Speed Sensor Fault Estimation and Passive Fault Tolerant Control of an Induction Motor based on the μ- Synthesis Approach

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Abstract: This article provides the design of fault tolerant control law (FTC), for induction motor (IM) drives, using rotor field-oriented control (FOC) with diagnosis speed sensor fault. The main idea consists of using the information provided by the Fault Detection (FD) block to detect speed sensor error signals in a closed-loop system. A passive fault-tolerant control associated with a robust sensor speed fault detection filter based on H∞/μ-synthesis technique, are presented to ensure induction motor control performances in presence of uncertainties, multiplicative and additive faults. Simulations results of the FD and FTC schemes of IM are presented to verify the effectiveness of the proposed approach.

Keywords: Fault tolerant control, Induction motor, Field-oriented control, H∞/μ-synthesis, Fault detection filter.

1. INTRODUCTION

Recent years, increasing complexity of industrial automation technologies, has made fault handling of such systems a challenging task. Indeed, although industrial systems are usually designed to perform optimally over time, performance degradation occurs inevitably. These are due, for example, to a fault associated with an actuator, sensor or aging of system components. Fault handling is also necessary to allow redesign of the control in such a way to recover, as much as possible, an optimal performance (Giri, 2013; Glumineau et al., 2016; Ding, 2021).

In this context, researchers have focused on a specific control design strategy, to compensate the faults effects and guarantee system stability with acceptable performance. This type of control strategy is called Fault-Tolerant Control System (FTC) (Puigand et al., 2021; Amin et al., 2019). Several approaches to fault-tolerant control applied to electrical systems have been proposed in the literature (Zhang et al., 2021; Zhang et al., 2024; Zapar et al., 2023; Lee et al., 2021).

FTC approaches can be categorized into two main categories namely passive and active approaches. Passive FTC can keep the desired controller performance and ensure reliable operation without considering the type and size of fault. The advantage with that concept is that no time delay will be included in the controller due to detection of faults. In the case of an active FTC approach, the objective is to ensure reliable operation and high performance of control systems when faults occur through accommodation and control reconfiguration (Tellili et al., 2021; Tran et al., 2021).

The control strategies of induction motor, torque and speed drives, require the sensors to have feedback information but the possible faulty speed sensor causes significant performance degradation and even instability of the system (Ding, 2021; Nguyen et al., 2023; Aguilera et al., 2022; Rkhissi-Kammoun et al., 2019; Verrelli et al., 2018; Green et al., 1995). Also, the problem of uncertainties model and external disturbances can significantly affect the system performance. H-infinity control strategy appears to be a possible solution to these problems (Safonov et al., 1985; Lundström et al., 1991; Pathak et al., 2019; Li et al., 2009).

An extension to the H-infinity approach, optimal control technique for robustness analysis has been developed, such as μ-synthesis control, which the stability margin in front of a perturbation is typically obtained by calculating the structured singular value (μ), to provide a general framework for solving the problem of robustness analysis in the face of uncertainty and disturbance conditions (Farhat et al., 2017; Chen, 2008).

In this paper, a passive fault tolerant control strategy based on robust fault estimation filter (FD) of sensor speed faults for an induction motor is proposed. The main idea in this work is to use a law mechanism to control speed sensor faults and to maintain nominal tracking performance. Exploiting the H∞/μ-synthesis approach to synthesize fault-tolerant controller (FTCs) and a robust filter (FD), able to tolerate faults and keep the control performance in the ideal range, in the presence of multiplicative and additive faults.

The FD has been synthesized in order to detect and estimate the sensor speed faults of induction motor. However, the important problem that arises when synthesizing a model-based monitoring system is to guarantee the residual robustness to uncertainties such as system deviation, disturbances, and unknown nonlinearities to achieve high detection rate with less false alarm rate and to separate between default effects and the effects of uncertain signals and disturbances. The controller $K_{\mu}(s)$, associated with the rotor field-oriented control of induction motor, offers very acceptable performance in the presence of parametric variations (multiplicative faults), and additive faults (sensor speed fault).

This work is organized as follows: In section 2, the IM direct rotor field orientation control is presented. A brief description of μ-synthesis theory and the robust speed controller for faulty situation is developed in section 3. In Section 4, H∞ descriptor fault detection filter based μ-synthesis is formulated. Simulation and results are reported in section 5, conclusion is given in section 6.

2. FIELD ORIENTED INDUCTION MOTOR MODEL

The ultimate objective of vector control is to enable decoupling control of torque and flux similar to the control of separately excited DC motor. This approach implies the alignment of the direct axis of (d−q) synchronous reference frame of Park with the rotor flux. ($\Phi_{rq} = 0$, $\Phi_{rd} = \Phi_r$), (Blaschke, 1972). The equivalent IM model, with rotor field orientation, is described by the following equations:

$$\begin{cases} \frac{di_{sd}}{dt} = -\delta\, i_{sd} + \omega_s\ i_{sq} + \alpha\, \beta\, \Phi_r + \frac{1}{\sigma L_s} u_{sd} \\ \frac{di_{sq}}{dt} = -\omega_s\ i_{sd} - \delta\, i_{sq} -\ \beta n_p \Omega\, \Phi_r + \frac{1}{\sigma L_s} u_{sq} \\ L_m \alpha\, i_{sd} + \frac{1}{T_r}\Phi_r - \frac{d\Phi_r}{dt} = 0 \\ L_m \alpha\, i_{sq} + \left(\omega_s - n_p \Omega\right)\Phi_r = 0 \\ T_e - T_l = J\frac{d\Omega}{dt} + f_v.\Omega \\ T_e = n_p \frac{L_m}{L_r}\Phi_r i_{sq} \end{cases} \tag{1}$$

With:

$$\alpha = \frac{R_r}{L_r} = \frac{1}{T_r},\ \beta = \frac{L_m}{\sigma\, L_s L_r},\ \sigma = 1 - \frac{L_m{}^2}{L_r L_s},\ \delta = \frac{L_m{}^2 R_r}{\sigma L_s L_r^2} + \frac{R_s}{\sigma L_s}$$

Where $i_{sd}, i_{sq}, \omega_s, \Omega$ are the stator currents, stator electrical speed and rotor speed. T_l is the load torque, considered as an unknown disturbance. n_p is the pole-pairs number, J is the inertia moment, f_v is the friction coefficient, R_r is the rotor, resistance, L_r is the rotor self-inductance and L_m is the stator/rotor mutual inductance.

According to (1), we obtain two independent action variables (i_{sd}, i_{sq}), the first variable controls the flux, yet the second controls the torque. To achieve the classical direct FOC control objective, two controllers are applied; the first is a conventional Proportional Integrator (PI) to control rotor flux and the second one is a robust μ-synthesis controller Kμ(s) to control rotor speed.

The orientation of the rotor flux consists in calculating the orientation angle $\hat{\theta}_s$

$$\hat{\theta}_s = \int \hat{\omega}_s dt = \int (\hat{\omega}_r + \hat{\omega})dt \tag{2}$$

The pulsation ω_r is deduced from the fourth equation of (1):

$$\hat{\omega}_r = \frac{\alpha\, L_m}{\hat{\Phi}_r} i_{sq} \tag{3}$$

Also, using the third equation of (1), the rotor flux can be estimated by the measured direct stator current component as:

$$\hat{\Phi}_r = \frac{L_m}{T_r s+1} i_{sd} \tag{4}$$

3. MU-SYNTHESIS SPEED FAULT TOLERANT CONTROLLER DESIGN

Robust controller using μ-synthesis technique $K_\mu(s)$, with D-K iteration algorithm (Safonov et al. (1985)), is developed to design a passive robust sensor fault-tolerant control of induction motor, Fig.1, based on information from a robust fault detection (FD) system.

In this study, only speed sensor faults are considered to guarantee closed-loop stability and performance for faulty conditions, external disturbances and model uncertainties. (Change in mechanical speed parameters (J, f_v) and speed sensor fault).

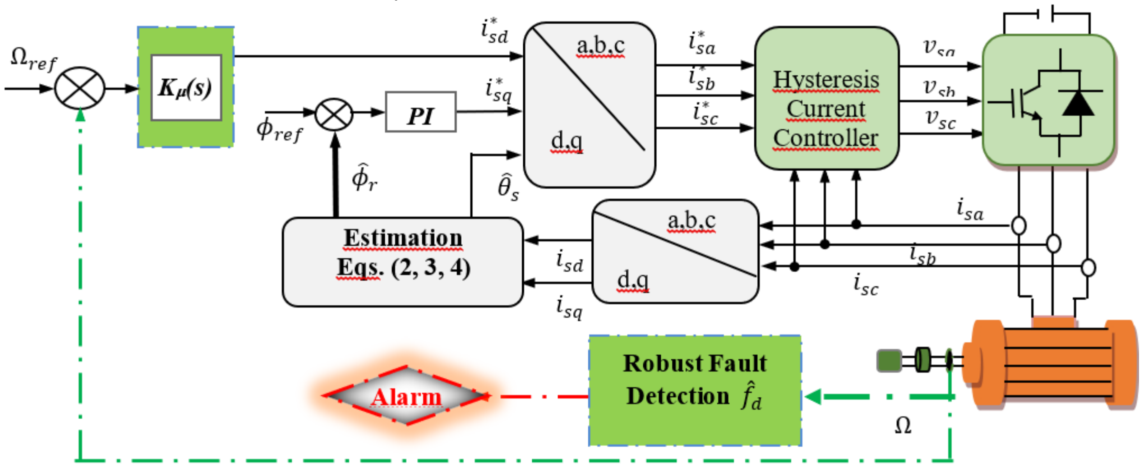


Fig. 1. Structure of proposed robust passive FTC control of induction motor.

3.1 Relationship between the operation of FD and Ku blocks

The difference between the roles of the FD and Ku blocks, during fault occurrence, is that the FD is not in a direct relationship with the Ku regulator, since the task of the FD is only to ensure sensor fault detection and is not involved in the design of the MAS control algorithm. On the other hand, the Ku regulator has the role of ensuring that the control continues to operate robustly even in the presence of errors.

The speed control configuration, using μ-synthesis approach is presented in Fig. 2, where: $w = [\tilde{r}\quad \tilde{d}\quad f_d]^t$, $\tilde{r} = \Omega_{ref}$ is the reference input, $\tilde{d} = T_l$ is the unknown disturbance and speed sensor fault f_d.

$\tilde{z} = [\tilde{z}_e, \tilde{z}_u]^t$ is the output vector of the interconnection matrix, $e = \Omega_{ref} - \Omega$ is error in rotor speed and $u = T_{e-ref}$ is the torque reference. Weighting functions $W_e, W_u\ W_d, W_p$ and W_{fd} are used to shape the closed loop system responses according to the robust performance and stability margin requirements. $P_\Omega(s)$ denote the nominal open-loop interconnected transfer function matrix, $\Delta_{sf}(s)$ is the structured uncertainties and speed sensor faults, $\Delta_p(s)$ is the unstructured uncertainty

(Safonov et al. (1985)). The electrical parameters are assumed to be known.

3.2 Uncertainty analysis

The control structure in Fig. 2, is represented in general standard block diagram of a robust control problem as shown in Fig. 3a, where $\Delta_\mu = diag(\Delta_p, \quad \Delta_{sf})$ (Safonov et al., 1985). To ensure the designed controller achieves robust performance, we introduce a fictitious uncertainty block Δ_F as shown in Fig. 3.b. Unstructured uncertainties $\Delta_p(s)$ are used to model the system's dynamic perturbations, such as non-modeled or high-frequency dynamics. $\Delta_p(s)$ is available in two forms: additive and/or multiplicative (Green, 1995).

Let $G_\Omega(s)$ the uncertain model and G(s) is a nominal model such as the stable weighting function $W_p(s)$ represents the upper bound of the multiplicative uncertainty where:

$$G_\Omega(s) = G(s)e^{\tau' s} = G(s).\left(1 + W_p(s).\Delta_p(s)\right) \tag{5}$$

Using the first-order *Padé-approximation*, the weighting function chosen is (Chen, 2008):

$$W_p(s) = \frac{\tau_m \cdot s}{1+\tau_m \cdot s/2} \quad , \quad \|\Delta_p\| < 1 \tag{6}$$

Where, τ_m is the maximum neglect delay time.

The structured uncertainties $\Delta_{sf}(s)$ are determined via intervals bound by unknown parameters and speed sensor fault. The open-loop transfer function of induction motor speed is given by:

$$G(s) = \frac{\frac{1}{J}}{s+\frac{f_v}{J}} \tag{7}$$

We put: $k = \frac{1}{J}$, $a = \frac{f_v}{J}$, where k and a are the uncertainties in the parameters, represented by following equations:

$$\begin{cases} k = k_0\left(1 + e_k\delta_{kf}\right) \\ a = a_0\left(1 + e_a\delta_{af}\right) \end{cases} \tag{8}$$

Where k_0 and a_0 are the nominal values of the parameters k and a, respectively.e_k and e_a represent the percentages of variation around the nominal values and. δ_{kf}, δ_{af} are the normalized uncertainty variable and speed sensor fault such that $|\delta_{kf}| < 1$ and $|\delta_{af}| < 1$.

Finally, the structured uncertainty faults matrix can be written as follows:

$$\Delta(s) = diag\left(\delta_{kf}, \delta_{af}, \Delta_p\right) \tag{9}$$

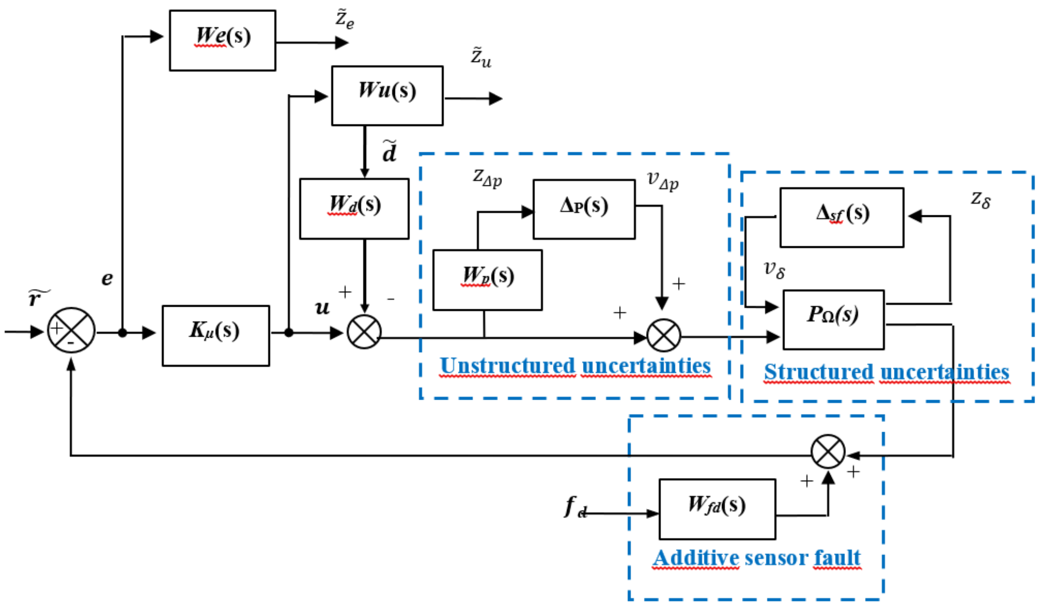


Fig. 2. Closed-loop interconnection structure for Kμ(s) speed controller.

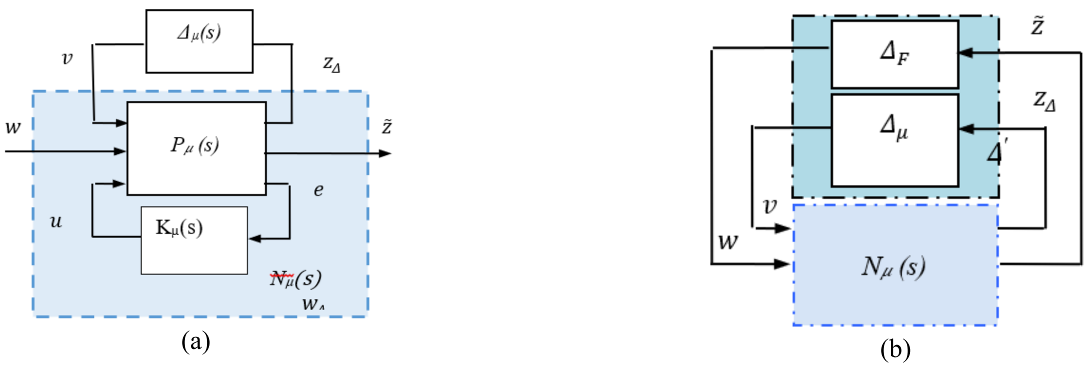


Fig. 3. Standard N-Δ configuration for μ-synthesis.

The augmented plant $P_\mu(s)$, having input vector $[v_{\Delta p} \quad v_{\delta_{kf}} \quad v_{\delta_{af}} \quad \tilde{r} \quad \tilde{d} \quad f_d \quad u]^t$ and the outputs, $[z_{\Delta_p} \quad z_{\delta_{kf}} \quad z_{\delta_{ka}} \quad \tilde{z}_e \quad \tilde{z}_u \quad e]^t$ which includes a nominal plant model G(s), is defined as:

$$P_\mu(s) = [P_{\mu_1} \quad P_{\mu_2}] \tag{10}$$

Such as:

$$P_{\mu_1} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ W_p & 0 & 0 & 0 \\ W_pG & G & G & 0 \\ -W_pW_eG & -W_eG & -W_eG & W_e \\ 0 & 0 & 0 & 0 \\ -W_pG & -G & -G & 1 \end{bmatrix}$$

$$P_{\mu_2} = \begin{bmatrix} -W_d & 0 & 1 \\ -W_d & 0 & 1 \\ -W_dG & 0 & G \\ W_dW_eG & -W_eW_{f_d} & -W_eG \\ 0 & 0 & W_u \\ W_dG & -W_{f_d} & -G \end{bmatrix}$$

As shown in Fig.3, *$P_\mu(s)$* can be combined with the controller transfer function K_μ (s) designed via the lower linear fractional transformation (LFT) to give the transfer function matrix N_μ(s), expressed as follows:

$$N_\mu(s) = [N_{\mu_1} \quad N_{\mu_2}]$$

Such as:

$$N_{\mu_1} = \begin{bmatrix} -T_\Delta W_p & -T_\Delta & -T_\Delta \\ S_\Delta W_p & -T_\Delta & -T_\Delta \\ GS_\Delta & GS_\Delta & GS_\Delta \\ -W_eGS_\Delta W_p & -W_eGS_\Delta & -W_eGS_\Delta \\ -W_uT_\Delta W_p & -W_uT_\Delta & -W_uT_\Delta \end{bmatrix}$$

$$N_{\mu_2} = \begin{bmatrix} K_\mu S_\Delta & -S_\Delta W_d & K_\mu S_\Delta W_{f_d} \\ K_\mu S_\Delta & -S_\Delta W_d & -S_\Delta K_\mu W_{f_d} \\ T_\Delta & -GS_\Delta W_d & -T_\Delta W_{f_d} \\ W_eS_\Delta & W_eGS_\Delta W_d & -W_eS_\Delta W_{f_d} \\ W_uK_\mu S_\Delta & W_uT_\Delta W_d & -W_uK_\mu S_\Delta W_{f_d} \end{bmatrix}$$

In terms of the (N-Δ) structure in Fig. 3, the requirements for stability and performance (SP) can be guaranteed via theorem given by Doyle (Safonov et al., 1985). Consequently, to achieve robust performance (RP); the stabilizing controller $K_\mu(s)$ should minimize, (Green, 1995; Safonov et al., 1985):

$$\max_{\omega \in R} \mu_{\underline{\Delta'}}[N_\mu(j\omega)] < 1 \tag{11}$$

The desired conditions of nominal performance are well achieved if the following condition is satisfied:

$$\left\| \begin{matrix} W_e(s)S_\Delta & W_e(s)GS_\Delta W_d & -W_e(s)S_\Delta W_{f_d}(s) \\ W_u(s)K_\mu S_\Delta & W_u(s)T_\Delta W_d(s) & -W_u(s)K_\mu S_\Delta W_{f_d}(s) \end{matrix} \right\|_\infty < 1 \tag{12}$$

The sensitivity S_Δ and complementary sensitivity T_Δ functions for the nominal system are defined as follows

$$S_\Delta = \frac{1}{1+K_\mu(s)G(s)}, \quad T_\Delta = \frac{K_\mu(s)G(s)}{1+K_\mu(s)G(s)} \tag{13}$$

The weighting functions selection is a critical step in the development of robust μ-synthesis control in order to attain the robust performance objectives of controller K_μ .

3.3 Weighting functions selection

The weighting functions selection is a critical step in the development of robust μ-synthesis control. These functions have a physical interpretation that is associated with the desired closed-loop behavior, in Fig.2 to achieve robust and stability performance of induction motor, the weighting functions should be properly selected in advance in order to find controller K_μ(s). The weight W_e is usually selected to get disturbance rejection, good tracking and zero steady state error, W_u is required to prevent the saturation of controller output, the weighting function W_d is used to scale the external disturbance and W_{f_d} is chosen to achieve the system robustness objectives with respect to the additive fault. The control problem is reduced to designing a controller that minimizes the weighted signals as much as possible, (Pathak, 2019). We can clearly see from criteria (21) and the properties of the norm H∞, stated in (Safonov et al., 1985), that closed-loop sensitivity functions S_Δ, KS_Δ, GS_Δ and T_Δ are constrained by desirable templates; consequently, checking the specifications is equivalent to testing the conditions (12). The choice weighting functions are given by:

$$W_e(s) = \frac{1}{M_e} \cdot \frac{s+\omega_e \cdot M_e}{s+\omega_e \cdot \varepsilon_e}, \quad W_d(s) = \beta_d$$
$$W_u(s) = \frac{s+\frac{\omega_u}{M_u}}{\varepsilon_u s+\omega_u}, \quad W_{f_d} = \beta_{fd} \tag{14}$$

Where: M_e is an upper bound for the peak sensitivity ε_e is a low-frequency tracking error specification and ω_e is approximately the bandwidth requirement. M_u and ω_u reflect the limited gain and bandwidth of the actuator and ε_u is a property influenced by the sensor noise characteristics.

3.4 Adaptations to the weighting functions parameters

D-K iteration in conjunction with the μ-synthesis is one of the most effective techniques to develop a robust controller. This technique provides an appropriate balance between robustness and system performance. The main disadvantage of this approach is that the desired performances are not achieved in presence of defaults or model parameters change, and consequently, the weights must be readjusted. An automatic weighting function selection algorithm, suggested in (Nair, 2011), is used in this work, to optimize these weights by introducing judiciously weighted function parameters. It is an iterative algorithm using the initial weighting functions that reflect the desired performance specifications. and detects a minimum structured singular value (μ) to have an appropriate response.

The values of the initial weighting function for controller K_μ(s) are selected by the flowing expressions:

$$W_e(s) = \frac{0.3326 \cdot s+3.952}{s+0.01875}, \; W_d(s) = 0.31$$

$$W_u(s) = \frac{8 \cdot 10^5 \cdot s+9.032 \cdot 10^6}{s+1.875 \cdot 10^8}, \quad W_{fd} = 0.01$$

Fig. 4 shows how the selected templates influence the different transfer functions: S_Δ, T_Δ and $K_\mu S_\Delta$ at low, medium and high frequency.

$K_\mu(s)$ is optimized by the *D-K* method using the "*dksyn*" Matlab function. Since the controller order is high, using the Hankel-norm approximation method, the reduced-order model of $K_\mu(s)$ is 3rd order with reasonable stability margins. The desired condition, of nominal performance given by (12), is achieved, which gives very good attenuation of multiplicative faults. $K_\mu S_\Delta$ is not constrained at low frequencies, but a constraint is imposed at high frequencies.

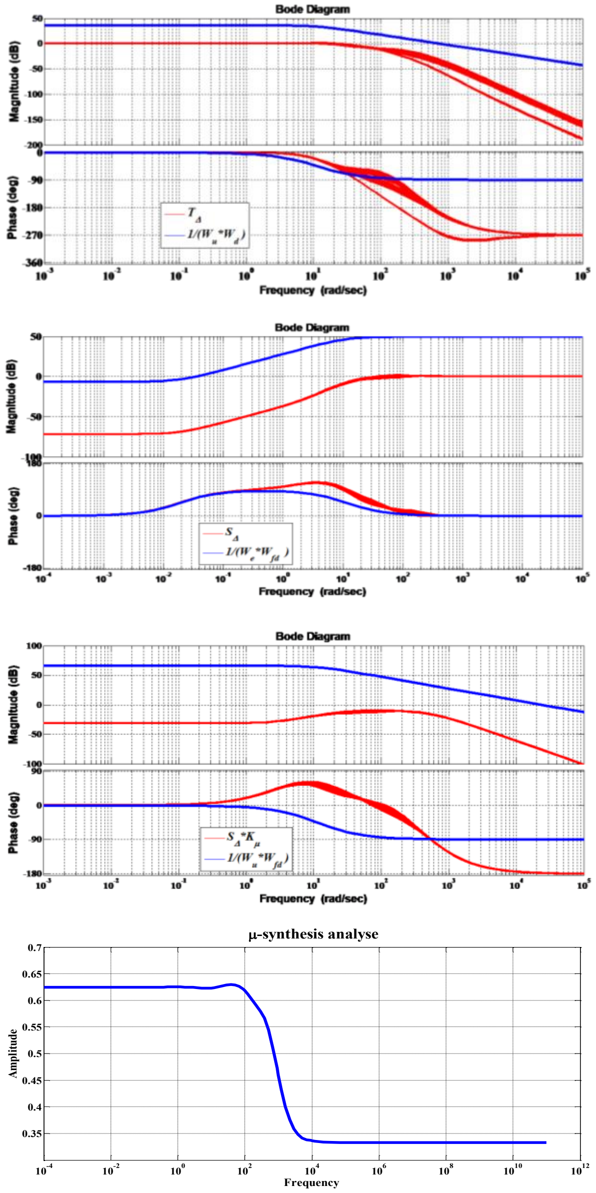


Fig. 4. Minimization of sensitivity functions, S, T, SKμ and μ-synthesis analyze.

4. H∞-MU-SYNTHESIS FAULT DETECTION FILTER DESIGN

Fault estimation is an advanced fault diagnosis method that not only informs when and where faults occur, but also presents the shape and dimension of the faults, which are critical for on-line fault tolerant control and decision making in real time (Ding, 2021; Zhang et al., 2021). In this paper, a robust diagnostic filter synthesis method is designed by H∞ approach μ-synthesis. The FD filter synthesis problem is described by an augmented model represented in the Fig. 5.

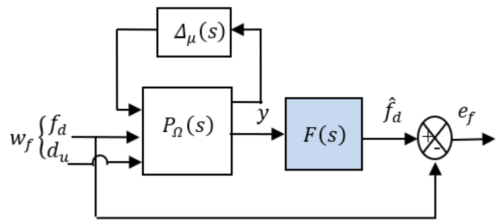


Fig. 5. Scheme principle of an FD filter using the H_∞/μ synthesis.

With: $\Delta_\mu(s) = \begin{bmatrix} \Delta_u & 0 & 0 \\ 0 & \Delta_d & 0 \\ 0 & 0 & \Delta_f \end{bmatrix}$

where $\hat{f}$ is the fault estimation and e_f is the signal which is used to evaluate the estimation quality, it gives by:

$$e_f = f_d - \hat{f}_d \qquad (15)$$

The design problem is to design a FD filter F(s) such that the estimation error e is minimized, consequently:

$$f_d = \hat{f}_d$$

Let's gives the input-output model of system, Fig (5):

$$y(s) = \begin{pmatrix} G_{\Delta u} & G_{\Delta d} & G_{\Delta f} \end{pmatrix} \begin{pmatrix} u \\ d_u \\ f_d \end{pmatrix} \qquad (16)$$

Where: $G_{yu}(s)$, $G_{yd}(s)$ and $G_{yf}(s)$ are the transfer functions from output y(t) to input u(t), perturbation d_u and fault f_d respectively. They can be expressed by:

$$\begin{cases} G_{\Delta u} = (I - \Delta_u)G_{yu} \\ G_{\Delta d} = (I - \Delta_d)G_{yd} \\ G_{\Delta f} = (I - \Delta_f)G_{yf} \end{cases} \qquad (17)$$

The fault estimation is given by:

$$\hat{f}_d = F(s)y(s) - F(s)G_{\Delta u} \qquad (18)$$

Substituting (16) into (18) the fault estimation is obtained as:

$$\hat{f}_d = F(s)G_{yf} + F(s)G_{\Delta d} \qquad (19)$$

The objective is to realize a robust filter $F(s)$ with a fault indicator that is only sensitive to faults. F(s) is synthesised to maximize the smallest singular value of the transfer function between f_d and $\hat{f}_d$ (sensitivity constraint) and to minimize the greatest singular value of the transfer function between d_u and $\hat{f}_d$ (robustness constraint). This problem can be formulated as follows:

$$J_f = \left[min \frac{\|d_u - \hat{f}_d\|}{\|d_u\|},\ max \frac{\|f_d - \hat{f}_d\|}{\|f_d\|} \right] \qquad (20)$$

The control structure in Fig.5 of FD filter using the H∞/μ synthesis, can take the standard diagram form of μ-synthesis problem given in Fig. 3.

$$P(s) = F_l\left(P_\Omega(s), \Delta_\mu(s)\right) = \begin{bmatrix} 1 & 0 & -1 \\ G_{\Delta f}(s) & G_{\Delta d}(s) & 0 \end{bmatrix} \quad (21)$$

The obtained FD filter given by the flowing expression:

$$F(s) = \frac{4.76 \cdot 10^2}{s^4 + 108.2 \cdot s^2 + 678.6 \cdot s + 131.9} \quad (22)$$

Remark: A fault can be detected by comparing the fault estimation evaluation function f_d with the threshold function T_h as described in the following test. (Variable A is the alarm signal).

$$\begin{cases} \|\hat{f}_d\| \le T_h \text{ for } f_d = 0 \Rightarrow A = 0 \\ \|\hat{f}_d\| > T_h \text{ for } f_d \neq 0 \Rightarrow A = 1 \end{cases} \quad (23)$$

5. SIMULATION RESULTS

In order to validate the proposed FTC strategy shown in Fig.1, simulations have been carried out for an induction motor using Matlab/Simulink. The detailed parameters of the IM are given in Appendix A.

The response of controller is observed under different operating conditions such as a step change in the load torque, faulty conditions. The objective will be ensuring the performances of this control in the presence of sensor faults. Two types of faults are considered; a multiplicative fault and additive ones, where different tests are considered. The rated load torque applied at t= 2s in closed loop during the motor operating.

In order to prove the effectiveness and robustness of the proposed FTC, the operating conditions have been specified by the following cases:

- In the first case, the fault is considered as intermittent sensor fault, and has been introduced into the speed sensor at t= 3s and 5s, lasts for one second. After the detection and identification of the sensor fault by the FD, the intermittent fault and its estimation take the form shown in Fig. 6, we can see that the fault estimate is perfect.

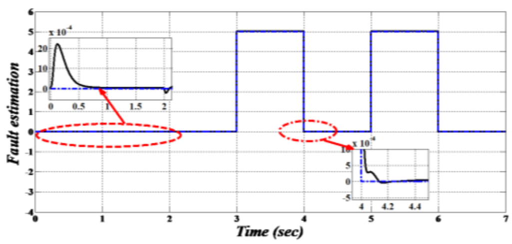
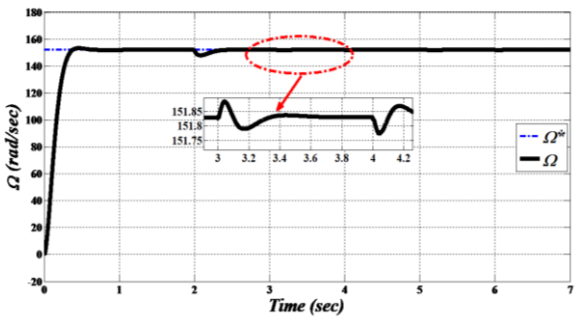


Fig. 6. Intermittent speed fault estimation.



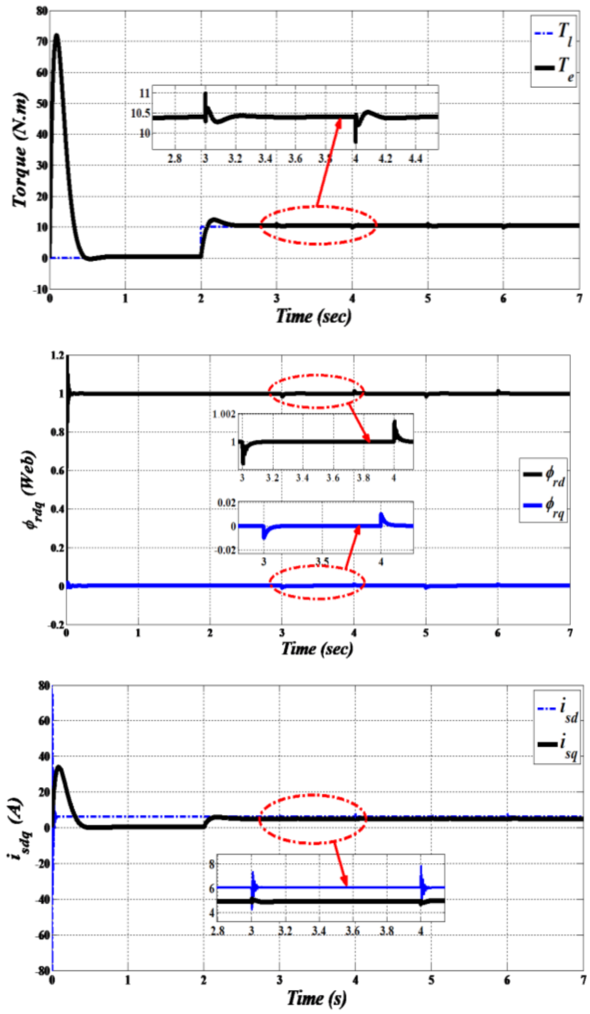


Fig. 7. Performance of speed sensor intermittent fault-tolerant control with load torque: Rotor speed Ω, electromagnetic torque T_e, rotor flux (ϕ_{rdq}) and Stator current (i_{sd}, i_{sq}).

In the second case, the fault is considered as gain and constant faults. A gain fault reduces the measured signal, it is considered as a multiplicative fault. With constant fault, the measured speed takes a constant value (the error may result from mal functioning electronics or data acquisition system), it considered as an additive defect. A gain fault is applied at t=3s, followed at t=4.5s by constant fault. The gain and constant faults and their estimations take forms given by Fig.8.

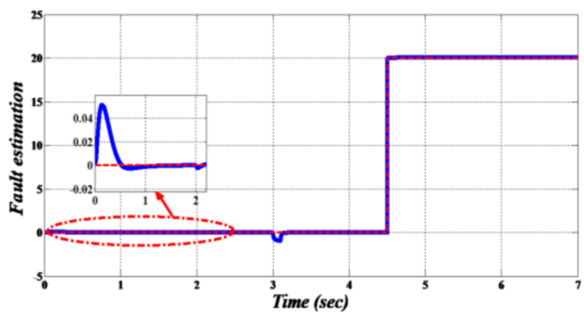


Fig. 8. Gain and constant faults estimation.

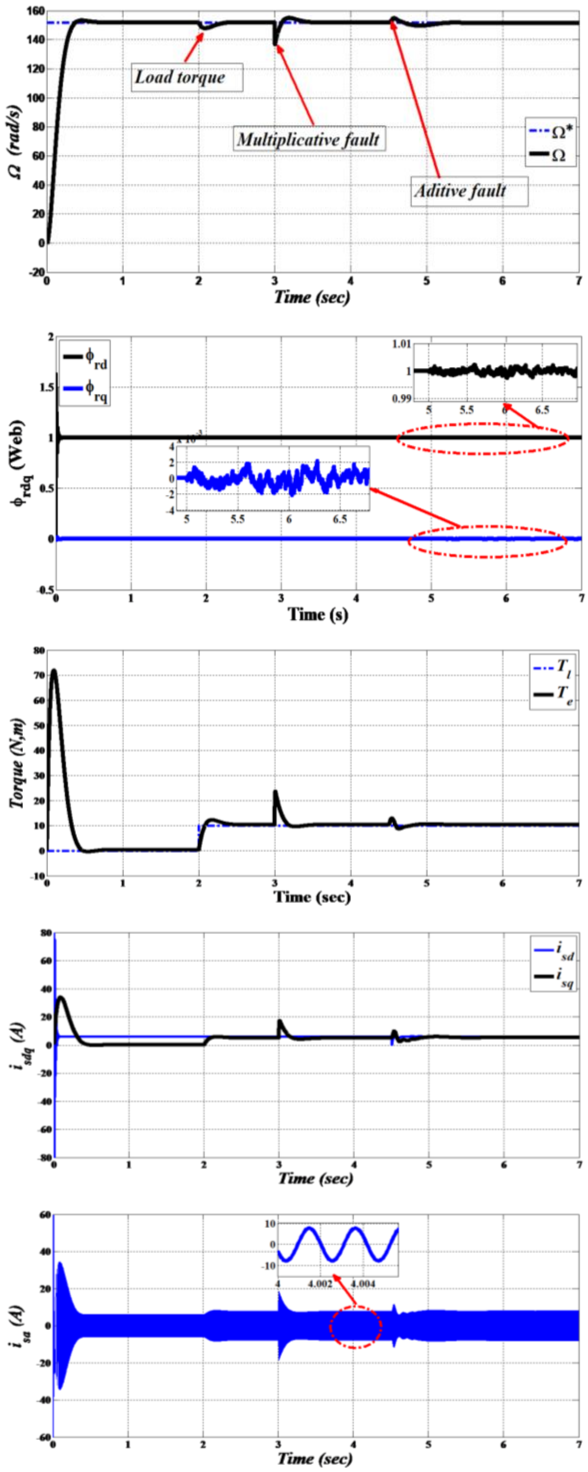


Fig. 9. Performance of fault tolerant control under multiplicative and additive faults in speed sensor (gain and abrupt faults).

In the last case, the fault considered as a parameter variation and a noise. It is assumed that all parameters of asynchronous motor will be considered as constant except rotor speed parameters (J, f_v) will be treated as uncertain parameters: $J = J_0 + 30\% J_0$, $f_v = f_0 + 50\% f_0$, applied at t=3s, followed by noise at t=5s, (J_0 , f_0 are the nominal values of J and f_v). Fault estimation is shown in Fig.10.

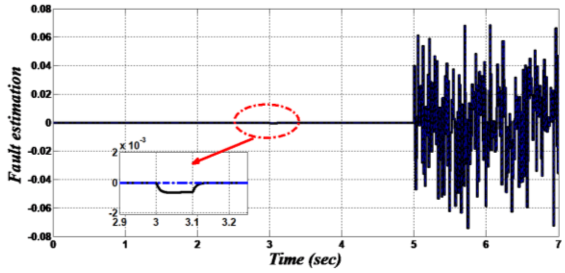


Fig. 10. Noise fault and uncertain parameters in speed sensor.

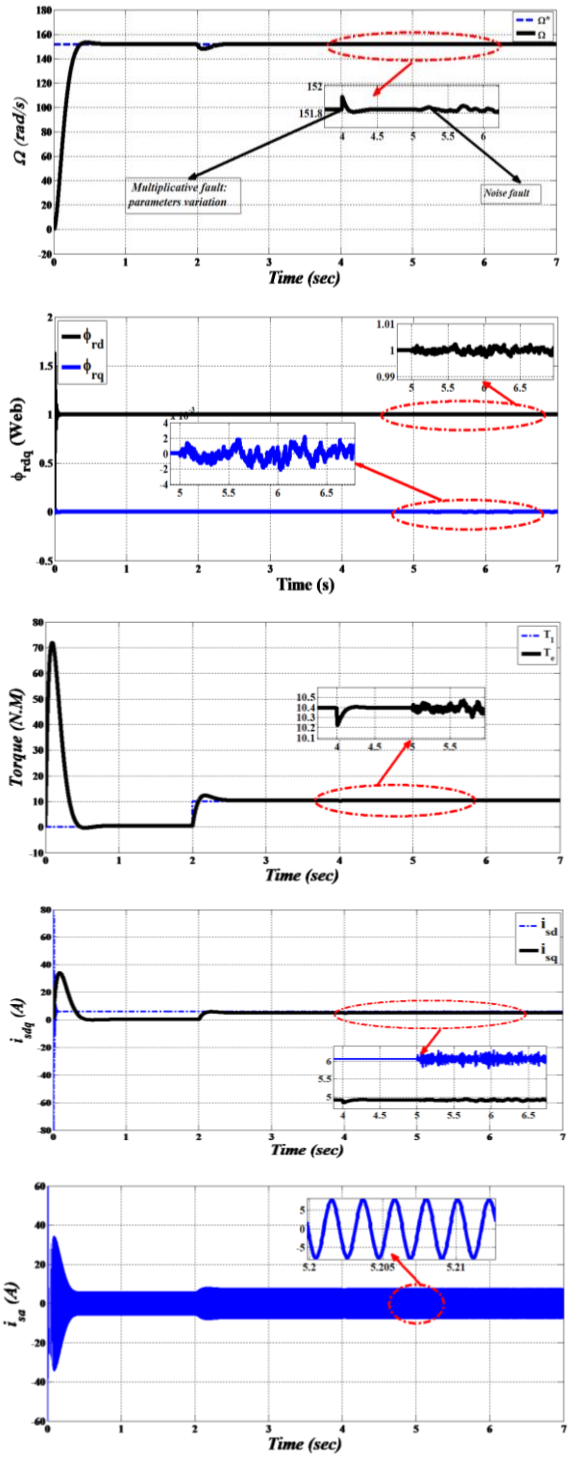


Fig.11. Performance of fault tolerant control under noise fault and uncertain parameters in speed sensor.

A performances of the designed controller K_μ are illustrated in the following simulation results:

- The results presented in Fig.7 show the effectiveness of the suggested FTC method against intermittent sensor fault. We can see that the speed, the electromagnetic torque, the two components of stator current, and the two components of rotor flux are unaffected.

- It is clear, from the simulation results presented in Fig.9 and Fig.11, that the proposed passive fault-tolerant control, using H∞-synthesis, provides highly satisfactory performances in terms of robustness, against gain and constant faults, or noise and a speed parameters variation fault. The speed and flux tracking are very maintained, with a good reject of the load torque perturbation. The stator current in the rotating reference frame (i_{sd}, i_{sq}) confirm that the decoupling control is perfect. The synthesized FD filter is robust with respect to multiplicative faults and disturbances, so only the effect of the additive fault remains, so if the additive fault appears the filter detects it and an alarm signal. The information given by the FD block is taken into account by the FTC and fault detection and identification is perfect.

Simulations results show the effectiveness of the H∞/µ synthesis control with sufficient fidelity to maintain good performance in tracking and rejecting uncertainties, on the effect of sensor faults on system behavior.

6. CONCLUSIONS

In this paper, a robust fault tolerant control approach (FTC) based on the H∞/µ synthesis technique is presented in order to eliminate the effect of speed sensor faults. We can conclude that the provided µ-synthesis method allowed us to synthesize a robust FD diagnostic filter tolerating an approximate decoupling of the exogenous residue disturbance and sensitizing only to the fault in additive form. The presented method offers a robust passive FTC control law and the H∞ controller ensures the FTC's passive mission and attenuating all these constraints. Simulation results show that the proposed algorithm can successfully, detect sensor faults in the presence of perturbations, and uncertainties, compensate the faults effect and maintain the stability and performance of IM control.

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APPENDIX A

INDUCTION MOTOR PARAMETERS

- $R_s = 5.72\,\Omega \quad R_r = 4.2\Omega$.
- $L_s = L_r = 0.462\ H$
- $M = 0.4402\ H, \quad n_p = 2$
- $J = 0.0049\ Kg.m^2, \quad f_v = 0.003\ Nm.s/rad$