefore, the Fuzzy system must take care about this aspect. Debt to this the shape of the output fuzzy functions over the ponderated ratio is not uniform distributed. Figures 9 and 10 show the response of the system that has been developed. Every figure shows the response during the star-up of the plant (the worst transient) in different values of the set-up. Both figures show how the response of the estimator is very close to the actual speed during the transients and they are superposed in the steady-state.

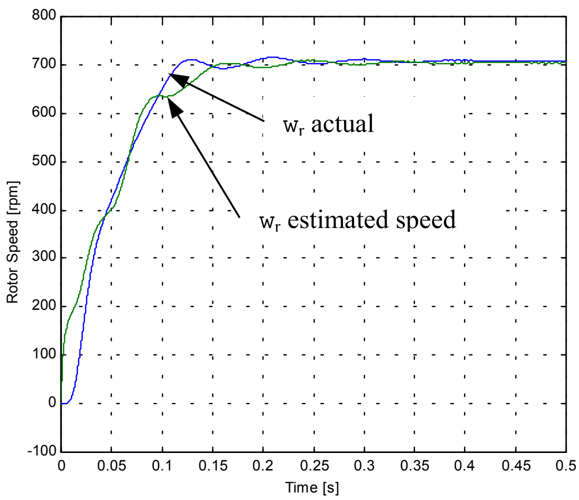

Figure 10. Actual and estimated speed during the start-up (110V / 25 Hz)

6. CONCLUSIONS

The system that has been implemented solves the filter problem in open-loop estimators, besides an accurate response can be obtained with the pondered average system even during the transient. The system mixes the accurate steady-state estimator response with the possibility of following the value of the speed in the transient with an open-loop estimator without noise. The good performance is debt to a fuzzy system that moves softly from one response to another. The same fuzzy structure controls the cut frequency of an adaptative filter.

The designed system has been thought to be implement in the easiest way that can be possible in order to minimise the computational charge of a microprocessor.

As the system is able to estimate accurately the speed in the steady-state and during the transient it can be used in a closed loop speed control.

7. ACKNOWLEDGEMENTS

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Annex I Plant Model

$$\begin{bmatrix} v_{sd} \\ v_{sq} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & Mp & 0 \\ 0 & R_s + L_s p & 0 & Mp \\ Mp & -M\omega_r & R_r + L_r p & -L_r \omega_r \\ M\omega_r & Mp & L_r \omega_r & R_r + L_r p \end{bmatrix} \cdot \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix}$$

$$\Gamma_{elec}(t) = M(i_{sq} i_{rd} - i_{sd} i_{rq})$$

$$\frac{d\omega_r}{dt} = \frac{1}{J}(\Gamma_{elec} - \Gamma_{mec})$$

$$\Gamma_{mec} = 1.087 + (-0.767 \cdot 10^{-3} + \frac{0.29937}{R_L}) * \omega_r + 6.1 \cdot 10^{-5} * \omega_r^2$$

Annex II: Mainly characteristics about the motor used

Supply	380 V/220V 3.5A /6 A (Rms Value)
Power	P_n=2 Cv = 1.5kW
Speed	ω_m=1450 r.p.m. (s=0.033)
Poles	p=2
Efficiency	76.9%
cos(ϕ)	0.8
Torque	Γ_n =9.8 N·m
Inertia	J=0.006 kg·m2
Stator Resistance	R1=4.3 Ω
Rotor Resistance	R2=8.18 Ω
Mutual or magnetising Ind.	Lm=0.3056 H
Serf Inductance	Ls= Lr=0.0301 H