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An improved parallel observer of speed and stator resistance for sensorless induction motor drives

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ABSTRACT

The purpose of this work is to contribute to the improvement of the dynamic performance of Rotor Flux-MRAS estimator for a simultaneous estimation of speed and stator resistance of induction motor in sensorless rotor field oriented control, having as available information voltages and stator currents. The conventional adaptation mechanism of stator resistance MRAS estimator using a proportional integral controller (PI) in first scheme is changed by a variable gain proportional integral controller (VGPI) in second scheme, then by an intelligent controller (fuzzy-PI) in third scheme. The value of estimate stator resistance is introduced online into the speed estimator with the Pl adaptation mechanism is substituted in last scheme with a fuzzy-PI controller. Tests are performed and validated by numerical simulation by MATLAB SIMULINK, environment, acquired results illustrate the contribution of every controller in quality terms of estimation and robustness, in relation to the variations of the stator resistance of the induction motor.

1. Introduction

Since its invention, the asynchronous motor has become for its low cost, robustness and reliability the most used electric motor in the industry. But, its use at variable speeds required the development of control strategies of three-phase power frequency and variable amplitude. The vector control strategy by the field orientation is based on effective control of the magnetic state, is for some years the most important axis of research and the best adapted to the industrial requirements.

However this structure requires knowledge of the instantaneous value of the angular speed of the machine and thus the implementation of mechanical sensor that can increase the cost and degrade the performance of the system. To overcome this problem, recent

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work have successful methods of estimation of the instantaneous speed of the machine such as the MRAS method using the currents and the stator voltages and thus replace the mechanical sensor of speed by currents and stator voltages electric sensors. This estimation method uses the values of the parameters of the machine such as the stator resistance value, thus it is very sensitive to variations of these parameters, the difference of the value of the stator resistance used in speed with its actual value estimator led not only to the estimation error, but also to the instability of the controlled system.

From this point of view, we try to identify online the stator resistance, which is a parameter very influencing the performance of the estimator of speed, the idea is based on the simultaneous identification of the speed and the stator resistance [1], By using an adaptive system to reference model (MRAS) with different mechanisms of adaptation.

2. MRAS technique estimation

The model reference adaptive system (MRAS) is one of the most famous techniques employed in adaptive control.

In this system, induction motor state variables are evaluated in the reference model based on the measured variables (stator voltages, stator currents).

The reference model is independent of estimated variable and uses the voltage machine model. The adaptive model uses the current model of the machine and the estimated variable is one of the input variables of this model.

The difference between state variables is adaptive signal (ε) which is evaluated and minimized by the PI regulator in the block adaptation mechanism which performs the estimate value and adapts adaptive model until the desired behavior.

With feedback, the observer is able to limit the impact of changes in machine parameters to the accuracy of the calculation [2].

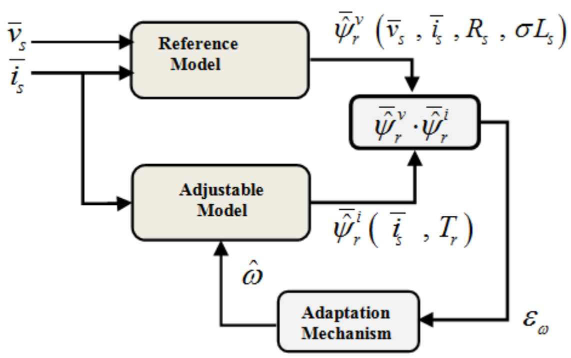

Fig. 1. MRAS speed estimator based on the rotor flux.

The MRAS structures will differ by the choice of the output variable of the two models, as well as by the choice of the adaptation mechanism. The approach by MRAS structure is used both for the estimation of the speed in sensorless control and for the parametric estimation in real time.

3. Mathematical description RF-MRAS

Rotor flux MRAS (RF-MRAS) is the simplest variant of observers working on the principle of MRAS. For the estimation, equations are used which determine derivation of the rotor flux of the machine [5].

The reference model of MRAS method is based on the application of voltage model with derivation of the rotor flux which is in the stator coordinate system described by the following equations :

$$\begin{cases} \psi_{r\alpha} = \frac{L_r}{L_m}\left(\int (v_{s\alpha} - R_s i_{s\alpha})\, dt - \sigma L_s i_{s\alpha}\right) \\ \psi_{r\beta} = \frac{L_r}{L_m}\left(\int (v_{s\beta} - R_s i_{s\beta})\, dt - \sigma L_s i_{s\beta}\right) \end{cases} \tag{1}$$

The adaptive model of the MRAS method is based on the application of the current model with derivation of rotor flux, which is in the stator coordinate system described by the following Eq. (2), which depends on the mechanical angular velocity :

$$\begin{cases} \hat{\psi}_{r\alpha} = \int \left(\frac{L_m}{T_r} i_{s\alpha} - \frac{1}{T_r}\hat{\psi}_{r\alpha} - \hat{\omega}\hat{\psi}_{r\beta}\right) dt \\ \hat{\psi}_{r\beta} = \int \left(\frac{L_m}{T_r} i_{s\beta} - \frac{1}{T_r}\hat{\psi}_{r\beta} + \hat{\omega}\hat{\psi}_{r\alpha}\right) dt \end{cases} \tag{2}$$

The error signal entering to the controller is corresponding to the deviation of the rotor flux and it is described by Eq. (3), after processing by PI controller ; we get an estimate angular speed on the output of adaptation algorithm - Eq. (4).

$$\varepsilon_\omega = (\hat{\psi}_{r\alpha} \cdot \psi_{r\beta}) - (\hat{\psi}_{r\beta} \cdot \psi_{r\alpha}) \tag{3}$$

$$\hat{\omega} = k_p \cdot \varepsilon_\omega + k_i \cdot \int \varepsilon_\omega \cdot dt \tag{4}$$

Equation (3) corresponds to the opening angle of both vectors. The sign of the error signal ε_ω then determines the type of request to change speed. Positive error requires $\varepsilon_\omega > 0$ an increase of the estimated speed and negative error $\varepsilon_\omega < 0$ requires reduction of the estimated speed [10].

4. Speed and stator resistance parallel estimation

4.1. PI Adaptation mechanism for the stator resistance controller

Proposed parallel rotor speed and stator resistance estimation scheme is designed based on the concept of hyperstability [11] in order to make the system asymptotically stable. For the purpose of deriving an adaptation mechanism, it is valid to initially treat rotor speed as a constant parameter, since it changes slowly compared to the change in rotor flux. The stator resistance of the motor varies with temperature, but variations are slow so that it can be treated as a constant parameter, too. The configuration of the proposed parallel rotor speed and stator resistance is shown in Fig. 2

The equations of the voltage model and the current model output errors are given by :

$$\frac{d}{dt}\bar{\varepsilon}^{v} = -\frac{L_r}{L_m}\left(R_s - \hat{R}_s\right)\bar{\imath}_s \tag{5}$$

$$\bar{\varepsilon}^{v} = \bar{\psi}_r^{v} - \bar{\hat{\psi}}_r^{v} = {\varepsilon_\alpha}^{v} + j{\varepsilon_\beta}^{v} \tag{6}$$

$$\frac{d}{dt}\bar{\varepsilon}^{i} = \left(j\omega - \frac{1}{T_r}\right)\bar{\varepsilon}^{i} + j\left(\omega - \hat{\omega}\right)\bar{\hat{\psi}}_r^{i} \tag{7}$$

$$\bar{\varepsilon}^{i} = \bar{\psi}_r^{i} - \bar{\hat{\psi}}_r^{i} = {\varepsilon_\alpha}^{i} + j{\varepsilon_\beta}^{i} \tag{8}$$

Symbols $\bar{\psi}_r^{v}$ and $\bar{\psi}_r^{i}$ represent the actual values of rotor flux of the two models. For the estimation of speed, the output of the reference model (Eq. 1) is taken equal to the actual value of the rotor field vector. The amount of error for the estimation of speed $\varepsilon_\omega(t)$ is therefore that of Equation (4).

$$\varepsilon_\omega(t) = \left(\hat{\psi}_{r\alpha}^{i} \cdot \hat{\psi}_{r\beta}^{v} - \hat{\psi}_{r\beta}^{i} \cdot \hat{\psi}_{r\alpha}^{v}\right) \tag{9}$$

It is necessary to take into account that, for stator resistance estimation, reference and adjustable model (1), (2) change the roles. The true value of the rotor flux space vector is now taken to be the output of (2). The error quantity for stator resistance estimation is therefore :

$$\varepsilon_{Rs}(t) = i_{s\alpha}\left(\hat{\psi}_{r\alpha}^{v} - \hat{\psi}_{r\alpha}^{i}\right) + i_{s\beta}\left(\hat{\psi}_{r\beta}^{v} - \hat{\psi}_{r\beta}^{i}\right) \tag{10}$$

The role of the reference and the adjustable models is interchangeable in the parallel system of rotor speed and stator resistance estimation.

The speed and stator resistance can be estimated in parallel at any speed using (11), (12) :

$$\hat{\omega} = \left(k_{p\omega} + \frac{k_{i\omega}}{s}\right)\left(\hat{\psi}_{r\alpha}^{i} \cdot \hat{\psi}_{r\beta}^{v} - \hat{\psi}_{r\beta}^{i} \cdot \hat{\psi}_{r\alpha}^{v}\right) \tag{11}$$

$$\hat{R}_s = \left(k_{PR_s} + \frac{k_{iR_s}}{s}\right)\left[i_{s\alpha}\left(\hat{\psi}_{r\alpha}^{v} - \hat{\psi}_{r\alpha}^{i}\right) + i_{s\beta}\left(\hat{\psi}_{r\beta}^{v} - \hat{\psi}_{r\beta}^{i}\right)\right] \tag{12}$$

$k_{p\omega}$ and $k_{i\omega}$ are respectively the value of the proportional gain and the value of the Integrator gain of PI speed controller. k_{PR_s} and k_{iR_s} are the proportional gain value and the value of integrating the PI stator resistance controller gain respectively.

Configuration of parallel rotor speed and stator resistance estimation is shown in Figure 2.

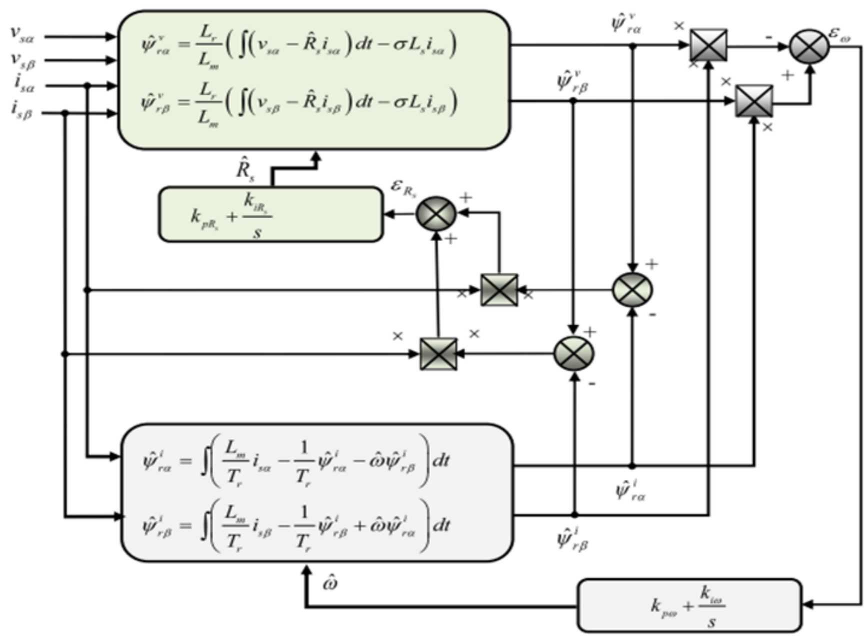

Fig. 2. Structure of the MRAS system for parallel rotor speed and stator resistance estimation.

4.2. VGPI adaptation mechanism for the stator resistance controller

The use of the PI controller for the estimation of the stator resistance is characterized by a large overshoot in the transient mode and during the variation of the stator resistance.

To address this problem and reduce drop of the estimation error over time, we propose the use of a variable gain PI controller (VGPI). The variable gain PI controller is a generalization of the classical PI, gains k_p and k_i of classical PI controller are fixed, whereas those of the variable gain controller vary with time according to the following functions

$$k_p = \begin{cases} (k_{pf} - k_{pi})\left(\frac{t}{t_s}\right)^n + k_{pi} \text{ if } t < t_s \\ k_{pf} \text{ if } t \geq t_s \end{cases} \tag{13}$$

$$k_i = \begin{cases} k_{if}\left(\frac{t}{t_s}\right)^n \text{ if } t < t_s \\ k_{if} \text{ if } t \geq t_s \end{cases} \tag{14}$$

k_{pi} and k_{pf} are respectively the initial value and the final value of the proportional gain and k_{if} the final value of the integrator gain of variable gain controller. t_s is the n saturation time and is the degree of the variable gain controller [8].

4.3. Fuzzy-PI adaptation mechanism for the stator resistance controller

The major disadvantage of estimation approaches to MRAS is their heavy dependence on motor parameters, this is compounded by the difficulties of adjusting gains adaptive mechanism of the variable estimated especially if it comes from a conventional PI controller.

In this context, a fuzzy adaptation mechanism will be proposed for the estimator of the stator resistance. The error derived from the two models of the MRAS technique will be adjusted by means of a fuzzy-PI substituting the PI controller.

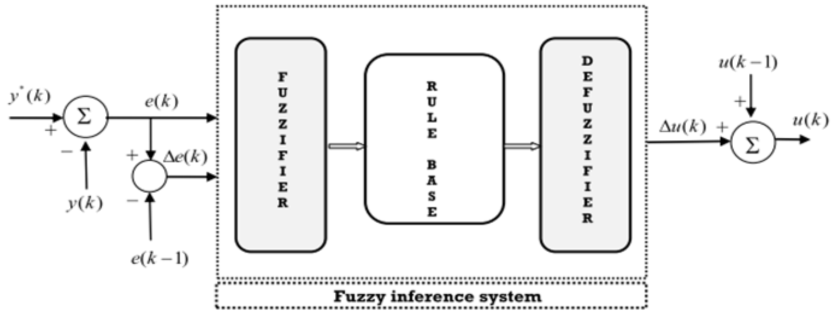

Fig. 3. The basic structure of fuzzy logic based controller.

Generally, a controller based on fuzzy logic uses the simple scheme, which is represented by the Figure 3 ; this configuration, analogous to that of a conventional PI, is often referred to as fuzzy-PI. For estimation of stator resistance, the inferred variance of both models of the MRAS technique will be adjusted with a fuzzy-PI controller.

Error :

$$e_{R_s}(k) = i_{s\alpha}\left(\hat{\psi}^{v}_{r\alpha} - \hat{\psi}^{i}_{r\alpha}\right) + i_{s\beta}\left(\hat{\psi}^{v}_{r\beta} - \hat{\psi}^{i}_{r\beta}\right) \tag{15}$$

And the variation in the error :

$$\Delta e_{R_s}(k) = e_{R_s}(k) - e_{R_s}(k-1) \tag{16}$$

are then considered as variables input of fuzzy controller, whose fuzzy output will give the variation $\Delta\hat{R}_s(k)$ of stator resistance estimated.

The value of estimated resistance is :

$$\hat{R}_s(k) = \hat{R}_s(k-1) + \Delta\hat{R}_s(k) \tag{17}$$

k_{eRs}, k_{dRs} and k_{uRs} re the scale factors respectively associated to $e_{R_s}(k)$, $\Delta e_{R_s}(k)$ and $\Delta\hat{R}_s(k)$.

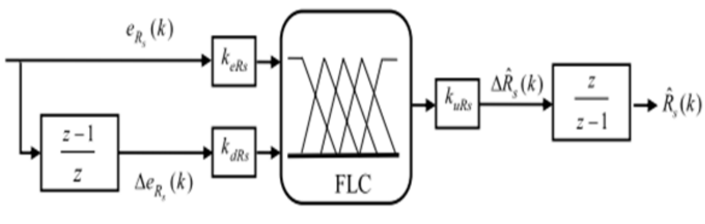

Fig. 4. Fuzzy-PI estimator of the stator resistance.

Fuzzification of the input and output linguistic variables was performed by symmetrical triangular membership functions. Each of the three variables is represented by seven linguistic fuzzy subsets, Figure 5.

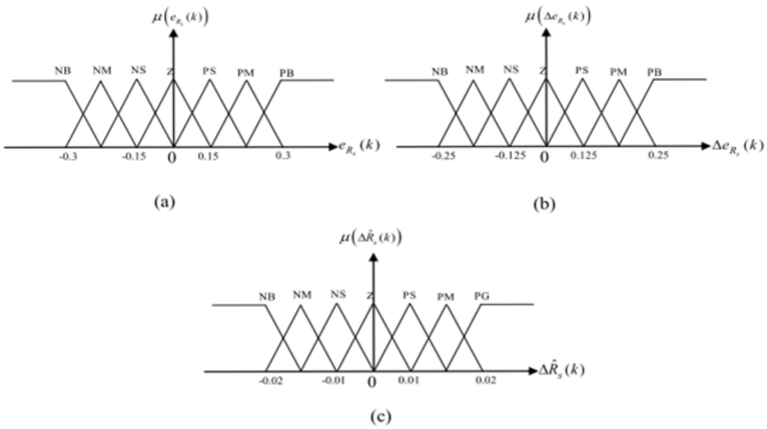

Fig. 5. Membership functions for the fuzzy-PI stator resistance.

The rules of inference used for estimation of stator resistance are summarized in table I. The following fuzzy sets are used : NB= NEGATIVE BIG, NM= NEGATIVE MEDUIM, NS= NEGATIVE SMALL, Z= ZERO, PS= POSITIVE SMALL, PM= POSITIVE MEDUIM, PB= POSITIVE BIG

Table 1. Fuzzy rules for fuzzy resistance estimator.

Δe_{R_s}	e_{R_s} / ΔR_s	NB	NM	NS	Z	PS	PM	PB
NB		NB	NB	NB	NB	NM	NS	Z
NM		NB	NB	NB	NM	NS	Z	PS
NS		NB	NB	NM	NS	Z	PS	PM
Z		NB	NM	NS	Z	PS	PM	PB
PS		NM	NS	Z	PS	PM	PB	PB
PM		NS	Z	PS	PM	PB	PB	PB
PB		Z	PS	PM	PB	PB	PB	PB

4.4. Speed fuzzy MRAS estimator

To improve our system consisting of two estimators MRAS, we substitute the PI controller of the mechanism of adaptation of MRAS speed estimator by a Fuzzy-PI whose structure is shown in Figure 6.

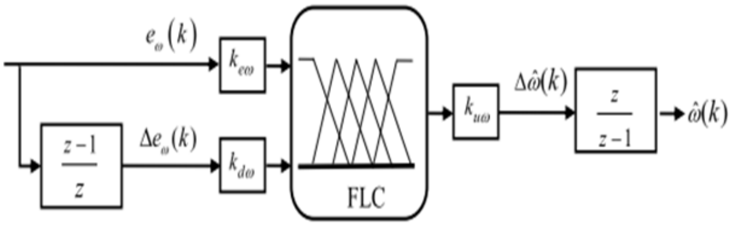

Fig. 6. Fuzzy- PI speed estimator.

To estimate the angular speed, the difference between the two models derived from the MRAS technique will be adjusted by means of a Fuzzy-PI
error :

$$\mathrm{e}_{\omega}(k) = \left(\hat{\psi}^{i}_{r\alpha} \cdot \hat{\psi}^{v}_{r\beta} - \hat{\psi}^{i}_{r\beta} \cdot \hat{\psi}^{v}_{r\alpha}\right) \tag{18}$$

and the variation in the error :

$$\Delta e_{\omega}(k) = e_{\omega}(k) - e_{\omega}(k-1) \tag{19}$$

are then considered as variables input of fuzzy controller, whose fuzzy output will give the variation $\Delta\hat{\omega}(k)$ of the estimated angular speed [9].

$$\hat{\omega}(k) = \hat{\omega}(k-1) + \Delta\hat{\omega}(k) \tag{20}$$

$k_{e\omega}$, $k_{d\omega}$ and $k_{u\omega}$ are the scale factors respectively associated to $e_{\omega}(k)$, $\Delta e_{\omega}(k)$ and $\Delta\hat{\omega}(k)$.

The controller allows for input variables and output variable five fuzzy as shown in Figure 7.

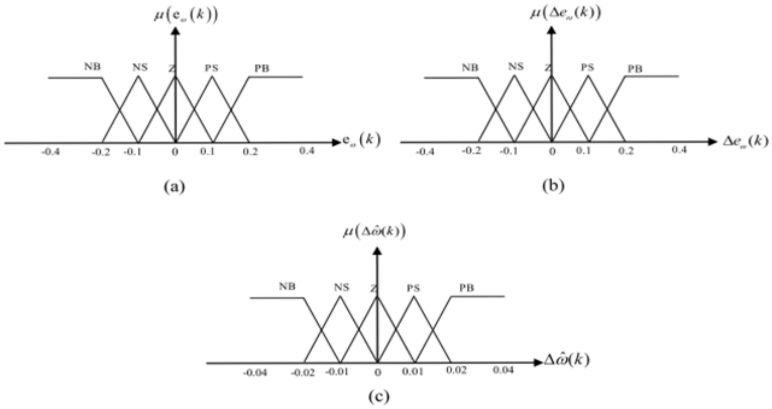

Fig. 7. Membership functions for the fuzzy speed estimator.

The rules of inference used for speed estimation are summarized in table II. The following fuzzy sets are used :NB= NEGATIVE BIG,NS= NEGATIVE SMALL, Z= ZERO, PS= POSITIVE SMALL, PB= POSITIVE BIG.

Table 2. Fuzzy rules for fuzzy resistance estimator.

e_{ω} / Δe_{ω} \ $\Delta\hat{\omega}$	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

Structure of the speed sensorless indirect rotor flux oriented induction motor drive with parallel MRAS estimator is represented in Figure 8.

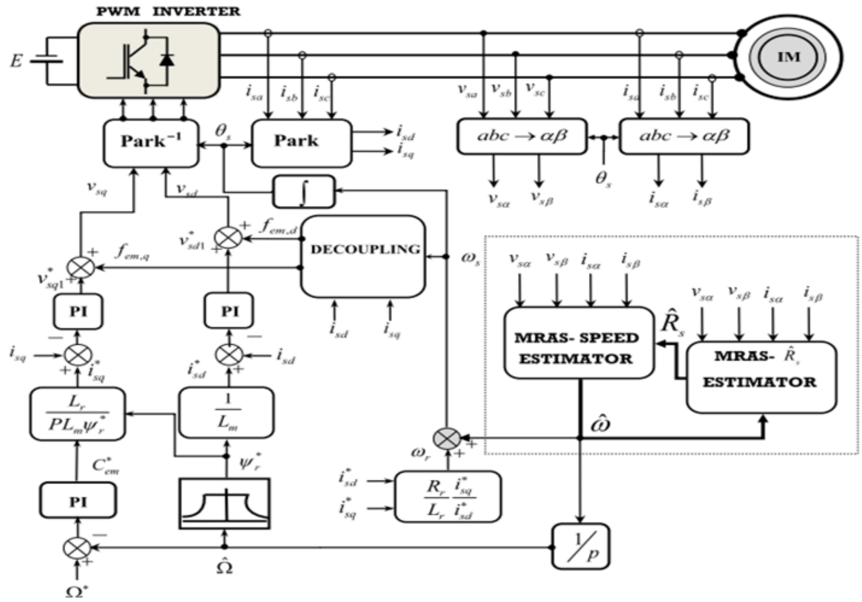

Fig. 8. Sensorless IRFOC with parallel MRAS estimator.

5. Simulation results

The parallel MRAS estimator proposed in this work has been simulated in MATLAB SIMULINK using the four schemes in the table.III.

The simulation have been carried out with speed and resistance estimate parallel , Stator resistance increased 100% suddenly at $3s$,and decreased 50% suddenly at $4s$. Reference speed equals $150rad/s$.

Induction motor parameters used are given in the appendix.

Table 3. Parameters

MRAS- Estimator	R_s	ω
Scheme (a)	PI	PI
Scheme (b)	VGPI	PI
Scheme (c)	FLC	PI
Scheme (d)	FLC	FLC

Figure 9 illustrates the estimation of the stator resistance ; the reaction of the estimated speed variations of the stator resistance is illustrated in Figure 10 for different used controllers. The drop in speed is significantly reduced with the use of fuzzy regulators.

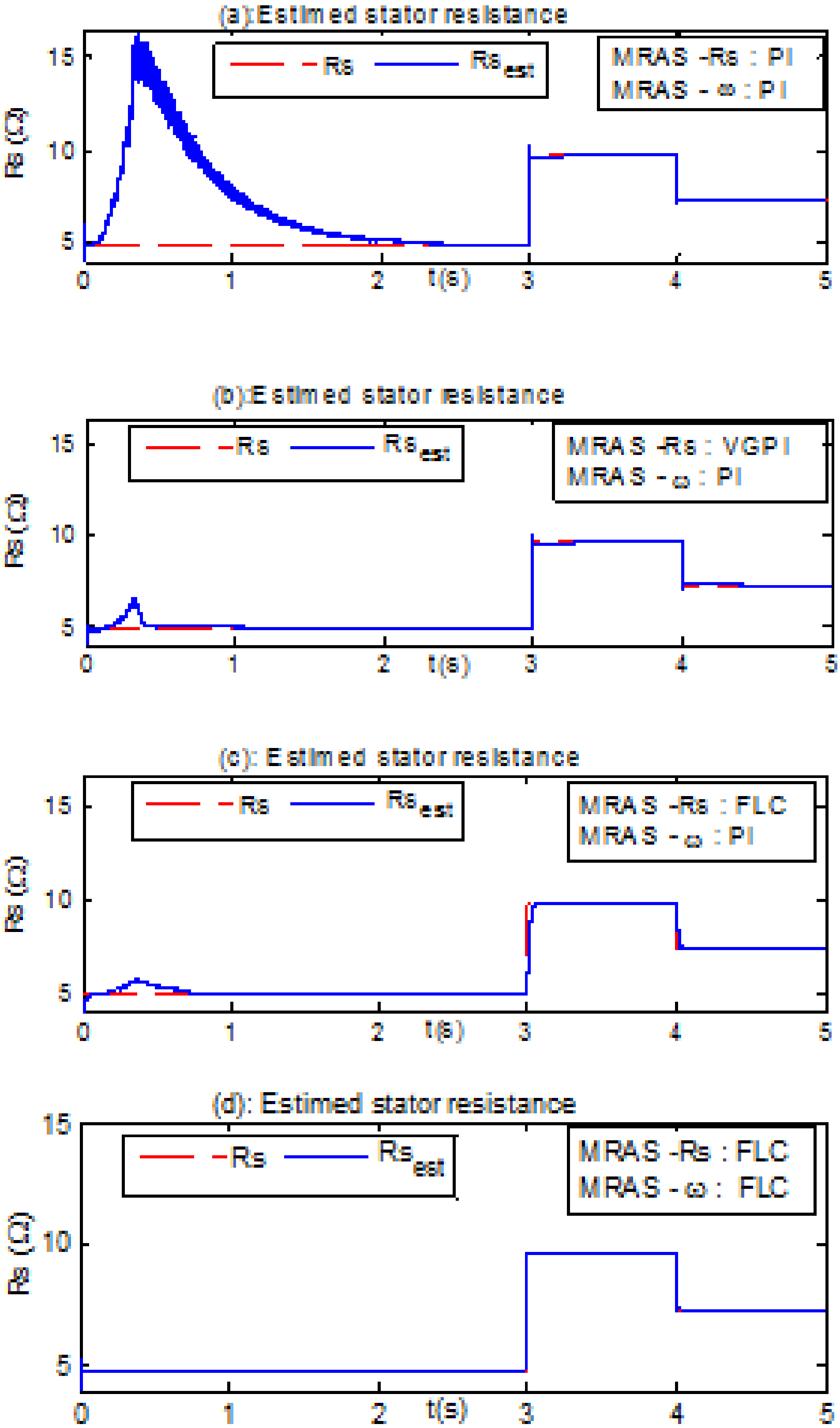

Fig. 9. Simulation of the estimated stator resistance. (a) : MRAS(PI-PI), (b) : MRAS(PI-VGPI), (c) : MRAS (PI-FLC), (d) : MRAS (FLC-FLC)

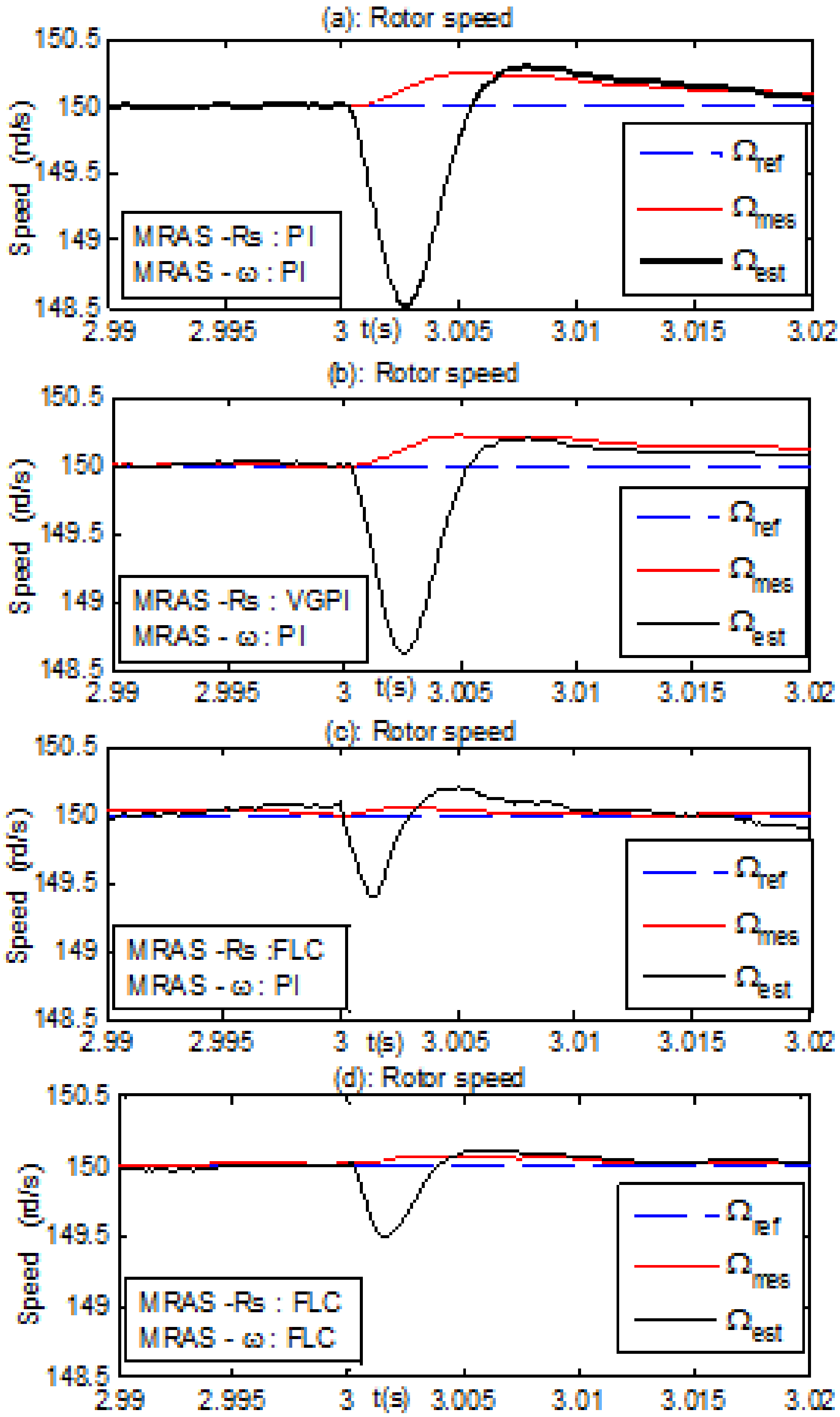

Fig. 10. Simulation of the mechanical speed (a) : MRAS(PI-PI), (b) :MRAS(PI-VGPI), (c) : MRAS (PI-FLC), (d) : MRAS (FLC-FLC)

6. Conclusion

The proposed method is a parallel MRAS estimator that enables simultaneous estimation of rotor speed and stator resistance of induction motor in sensorless indirect vector control with MRAS approach. The effectiveness of the developed structure is verified by simulation.

Results analysis confirm the feasibility and the performance of the parallel estimator in terms of the quality of the estimate, compensation of the static error of estimated values, and in term of response of the estimated speed at the sudden variation of the stator resistance under different types of regulators including the Fuzzy -PI.

Appendix

Parameters of the induction motor
$1.5KW$, $220/380V$, $11.25/6.4A$, 03 phases, coupling Y,
$50Hz$, 04 poles, $1420rpm$.
$R_s = 4.85\Omega$, $R_r = 5.805\Omega$, $L_s = 274mH$,
$L_m = 258mH$, $J = 0.031Kg.m^2$, $f = 0.00114Kg.m/s$

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