NEW ADAPTIVE METHOD OF PARAMETERS ESTIMATION FOR INDUCTION MOTOR DRIVES USING FUZZY LOGIC

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Abstract

A new approach to estimating induction motor parameters from measured quantities for speed-sensorless control is described. The reference model comprises two parts: in the first section, the rotor speed is determined. Next, the stator currents are calculated and compared to the real measures. The error is used in a Fuzzy system to correct the rotor and stator resistances. The method also includes an off-line estimation of the initial parameters and estimation of load torque and moment of inertia. Computer simulations are compared with experimental results to demonstrate the effectiveness of this method.

Keywords: Parameter Estimation , Induction Motor, Fuzzy Logic.

1. INTRODUCTION

High-performance motion control applications require exact knowledge of the electrical and mechanical motor parameters such as resistances, inductances and moment of inertia. Combined with measured voltages and currents the motor driver is able to calculate the rotor and stator fluxes, estimate rotor speed and adjust the control parameters so the optimum performance is maintained. Rotor and stator resistance are very sensitive to temperature variations and errors in these resistances highly affect speed and fluxes estimation in open loop (Kanmachi & Takahashi, 1995) and closed loop approaches (Tamai et al., 1987; Schauder, 1989). Different implementations and techniques have been proposed to obtain a more robust system like MRAS (Peng; Fukao 1994), and EKF (Wade et al., 1997). The main inconvenience of these systems is the need of high speed A/D converters due to high frequency injection in torque control and PWM operation.

Fuzzy Logic and Neural Networks were recently introduced in speed estimation (Krzeminski, 1995; Ben-Brahim, 1995) but these methods still presents high estimation errors at low speeds. To overcome this problem, this paper presents a new adaptive method of electrical and mechanical parameter estimation with R_s (stator resistance) and R_r (rotor resistance) correction by a Fuzzy Logic system. By using two equations, one little sensitive to rotor resistance variations and the other little sensitive to stator resistance variations, the estimator is robust and it is not restricted to PWM operation or high frequency injection in torque control as other methods are.

Experimental tests are performed in a 1/3 hp induction motor drive to validade the models.

2. PROPOSED METHOD

The proposed method has a stator current estimator and a Fuzzy Logic corrector in the adaptive mechanism. The current estimator has two parts: the first estimates the rotor speed and the second, the stator currents. The difference between estimated and measured currents is used to correct the stator and rotor resistances for the adjustable model.

2.1 Proposed scheme

Two equations are used by the rotor speed estimator: one is derived from the steady state equations and the other derived from the dynamic equations of the motor model. The equations are obtained so that the steady state equation output is not affected by R_s variations and the transient equation output is not affected by R_r variations. These characteristics are used by the system to determine the correction of the resistance parameters.

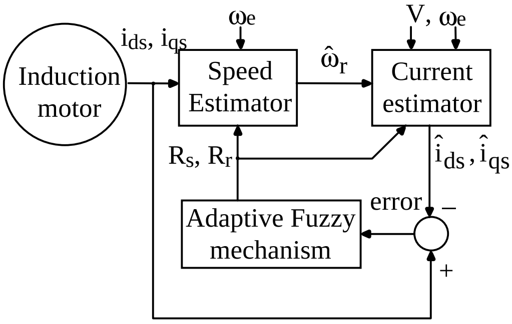


Figure 2.1: Proposed adaptive estimator

2.2 Stator current estimator

The folowing equations of the induction motor dynamic model in synchronous reference frame is used to estimate de stator currents, using as inputs, the motor parameters, synchronous and estimated rotor speeds, and stator voltages.

$$\lambda_{ds} = L_s \cdot i_{ds} + L_m \cdot i_{dr} \tag{2.1}$$

$$\lambda_{qs} = L_s \cdot i_{qs} + L_m \cdot i_{qr} \tag{2.2}$$

$$\lambda_{dr} = L_m \cdot i_{ds} + L_r \cdot i_{dr} \tag{2.3}$$

$$\lambda_{qr} = L_m \cdot i_{qs} + L_r \cdot i_{qr} \tag{2.4}$$

$$\lambda_{ds} = 1/p \cdot \lfloor v_{ds} - R_s \cdot i_{ds} + \omega_e \cdot \lambda_{qs} \rfloor \tag{2.5}$$

$$\lambda_{dr} = 1/p \cdot \lfloor v_{dr} - R_r \cdot i_{dr} + (\omega_e - \omega_r) \cdot \lambda_{qr} \rfloor \tag{2.6}$$

$$\lambda_{qs} = 1/p \cdot \lfloor v_{qs} - R_s \cdot i_{qs} - \omega_e \cdot \lambda_{ds} \rfloor \tag{2.7}$$

$$\lambda_{qr} = 1/p \cdot \lfloor v_{qr} - R_r \cdot i_{qr} - (\omega_e - \omega_r) \cdot \lambda_{dr} \rfloor \tag{2.8}$$

$$C_e = 3/2 \cdot P \cdot L_m \cdot (i_{qs} \cdot i_{dr} - i_{ds} \cdot i_{qr}) \tag{2.9}$$

$$\sigma = 1 - L_m^2 / (L_r \cdot L_s) \tag{2.10}$$

where:
λ_{ds}, λ_{qs} = d- and q-axis stator fluxes
λ_{dr}, λ_{qr} = d- and q-axis rotor fluxes
i_{ds}, i_{qs} = d- and q-axis stator currents
i_{dr}, i_{qr} = d- and q-axis rotor currents
v_{ds}, v_{qs} = d- and q-axis stator voltages
v_{dr}, v_{qr} = d- and q-axis rotor voltages
σ = leakage coefficient
L_s, L_m, L_r = stator, magnetizing and rotor inductances
R_r, R_s = rotor and stator resistances
P = number of poles
p = diferencial operator
ω_e, ω_r = synchronous and rotor speed
T_e = electromagnetic torque

2.3 Rotor speed estimator

2.3.1 Steady state equation

By eliminating i_{qr} from (2.4) and (2.8) and assuming v_{qr} = 0 for squirrel-cage induction motor:

$$(\omega_e - \omega_r) = \frac{1}{\lambda_{dr}} \cdot \left[-p\lambda_{qr} - R_r \cdot \frac{\lambda_{qr}}{L_r} + R_r \cdot \frac{L_m}{L_r} \cdot i_{qs} \right] \quad (2.11)$$

In stady state, $p\lambda_{qr} \approx 0$ and $|\lambda_{qr}| << |L_m \cdot i_{qs}|$ can be assumed. Then (2.11) can be rewritten as:

$$(\omega_e - \omega_r) = \frac{R_r \cdot L_m}{L_r} \cdot \frac{i_{qs}}{\lambda_{dr}} \quad (2.12)$$

Solving for λ_{dr} from (2.1) and (2.3) and substituting in (2.12):

$$\omega_r = \omega_e - \frac{K_1 \cdot i_{qs}}{(K_2 - i_{ds})} \quad (2.13)$$

where K_1 e K_2 are fixed values and given by $\frac{L_m^2 \cdot R_r}{L_r^2 \cdot L_s \cdot \sigma}$ and $\frac{1}{L_s \cdot \sigma} \cdot \lambda_{ds}$, respectively.

From (2.7), assuming $p\lambda_{qs} \approx 0$ for the steady state condition and $R_s \cdot i_{qs} << v_{qs}$ (negligible ohmic losses), then the flux λ_{ds} is calculated as:

$$\lambda_{ds} = v_{qs} / \omega_e \quad (2.14)$$

The equation (2.13) estimates rotor speed directly from the measured currents and integrators are not required, thus making it easy to implement.

2.3.2 Transient equation

Solving (2.6) and (2.8) for ω_r and eliminating R_r, the transient equation is obtained (Kanmachi & Takahashi, 1995):

$$\omega_r = \omega_e - \left(\frac{p\lambda_{dr} \cdot i_{qr} - p\lambda_{qr} \cdot i_{dr}}{\lambda_{dr} \cdot i_{dr} + \lambda_{qr} \cdot i_{qr}} \right) \quad (2.15)$$

The rotor fluxes (λ_{dr} and λ_{qr}) and rotor currents (i_{dr} and i_{qr}) can be calculated from measured voltages and currents.

2.4 Fuzzy estimator of R_s and R_r

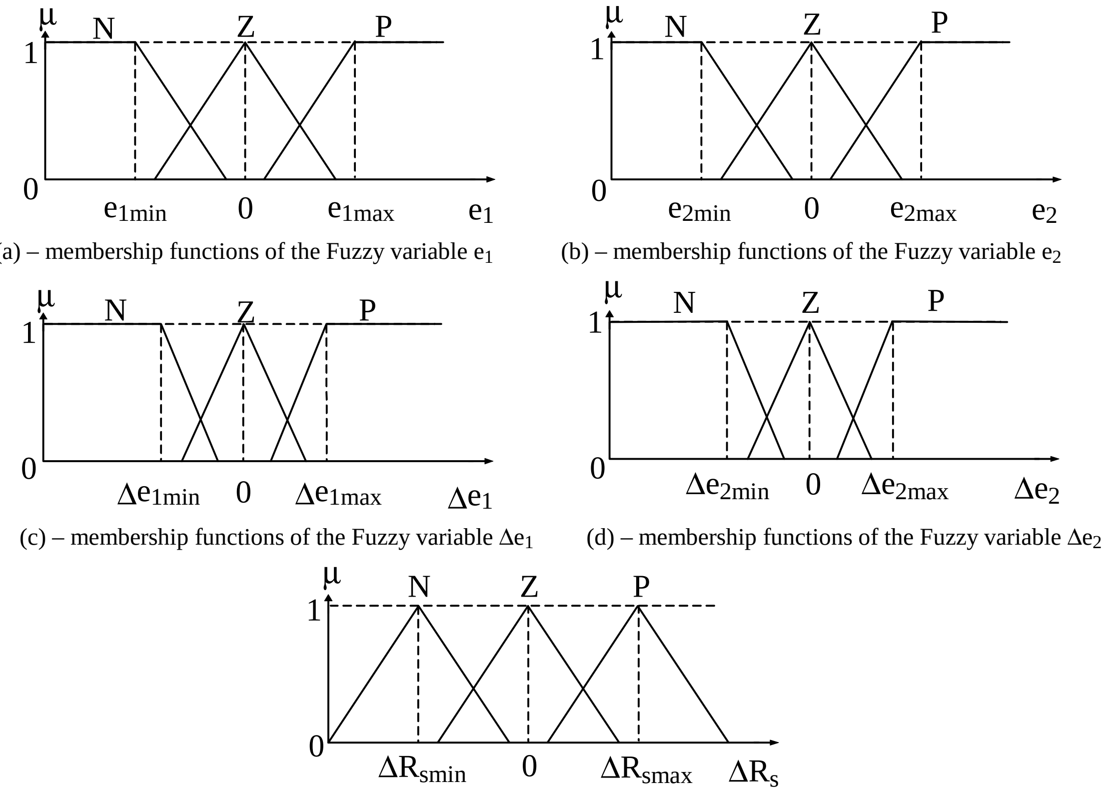
The Fuzzy estimator uses the stator current error to determine the correction ΔR_s or ΔR_r added to the parameters R_s and R_r, respectively. ΔR_s is calculated in the steady state condition and ΔR_r, in the transient condition. The feedback mechanism is used to minimize the stator current error.

Each input and output variable has 3 Fuzzy sets: positive (P), negative (N) and zero (Z).

2.4.1 R_s estimator

Four input variables (e_1, e_2, Δe_1 and Δe_2) and one output variable (ΔR_s) are defined for the R_s estimator. Figure 2.2 shows the membership functions of these Fuzzy variables, defined as follows: e_1 and Δe_1 are the i_{ds} current error and its derivative, respectively; e_2 and Δe_2 are the i_{qs} current error and its derivative, respectively; and ΔR_s is the correction added to the variable R_s.

Tables 2.1 and 2.2 summarizes the rule sets used by the Fuzzy estimator.



(a) – membership functions of the Fuzzy variable e_1

(b) – membership functions of the Fuzzy variable e_2

(c) – membership functions of the Fuzzy variable Δe_1

(d) – membership functions of the Fuzzy variable Δe_2

(d) – membership functions of the Fuzzy variable ΔR_s

Figure 2.2: membership functions of the Fuzzy variables e_1, e_2, Δe_1, Δe_2 and ΔR_s

Table 2.1: Rule set table for the inputs e_1 and e_2

e_2 \ e_1	N	Z	P
N	–	–	P
Z	–	Z	–
P	N	–	–

Table 2.2: Rule set table for the inputs Δe_1 and Δe_2

Δe_2 \ Δe_1	N	Z	P
N	–	–	P
Z	–	Z	–
P	N	–	–

2.4.2 R_r estimator

Table 2.3: Rule set table for the inputs ITAE and ΔITAE

ΔITAE \ ITAE	N	Z	P
N	–	–	P
Z	–	Z	–
P	N	–	–

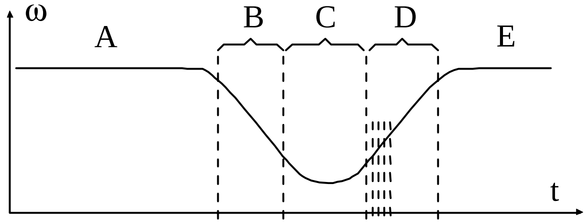
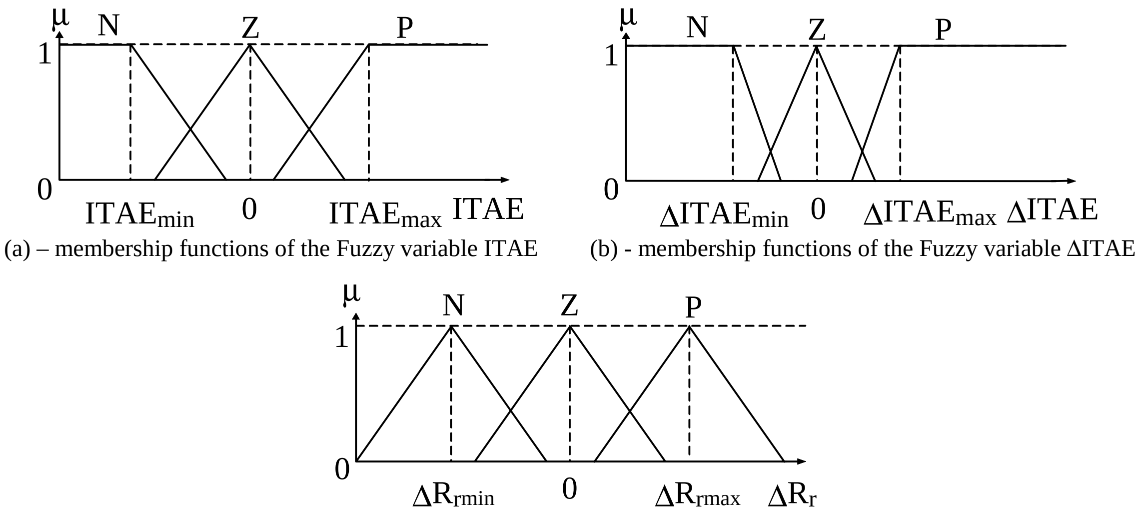


Figure 2.4: Moment of inertia estimation

The process to estimate de R_r is similar to the one used to estimate R_s. The difference is that this system uses as input variables an error function ITAE and its derivative, ΔITAE. Figure 2.3 shows the correspondent membership functions and table 2.3, the rule sets.



(a) – membership functions of the Fuzzy variable ITAE (b) - membership functions of the Fuzzy variable ΔITAE

(c) – membership functions of the Fuzzy variable ΔR_r

Figure 2.3: membership functions of the Fuzzy variables ITAE, ΔITAE and ΔR_r

2.5 Estimation of moment of inertia and load torque

From the general electromechanical equation at time (k):

$$T_e(k) = I \cdot \dot{\omega}(k) + T_l(k) \tag{2.16}$$

where T_e is the electromagnetic torque, $\dot{\omega}$ is the angular acceleration, I is the moment of inertia and T_l, the load torque.

And at time (k+1):

$$T_e(k+1) = I \cdot \dot{\omega}(k+1) + T_l(k+1) \tag{2.17}$$

Subtracting (2.16) from (2.17) and assuming that there is no variation in load torque, the following equation is obtained for the moment of inertia I:

$$I = \frac{T_e(k+1) - T_e(k)}{\dot{\omega}(k+1) - \dot{\omega}(k)} \tag{2.18}$$

In the proposed method, a variation in produced torque is necessary in order to calculate the result of equation (2.18). In interval time B, $T_e(k) = 0$ and $\dot{\omega}(k)$ is measured. Electromagnetic torque is reapplied after B (C, D and E). $T_e(k+1)$ and $\dot{\omega}(k+1)$ are measured in interval D.

Once the moment of inertia is known, the load torque can be calculated using (2.19):

$$T_l = T_e(k) - I \cdot \dot{\omega}(k) \tag{2.19}$$

To attenuate the effects of torsional vibrations and make the acceleration signal usable, it must be heavily filtered. The electromagnetic torque must also be filtered so the same time delay is created. The amount of filtering is not crucial as long as they are in phase with each other and adequately filtered from the effects of torsional vibrations.

2.6 Initial parameters calculation

The initial parameters are calculated using the usual free run, rotor locked and direct current tests. The free run and rotor locked tests gives the stator currents i_{ds0} and i_{qs0} and i_{dsL} and i_{qsL}, respectively. The electric parameters of the dynamic model are calculated by (2.20), (2.21) and (2.22), assuming a known relation between X_s and X_r. The stator resistance is obtained in the direct current test.

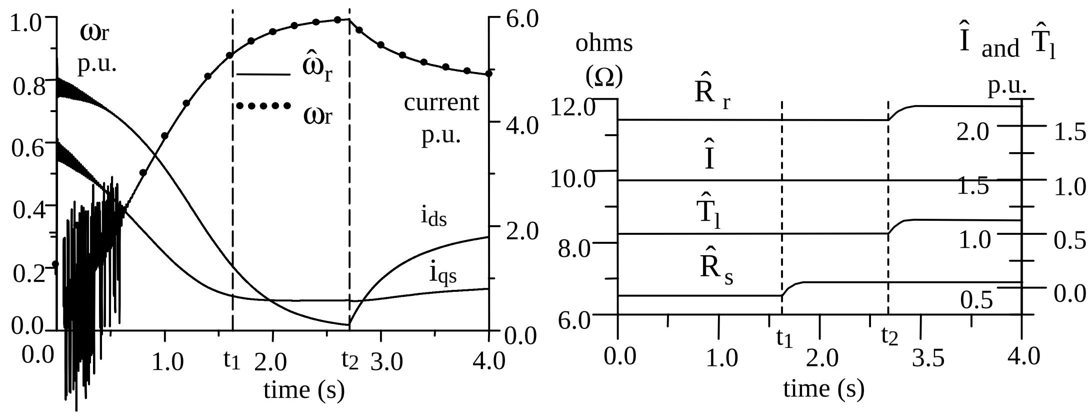
$$R_r = \frac{v_{qs} \cdot i_{qs}}{\left(i_{ds}^2 + i_{qs}^2\right)} - R_s \tag{2.20}$$

$$X_m = \frac{v_{qs0}^2}{v_{qs0} \cdot i_{ds0} - (i_{ds0}^2 + i_{qs0}^2) \cdot X_s} \cdot \frac{1}{1+\dfrac{X_s}{X_m}} \tag{2.21}$$

$$X_s = \frac{v_{qsL} \cdot i_{dsL}}{\left(i_{dsL}^2 + i_{qsL}^2\right) \cdot \left(1+\dfrac{X_s}{X_r}+\dfrac{X_s}{X_m}\right)} \cdot \left(\frac{X_s}{X_r}+\frac{X_s}{X_m}\right) \tag{2.22}$$

3. SIMULATION RESULTS

3.2 Response to R_s and R_r variation



(a)- Simulated rotational speed and stator currents. (b) - Parameter estimation under R_s and R_r variation.

Figure 3.2: System response to R_s and R_r variation.

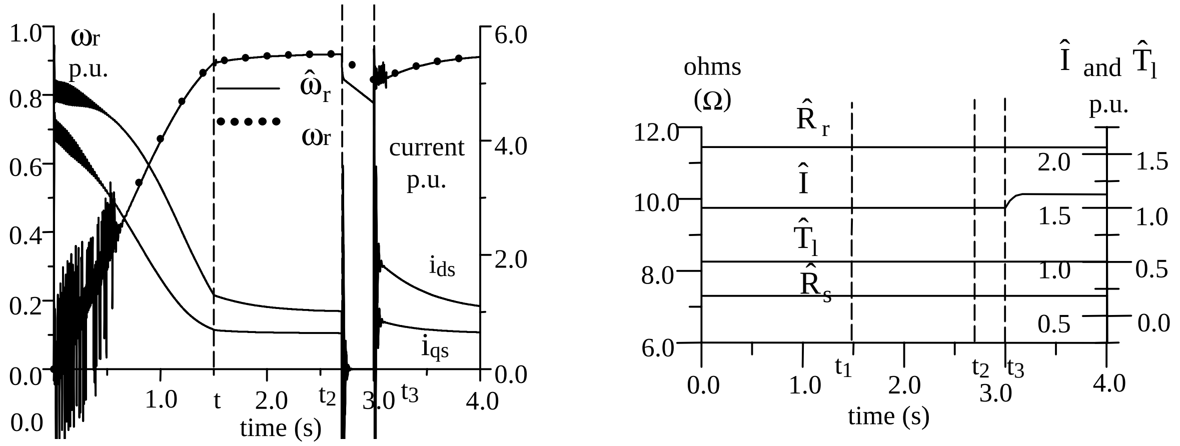
Figure 3.2 shows the estimation results of +20% variation in both resistances simultaneously. The test conditions were v_s = 0.22 p.u., ω_s = 1 p.u. and torque step of T_l = 0.37 p.u. at t_2 = 2.7s. The stator resistance, is updated during interval time t_1 to t_2, when equation (2.13) is used; and rotor resistance is updated after time t_2 when (2.15) is used.

Under these simulated conditions, the estimated speed error is less than 1% in the steady state condition and less than 0.3% in the transient condition.

3.3 Estimation of moment of inertia

Figure 3.3 shows how the estimated parameters behave under the estimation of moment of inertia. At t_1 = 1.5s, the load torque of 0.37 p.u. magnitude is applied. The produced electromagnetic torque is removed at t_2 = 2.7s and reapplied at t_3 = 3.0s. During the interval time between t_2 and t_3, $\dot{\omega}(k)$ is sampled and after t_3, $\dot{\omega}(k+1)$ is sampled.

The transient equation is used in the interval time 0s to t_1. Between t_2 and t_3, the error in the speed estimation is higher than the error observed in other intervals because the stators currents are close to zero. If this interval is not considered, the maximum error in speed estimation is less than 0.10% during steady state and less than 0.01% during transient.



(a) – Speed estimation during T_e oscilation. (b) – Parameter estimation during T_e oscilation.

Figure 3.3: estimation of moment of inertia.

4. EXPERIMENTAL RESULTS

Table 4.1: Electrical and mechanical parameters of the induction motor - 220V – 1/3 hp

$\mathbf{R_s}$ = 6.500 Ω	$\mathbf{L_m}$ = 546.184547 mH	**Nominal current** = 0.376 A
$\mathbf{R_r}$ = 9.137 Ω	$\mathbf{Z_b}$ = 584.15 Ω	**Number of poles** = 2
$\mathbf{L_s}$ = 556.400662 mH	$\mathbf{L_{ls}}$ = 10.21612 mH	**Nominal speed** = 3500 rpm
$\mathbf{L_r}$ = 569.942954 mH	$\mathbf{L_{lr}}$ = 23.75841 mH	**I (motor and load)** = 7.72 x 10^{-4} kg.m^2

4.1 Simulation and experimental results comparison

Figure 4.1 shows both the real and estimated speed, for comparison, along with the estimated produced torque $\hat{T}_e$ and the real load torque T_l. The data were obtained under free run. The actual voltages, currents and torque were measured in the test bench.

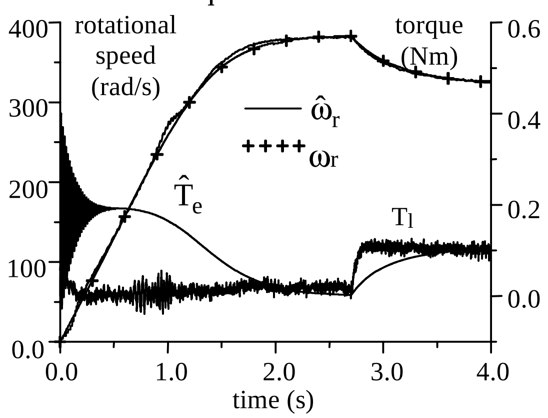


Figure 4.1: Measured and estimated rotational speed, and produced torque $\hat{T}_e$ and load torque T_l.

4.2 Response of the new speed estimator

The new speed estimator for steady state (2.13) was tested in free-run and in variable speed (figure 4.7).

The results of the proposed estimator are close to the real measures for speeds above 0.6 p.u. as shown on figure 4.6. The measured speed errors are 0.3% during no-load condition and 0.9% after the load torque is applied.

In the variable speed test, shown on figure 4.7, the estimated speed was also close to the real measures: the speed error was between 0.3%, with ω_e = 405 rad/s, and 2.0%, with ω_e = 257 rad/s.

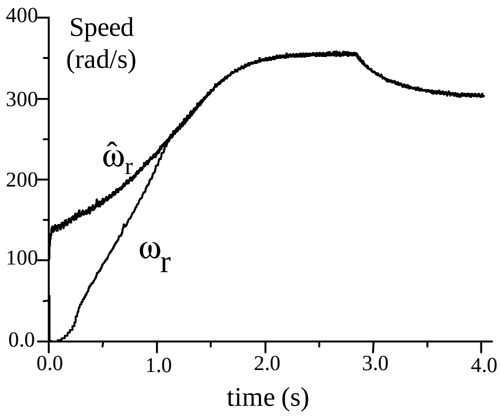


Figure 4.6: Actual and estimated rotational speed

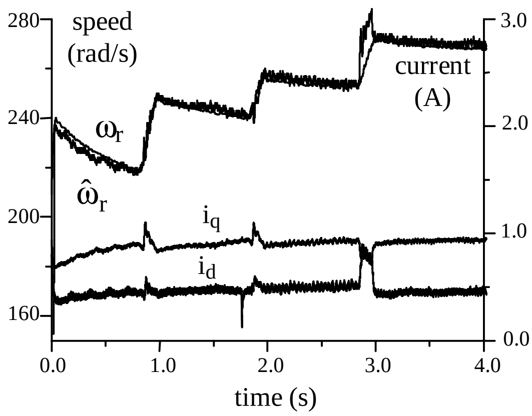


Figure 4.7: Actual and estimated speeds for various ω_e

5. CONCLUSIONS AND FINAL ANALYSIS

A new parameter estimation method using Fuzzy Logic correction of R_s and R_r was presented. This work also includes the initial parameter determination and estimation of speed, moment of inertia and load torque. Using direct current, free run and rotor lock tests, the initial parameters can be calculated. The estimation and correction of parameters is possible using simple algorithms.

The new system was evaluated through computer simulations and validated by experimental results. In the computer simulations the maximum observed error in the steady state condition was 0.3% and in the transient condition was 0.2% for 50% variation in both R_r and R_s. The experimental results using a 1/3 hp three-phase induction motor showed error between 0.3% with no load and ω_e = 405 rad/s, and 2.0% with load and ω_e = 257 rad/s.

This new method can be simplified for using in low cost induction motor drivers through the implementation of the steady state equation (2.13) alone, which proved to give good results over a wide range of speeds.

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