

Robust Control Facing a Large Scale Parameter Variation in a Sensorless Vector Controlled Induction Motor Drive

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Abstract: In vector control systems using the slip frequency control method, the rotor resistance of induction motors is used to calculate a slip frequency. Thus the change in temperature and saturation levels cause the variation of rotor resistance value and hence the deterioration of the whole torque control characteristic. This paper presents a simulation of induction motor behavior facing a sudden parameter variation in very low speed basing on fuzzy logic perturbation rejection controllers, the rotor flux and speed are observed by an adaptive Luenberger observer based fuzzy adaptation mechanism. Simulation results show that the proposed control with the proposed fuzzy regulation provide good performance dynamic characteristics for a large scale parameter variation. All simulations have been realized in MatLab/Simulink.

Key-Words: Parameter variation, Rotor resistance variation, Induction motor drive, Direct vector control, Fuzzy logic regulation, Fuzzy adaptation mechanism, Speed sensorless, Adaptive Luenberger observer

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1 Introduction

Induction motors (IM) are the most commonly and widely used electrical machines in several industrial applications, they are cheaper, rugged and easier to maintain comparing to other alternatives. But, their control is complex because of their nonlinear structure; accordingly, the main objective of the IM vector control methods is to provide an efficient performance in a simple structure. Vector control schemes are used in inverter-fed IM drives to obtain high performance [1] [2]. Crucial to the success of the vector control scheme is the knowledge of the instantaneous position of the rotor flux [3] [4].

The vector controlled IM drive is a very accepted method for high performance system response [1]. This technique was first formulated by Haase, in 1968, and Blaschke, in 1970. The direct version of the vector control requires a good knowledge of the module and the phase of the flux, measured quantities such as voltages and stator currents can be used to estimate or observe the rotor flux. However, the estimation accuracy is affected by the variation of machine parameters. Particularly, the rotor resistance variation becomes dominant by temperature and skin effect [5]. Compensation of this parameter is difficult because of inaccessibility [3].

The parameters in the machine model vary with temperature especially in low speed or because of magnetic saturation, therefore both the steady state and the dynamic operation of the system drive are then influenced [6] [7] [8] [9] [10]. Thus, the performance degradation is in the form of input-output torque nonlinearity and saturation of the machine, and several methods have come to the forefront to minimize the consequences of parameter sensitivity [11].

The design of a conventional control system is normally based on the mathematical model of a plant. if an accurate mathematical model is available with known parameters, it can be analyzed and a controller can be designed for the specified performance. Even if a plant model is well-known, there may be parameter variation problems. The d-q dynamic model of IM is multivariable, complex and nonlinear, and may be a wide parameter variation problem in the system. To combat such problems, fuzzy logic control (FLC) replaces conventional control and it gives robust performance. Fuzzy theory has been introduced by Lotfi Zadeh [12] and it is one of the most used intelligent techniques.

Over the last few years, the sensorless speed control of IM has received a great interest. Therefore, it is necessary to eliminate the speed sensor in order to reduce hardware and increase mechanical robustness. The main techniques of sensorless control of IM are: model reference adaptive systems (MRAS), extended Kalman filter (EKF) and adaptive Luenberger flux observer (ALO). Speed sensorless control methods of IM drive using the observed speed instead of the measured one have been studied in detail [2]. In this paper, the speed is observed from the instantaneous values of stator currents and voltages using the IM dynamic model in field rotating reference frame.

2 IM Drive Modeling

The mathematical model of a three-phase squirrel cage IM in d-q reference frame is given as [5]:

$$\begin{cases} \dot{x} = \mathbf{A}.x + \mathbf{B}.u \\ y = \mathbf{C}.x \end{cases} \quad (1)$$

Where x , u and y are the state vector, the input vector and the output vector respectively.

$$x = [i_{ds} \ i_{qs} \ \phi_{dr} \ \phi_{qr}]^t ; u = [u_{ds} \ u_{qs}]^t ; y = [i_{ds} \ i_{qs}]^t$$

$$\mathbf{A} = \begin{bmatrix} -\lambda & \omega_s & \frac{K}{T_r} & K\omega_r \\ \omega_s & -\lambda & -K\omega_r & \frac{K}{T_r} \\ \frac{L_m}{T_r} & 0 & -\frac{1}{T_r} & \omega_{sl} \\ 0 & \frac{L_m}{T_r} & -\omega_{sl} & -\frac{1}{T_r} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

With

$$\lambda = \frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r} ; K = \frac{1-\sigma}{\sigma L_m} ; \sigma = 1 - \frac{L_m^2}{L_s L_r} ; T_r = \frac{L_r}{R_r}$$

Figure 1 demonstrates the state space mathematical model of the IM drive and Table 1 lists its rated power and parameters.

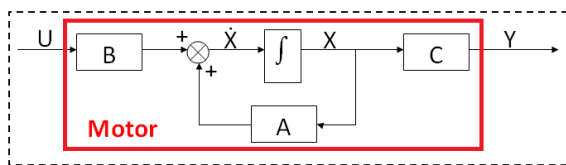


Figure 1: State space mathematical model of the IM drive

3 Direct Vector Control

In this type of control, the principal vector control parameters, i_{ds} and i_{qs} , which are dc values in syn-

Table 1: IM rated power and parameters

| | |
|------------------------------|----------------|
| Rated power | 3 kW |
| Voltage | 380 V STAR |
| Frequency | 50 Hz |
| Pair pole | 2 |
| Rated speed | 1440 rpm |
| Stator resistance | 2.2 Ω |
| Rotor resistance | 2.68 Ω |
| Stator inductance | 0.229 H |
| Rotor inductance | 0.229 H |
| Mutual inductance | 0.217 H |
| Moment of inertia | 0.047 $kg.m^2$ |
| Viscous friction coefficient | 0.004 N.s/rad |

chronously rotating frame, are converted to stationary frame with the help of unit vector θ_s generated from flux vector signals $\phi_{r\alpha}$ and $\phi_{r\beta}$. The resulting stationary frame signals are then converted to phase current commands for the inverter [5].

The norm of the rotor flux ϕ_r and its position θ_s used for the transformation of the coordinates are determined as follows:

$$\phi_r = \sqrt{\phi_{r\alpha}^2 + \phi_{r\beta}^2} \quad (2)$$

$$\theta_s = \arctan\left(\frac{\phi_{r\beta}}{\phi_{r\alpha}}\right) \quad (3)$$

Where $\phi_{r\alpha}$ and $\phi_{r\beta}$ are the rotor flux components in α - β reference frame.

In the proposed control scheme shown in Figure 2, ϕ_r and θ_s are not estimated but are instead observed by the adaptive Luenberger observer (ALO).

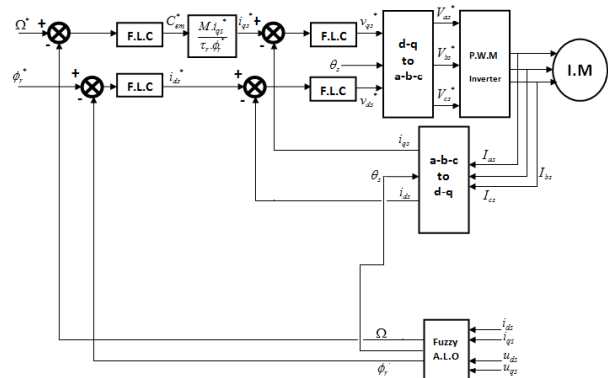


Figure 2: Block diagram of the proposed control

4 Fuzzy logic regulation

The introduction of robust techniques such as fuzzy logic into process control has attracted an increasing interest in recent decades. Fuzzy control is applied when there is no precise mathematical model of the process to be controlled or when the latter has strong nonlinearities or inaccuracies [12] [13].

Generally, the design of a fuzzy controller for the regulation of electrical drives requires the choice of the following parameters: linguistic variables, membership functions, inference method and defuzzification strategy.

Figure 3 shows the design of a fuzzy regulator.

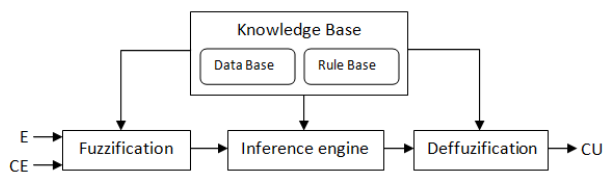


Figure 3: Fuzzy regulator design

4.1 Speed loop regulation

The structure of the speed fuzzy regulator is shown in Figure 4.

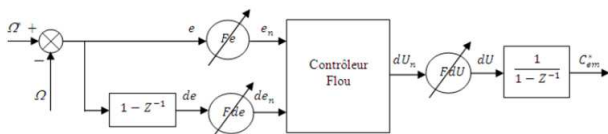


Figure 4: Speed fuzzy regulator structure

It generates an incremental output from the error signals and the variation of the error, where the error is expressed by:

$$e_k = \Omega_k^* - \Omega_k \quad (4)$$

The variation of the error can be approximated by:

$$de_k = \frac{e_k - e_{k-1}}{T_s} \quad (5)$$

With T_s is the sampling period, and the output of the regulator is given by:

$$C_{em_k}^* = C_{em_{k-1}}^* + dU_k \quad (6)$$

The input-output variables of the fuzzy controller can be normalized using gains called scaling factors. $e_{\Omega_n} = K_{e_{\Omega}} e_{\Omega}$; $de_{\Omega_n} = K_{de_{\Omega}} de_{\Omega}$; $dU_n = K_{u_{\Omega}} dU$. K_e , K_{de} and $K_{C_{em}^*}$ are scaling gains and are adjusted

by trial and error. The proper choice of them allows to guarantee the stability and to improve the dynamic and static performances targeted of the system to be regulated [8].

Symmetrical triangular membership functions with 7 fuzzy sets are used for the input, output variables and the universe of discourse of all variables, covering the whole region, is expressed in per unit values. Linguistic variables are defined as: NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big), see Figures 5, 6 and 7 [14].

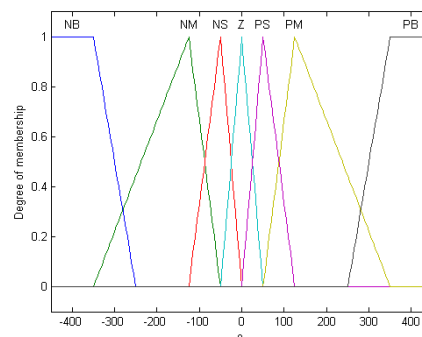


Figure 5: Membership function for input E

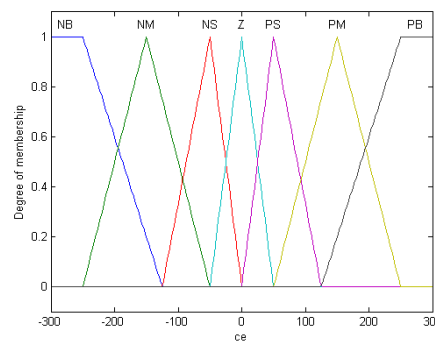


Figure 6: Membership function for input CE

The fuzzy rules, making it possible to determine the output variable of the regulator according to the input variables, are deduced from a table called inference table. In this case, it includes $7 \times 7 = 49$ rules as shown in Table 2.

$$dU_n = \frac{\int x \mu_R(x) dx}{\int \mu_R(x) dx} \quad (7)$$

The same structure was chosen also for the other controllers even that one of the adaptation mechanism. Except scaling gains, each controller has its own ones.

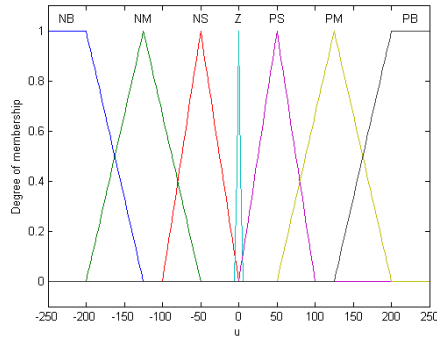


Figure 7: Membership function for output U

Table 2: Fuzzy rule base

| ce/e | NB | NM | NS | ZE | PS | PM | PB |
|------|----|----|----|----|----|----|----|
| NB | NB | NB | NB | NB | NM | NS | ZE |
| NM | NB | NB | NB | NM | NS | ZE | PS |
| NS | NB | NB | NM | NS | ZE | PS | PM |
| ZE | NB | NM | NS | ZE | PS | PM | PB |
| PS | NM | NS | ZE | PS | PM | PB | PB |
| PM | NS | ZE | PS | PM | PB | PB | PB |
| PB | ZE | PS | PM | PB | PB | PB | PB |

5 Adaptive Luenberger observer for rotor flux and speed estimation

The Adaptive flux observer is a deterministic type of observers based on a deterministic model of the system [2]. In this work, the adaptive Luenberger state observer is used to estimate the flux components and rotor speed of IM by including an adaptive mechanism based on the Lyapunov theory. In general, the equations of the ALO can be expressed as follow:

$$\begin{cases} \hat{\dot{x}} = \mathbf{A}.\hat{x} + \mathbf{B}.u + \mathbf{L}.(y - \hat{y}) \\ \hat{y} = \mathbf{C}.\hat{x} \end{cases} \quad (8)$$

The symbol $\hat{\cdot}$ denotes estimated value and \mathbf{L} is the observer gain matrix. The mechanism of adaptation speed is deduced by Lyapunov theory. The estimation error of the stator current and rotor flux, which is the difference between the observer and the model of the motor, is given by [2]:

$$\dot{e} = (\mathbf{A} - \mathbf{L}.\mathbf{C}).e + \Delta\mathbf{A}.\hat{x} \quad (9)$$

Where

$$e = x - \hat{x} \quad (10)$$

$$\Delta\mathbf{A} = \mathbf{A} - \tilde{\mathbf{A}} = \begin{bmatrix} 0 & 0 & 0 & K.\Delta\omega_r \\ 0 & 0 & -K.\Delta\omega_r & 0 \\ 0 & 0 & 0 & -\Delta\omega_r \\ 0 & 0 & \Delta\omega_r & 0 \end{bmatrix} \quad (11)$$

$$\Delta\omega_r = \omega_r - \hat{\omega}_r \quad (12)$$

We consider the following Lyapunov function:

$$V = e^t.e + \frac{(\Delta\omega_r)^2}{\lambda} \quad (13)$$

where λ is a positive coefficient, its derivative is given as follow:

$$\begin{aligned} \dot{V} = e^t[(\mathbf{A} - \mathbf{L}.\mathbf{C})^t + (\mathbf{A} - \mathbf{L}.\mathbf{C})]e - 2K\Delta\omega_r.(e_{i_{s\alpha}}.\hat{\phi}_{r\beta} - e_{i_{s\beta}}.\hat{\phi}_{r\alpha}) \\ + \frac{2}{\lambda}\Delta\omega_r.\dot{\omega}_r \end{aligned} \quad (14)$$

With $\hat{\omega}_r$ is the estimated rotor speed. The adaptation law for the estimation of the rotor speed can be deduced by the equality between the second and third terms of Equation (16):

$$\dot{\omega}_r = \int \lambda.K.(e_{i_{s\alpha}}.\hat{\phi}_{r\beta} - e_{i_{s\beta}}.\hat{\phi}_{r\alpha}).dt \quad (15)$$

The feedback gain matrix \mathbf{L} is chosen to ensure the fast and robust dynamic performance of the closed loop observer [2].

$$\mathbf{L} = \begin{bmatrix} l_1 & -l_2 \\ l_2 & l_1 \\ l_3 & -l_4 \\ l_4 & l_3 \end{bmatrix} \quad (16)$$

with l_1, l_2, l_3 and l_4 are given by:

$$l_1 = (k_1 - 1).(\gamma + \frac{1}{T_r}); l_2 = -(k_1 - 1).\hat{\omega}_r$$

$$l_3 = \frac{(k_1^2 - 1)}{K}.(\gamma - K.\frac{L_m}{T_r}) + \frac{(k_1 - 1)}{K}.(\gamma + \frac{1}{T_r})$$

$$l_4 = -\frac{(k_1 - 1)}{K}.\hat{\omega}_r$$

where k_1 is a positive coefficient obtained by pole placement approach [2], a wise choice was made for its value which is 1.06. Fuzzy logic control (FLC) in adaptation mechanism replaces conventional control and it gives robust performance against parameter variation and machine saturation.

The state space mathematical model of the observer is illustrated by Figure 8.

6 Simulation Results

The reference speed chosen for all tests is a step of 5 rad/s, because it is the hardest for most control processes.

A load of 10 N.m is applied at 0.4 s and removed at 0.8 s in order to show the system stability.

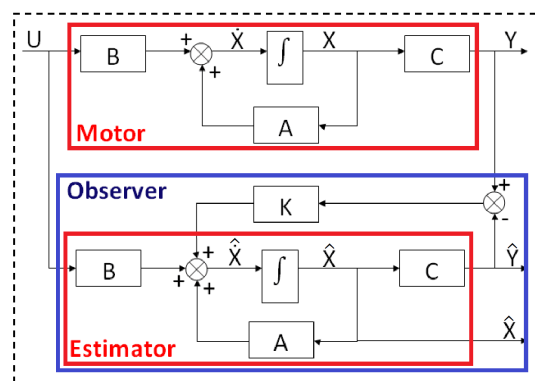


Figure 8: State space mathematical model of the observer

6.1 Operating up to 300% of rotor resistance variation at very low speed 5 rad/s

The rotor resistance is the main parameter of the vector control scheme because it is used to calculate the slip frequency. In Figure 9, the rotor resistance is suddenly varied 3 times of its rated value from 2.68 Ω to 8.04 Ω at 1s.

In classical PI vector controlled IM drive, the control will normally be lost especially at very low speed and the system will not be able to track the reference perfectly. But with FLC controllers, the rotor speed fluctuate a little and did not deviate from the reference after varying the rotor resistance value.

6.2 Operating up to 150% of stator resistance variation at very low speed 5 rad/s

Stator resistance is a delicate parameter, a tiny variation of its value leads to a deterioration of the whole system characteristic. In Figure 10, the stator resistance is suddenly varied one and half times of its rated value from 2.2 Ω to 3.3 Ω at 1s. The rotor speed did not fluctuate but deviate a little from the reference and is still tracking it well.

Speed error demonstrates the good performance of fuzzy ALO against instant load perturbation and parameter variation.

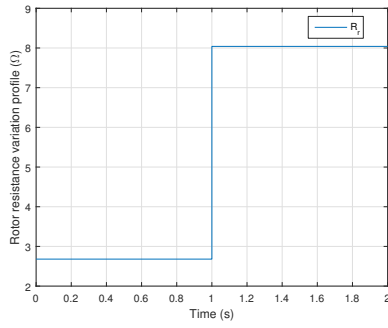
7 Conclusion

This paper proposed a method to compensate the rotor and stator resistance sudden variation basing on fuzzy logic perturbation rejection capabilities. The obtained results have confirmed the efficiency and the precision of this control during the sudden parameter variation and load torque disturbance. The overall system was tested under a large rotor resistance inter-

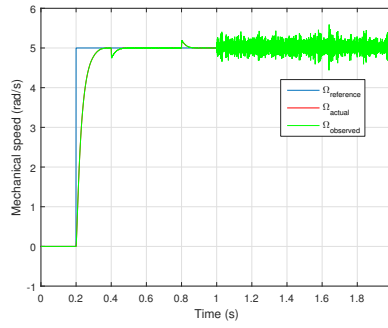
val up to 300% of its rated value, and up to 150% of stator resistance variation. Simulation results showed also the good performance of the speed observation at very low speed because the fuzzy logic controller in adaptation mechanism gives better robustness against the instant load torque disturbance.

[Nomenclature]

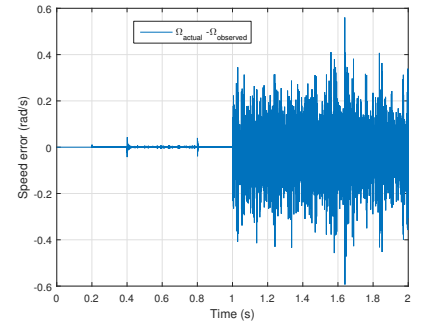
| | |
|---------------------------------|--|
| i_{ds}, i_{qs} | d-q stator current components |
| $\phi_{r\alpha}, \phi_{r\beta}$ | α - β rotor flux components |
| ϕ_{dr}, ϕ_{qr} | d-q rotor flux components |
| u_{ds}, u_{qs} | d-q stator voltage components |
| T_r | Rotor time constant |
| Ω | Rotor mechanical speed |
| ω_r | Rotor electrical speed |
| ω_s | Stator frequency |
| ω_{sl} | Slip frequency |
| p | Number of pole pairs |
| C_{em} | Electromagnetic torque |
| R_s, R_r | Stator, rotor resistance |
| L_s, L_r, L_m | Stator, rotor, mutual inductance |
| σ | Leakage coefficient |



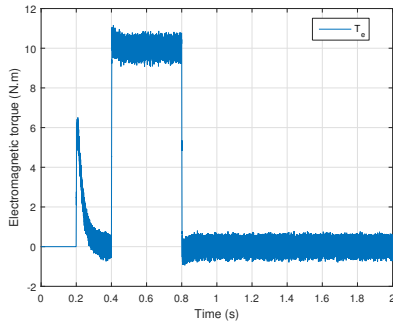
(a) Rotor resistance variation profile



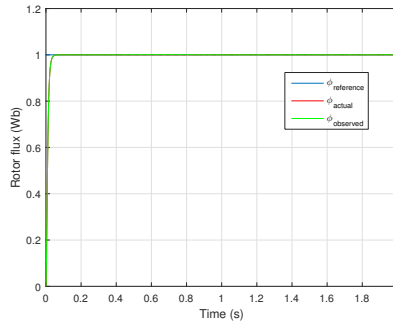
(b) Speed



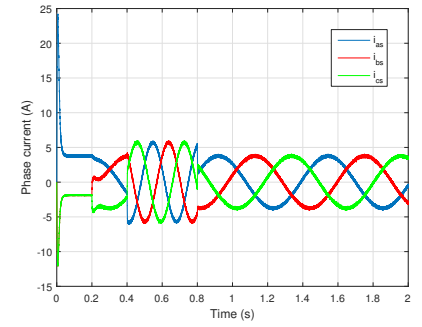
(c) Speed error



(d) Torque

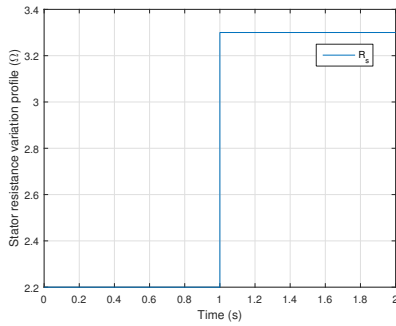


(e) Rotor flux

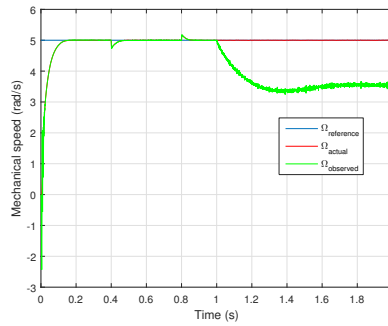


(f) Stator phase current

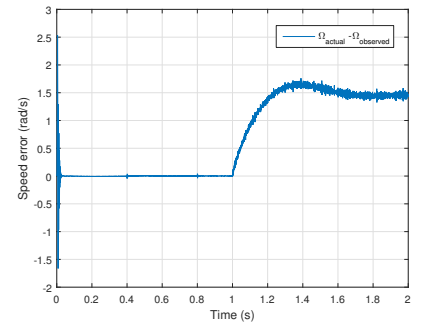
Figure 9: Operating up to 300% of rotor resistance variation at 5 rad/s



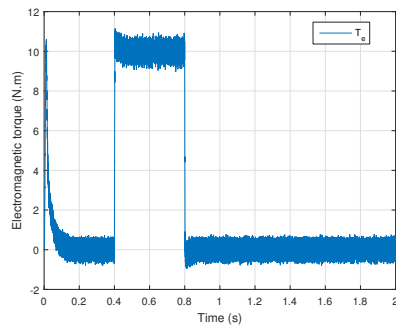
(a) Stator resistance variation profile



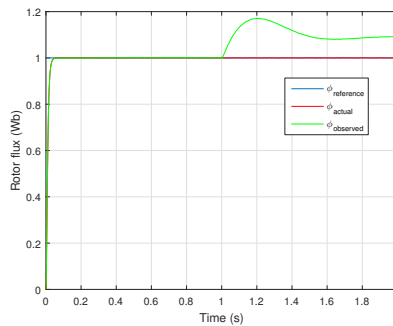
(b) Speed



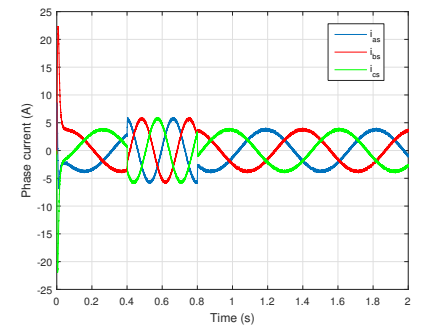
(c) Speed error



(d) Torque



(e) Rotor flux



(f) Stator phase current

Figure 10: Operating up to 150% of stator resistance variation at 5 rad/s

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