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# Application of homogeneous observers with variable exponent to a mechatronic system

Syrine Derbel, Nabih Feki, Florentina Nicolau, Jean Pierre Barbot, Mohamed Slim Abbas, and Mohamed Haddar

**Abstract**—Preventive maintenance becomes nowadays more and more essential in many industrial applications. In fact, researchers are always looking for new techniques and analysis tools to monitor the dynamic behavior of their machines. In this context, firstly, we deal with the modeling of an electromechanical system which is accounted for by a hybrid model obtained by assembling the mechanical model of a gear element and the electrical model of an asynchronous motor. Secondly, we use Sliding Mode Observers to supervise the gear dynamic behavior. The observers parameters are suitably chosen to ensure rapid and accurate convergence between the real and the estimated system quantities. Finally, a comparative study between three simulations is presented in order to illustrate the observers performances and the influence of the mechanical dynamics on the electrical ones.

**Index Terms**—Electro-mechanical modeling, Gear transmission, Sliding Mode Observers.

## I. INTRODUCTION

TECHNICAL systems have become more and more complex and, nowadays, mechatronics is an essential tool for many industries. As technology advances, the subfields of engineering multiply and adapt. The aim of mechatronics is a design process that unifies these subfields by closely associating mechanical engineering, electronics, computer engineering, systems engineering and automatic control, as well as production and maintenance phase. In the recent decades, automatic transmission has known an unprecedented development and, in particular, automatic monitoring of gearbox transmission has become an important aspect of preventive maintenance in many industries. Therefore, many researchers have been working on developing the gear transmission model and supervising the dynamic behavior of the gear. In some papers, there has been studied the influence of spalling [1], shape deviations and mounting errors [2] and mesh stiffness fluctuations [3] on the gear units, while in other papers, the gear modeling is used to detect and locate the mechanical faults (see, *e.g.*, [4], [5], [1]).

In [6], an electro-mechanical coupling of a gear and an asynchronous motor (considered under the assumption that the steady-state of the motor is established), has been developed in order to determinate the type of the mechanical faults and detect where they occur with the help of the electrical measurements. Based on this coupling, in this paper, we present, a novel approach that consists of combining the automation with electrical and mechanical engineering works.

A reduced part of the gearbox will be studied considering only the torsional effect which is modeled by a single stage gear transmission driven by an induction motor. The gear excitation will be made, firstly, by an internal source which is obtained by time varying mesh stiffness [7] and, secondly, by an external sources of excitation which is induced by the electromagnetic torque of the motor. The main difficulty in coupling the dynamics of the asynchronous motor with that of the pinon-wheel element consists in a) making the gear element to rotate with the electromagnetic torque provided by the motor, and b) adding the gear vibration to the rotor mechanical speed. The contribution of this work aims firstly, to model the electro-mechanical system taking into account the transitional regime of the motor and secondly, to implement the observers in order to estimate the dynamics evolution of the motor-gear system. In fact, the knowledge of all physical states of the system is important to design an observer. However, in the general case, only some states variables are available from direct sensors measurements. The unknown variables can be estimated by the states observers using a priori knowledge of the actual model and the measured variables. Therefore, the design of efficient and robust observers has been the goal of many works (see, *e.g.*, [8], [9]). In this article, given the difference of dynamics between the electrical and mechanical quantities and in order to reduce the chattering phenomena, we apply Sliding Mode Observers for the electro-mechanical model to estimate the unavailable states. Another important issue in this work is the choice of the parameters for the observers implementation. It is well know that, in general, the dynamic behavior of the mechanical part is slower than that of the electrical one, therefore, it may be difficult to find the most suitable tuning for the time constants, the constants parameters and the observers gains. Based on the observer's informations and the motor-gear modeling, the simulations show firstly, that the estimated variables given by the proposed observers converge in finite time to the real ones and secondly, that the mechanical properties of the gear model are recovered in the electrical quantities.

The paper is organized as follows: In Section 2, the electro-mechanical modeling, obtained by developing the electrical and mechanical equations, will be presented. In Section 3, we develop the monitoring of the electro-mechanical system based on observers. Finally, the simulations results are given in Section 4 illustrating the performances and the effectiveness of proposed observers (second order differentiators).

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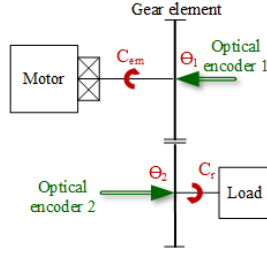


Fig. 1: Global electro-mechanical system.

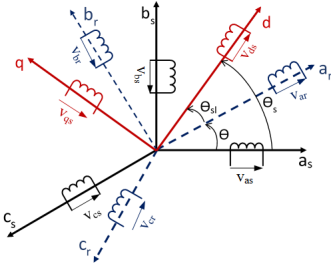


Fig. 2: Various magnetic axes of the asynchronous machine.

## II. ELECTRO-MECHANICAL MODELING

In this section, we present, following [6], the coupling of the gear model and the asynchronous motor. While in [6], the electro-mechanical modeling takes into account the six degrees of freedom of every gear node, here, we assemble the electrical model, which is an synchronous motor, with the torsional mechanical model (only, two degrees of freedom) of the spur or the helical gear (see Fig. 1). Another particularity of this work is that, comparing to [6], we no longer suppose that the steady state is reached.

### A. Asynchronous Motor Modeling

We apply the Faraday Law for the three phases of the stator (leading to equation (1)) and of the rotor (yielding equation (2)):

$$v_s = R_s i_s + \frac{d\phi_s}{dt}, \quad (1)$$

$$v_r = R_r i_r + \frac{d\phi_r}{dt}, \quad (2)$$

where:  $v_s = [v_{as} \ v_{bs} \ v_{cs}]^t \in \mathbb{R}^3$ ,  $v_r = [v_{ar} \ v_{br} \ v_{cr}]^t \in \mathbb{R}^3$  represent, respectively, the voltages of the three stator and rotor phases,  $i_s = [i_{as} \ i_{bs} \ i_{cs}]^t \in \mathbb{R}^3$  and  $i_r = [i_{ar} \ i_{br} \ i_{cr}]^t \in \mathbb{R}^3$  are, respectively, the currents vectors of the three stator and rotor phases,  $\phi_s = [\phi_{as} \ \phi_{bs} \ \phi_{cs}]^t$  and  $\phi_r = [\phi_{ar} \ \phi_{br} \ \phi_{cr}]^t \in \mathbb{R}^3$  correspond to the vectors of the fluxes through the windings of the stator and rotor, and  $R_s$  and  $R_r$  represent, respectively, the stator and the rotor resistances. By neglecting the saturation, the mutual and self inductances are independent of the currents in the windings so the fluxes equations can be written as below:

$$\phi(t) = L i(t), \quad (3)$$

where  $\phi(t) = [\phi_s^t \ \phi_r^t]^t \in \mathbb{R}^6$  represents the stator and rotor fluxes,  $i(t) = [i_s^t \ i_r^t]^t \in \mathbb{R}^6$  corresponds to the stator and rotor

currents and  $L \in \mathbb{R}^{6 \times 6}$  is a symmetric matrix, composed on its diagonal by the stator and rotor self-inductances, and on the triangular parts by the mutual inductances between the rotor and the stator phases or between two rotor (or stator) phases. In order to simplify the model, we apply the orthonormal Kron transformation (see Fig. 2) which consists of converting the three phases asynchronous machine  $(abc)_s/(abc)_r$  into an equivalent two phases machine  $(dq)$ , see [10],

$$x_{dq} = T_{2/3} x_{abc}, \quad (4)$$

with  $x_{dq} = [x_d \ x_q]^t \in \mathbb{R}^2$ ,  $x_{abc} = [x_a \ x_b \ x_c]^t \in \mathbb{R}^3$  and

$$T_{2/3} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\Psi) & \cos(\Psi - \frac{2\pi}{3}) & \cos(\Psi + \frac{2\pi}{3}) \\ -\sin(\Psi) & -\sin(\Psi - \frac{2\pi}{3}) & -\sin(\Psi + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}, \quad (5)$$

where  $\Psi$  is the angle transformation (which, in our study, equals  $\theta_s$ ,  $\theta_{sl}$  and  $\theta$  corresponding, respectively, to the Park transformation angle of the stator, sliding and rotor). The  $(dq)$ -frame can be fixed either at a) the stator, b) the rotor or c) the rotating field. Fixing the  $(dq)$ -frame at the stator corresponds to  $\theta_s = 0$  (thus  $\Psi = \theta_s$ ), and to the electrical variables evolving in permanent regime at constant stator pulsation  $\omega_s$ . Case a) is applied to study the variation of the supply frequency that may or may not to be associated with the rotation speed variation  $\omega_m$ . In the second case, we have  $\theta_{sl} = 0$  (thus  $\Psi = \theta_{sl}$ ), the electrical variables evolve in permanent regime at rotor currents pulsation  $\omega_{sl}$ . Therefore, case b) is used to analyze the transient regimes where the rotational speed of the rotor is considered constant. Finally, case c) is the most suitable for our system because it enables us to obtain constant magnitude in steady state. In fact, in the electrical modeling, we take into account the mechanical rotation speed variation  $\omega_m$ , however, in the simulations part (see Section 4), we suppose that the permanent regime is established, meaning that  $\omega_m$  is constant. For case c), the rotating field is the field created by the stator winding, and rotates, in steady state, at the synchronous speed  $\omega_s = \omega_{sl} + \omega = \omega_{sl} + p\omega_m$ , see [11].

We apply the matrix transformation (5) for (1), (2) and (3), for instance with  $x_{dq} = [v_{ds} \ v_{qs}]^t$  and  $x_{abc} = [v_{as} \ v_{bs} \ v_{cs}]^t$ . We thus obtain the following equations describing the dynamics of the asynchronous machine (see, e.g., [6], [12], with the difference that here  $\omega_m$  is no longer supposed constant):

$$\begin{cases} \frac{di_{ds}}{dt} = ai_{ds} + \omega_s i_{qs} + c\phi_{dr} + dp\omega_m \phi_{qr} + \frac{1}{L_s \sigma} v_{ds}, \\ \frac{di_{qs}}{dt} = -\omega_s i_{ds} + ai_{qs} - dp\omega_m \phi_{dr} + c\phi_{qr} + \frac{1}{L_s \sigma} v_{qs}, \\ \dot{\phi}_{dr} = ei_{ds} + f\phi_{dr} + (\omega_s - p\omega_m)\phi_{qr}, \\ \dot{\phi}_{qr} = ei_{qs} - (\omega_s - p\omega_m)\phi_{dr} + f\phi_{qr}, \\ \dot{\omega}_m = \frac{1}{J} [ \frac{pL_m}{L_r} (\phi_{dr} i_{qs} - \phi_{qr} i_{ds}) - C_r - f_1 \omega_m ], \end{cases} \quad (6)$$

with  $[i_{ds} \ i_{qs} \ \phi_{dr} \ \phi_{qr} \ \omega_m]^t \in \mathbb{R}^5$  the states vector whose components are the two stator currents  $i_{ds}$ ,  $i_{qs}$ , the two rotor fluxes  $\phi_{dr}$ ,  $\phi_{qr}$  expressed in  $(dq)$ -frame and the rotor mechanical speed  $\omega_m$ , and, all other parameters are constant and explained below:

$$a = -(\frac{1}{T_s \sigma} + \frac{1}{T_r} \frac{1-\sigma}{\sigma}), \quad c = \frac{1-\sigma}{\sigma} \frac{1}{L_m T_r}, \quad d = \frac{1-\sigma}{\sigma} \frac{1}{L_m}, \\ e = \frac{L_m}{T_r}, \quad f = -\frac{1}{T_r}, \quad \sigma = 1 - \frac{L_m^2}{L_s L_r}, \quad T_s = \frac{L_s}{R_s}, \quad T_r = \frac{L_r}{R_r}, \quad J: \text{mo-}$$

ment inertia of the motor,  $f_1$ : friction coefficient,  $C_r$ : resistant torque,  $v_{ds}, v_{qs}$ : stator supply voltages and  $L_s, L_r$  and  $L_m$  are, respectively, the stator, rotor and the magnetizing synchronous inductances.

We denote by  $C_{em}$  the electromagnetic torque (associated to the magnetic and the electrical parameters) defined by:

$$C_{em} = \frac{pL_m}{L_r}(\phi_{dr}i_{qs} - \phi_{qr}i_{ds}), \quad (7)$$

where  $p$  is the number of pole-pairs.

By solving (6), we determine the currents and the magnetic fluxes of the asynchronous motor and, consequently, deduce the instantaneous electromagnetic torque transmitted by the motor to the gearbox transmission.

### B. Gear Modeling

The mechanical part of the global model is composed of four elements [12]: a) four shafts, b) a gear element made of two gears (pinion, wheel), c) four bearings represented by additional stiffnesses, d) a load placed at one node of the gear shaft called output shaft. In this paper, the mechanical part is simplified: we take into account only element b) mentioned above which corresponds to the torsional model (meaning that we consider only two degrees of freedom of the gear).

In order to obtain the state space representation of the gear, Euler-Lagrange equations are applied:

$$\frac{d}{dt}\left(\frac{\partial E_c}{\partial \dot{q}}\right) - \frac{\partial E_c}{\partial q} + \frac{\partial E_p}{\partial q} + \frac{\partial D}{\partial \dot{q}} = \frac{\partial W}{\partial q}, \quad (8)$$

where:  $E_c$  is the kinetic energy of the system,  $E_p$  represents the potential energy of the system,  $D$  is the dissipation function (e.g., viscous friction forces),  $W$  represents the virtual work of the generalized external forces, and  $q$  is the degrees of freedom's vector. For the gear element, the kinetic and potential energy are given by:

$$E_c = \sum_{n=1}^2 \left( \frac{1}{2} (\tilde{\Omega}_n)^t I_n \tilde{\Omega}_n \right), \quad (9)$$

$$E_p = \frac{1}{2} q^t \left( k(t) \vec{V} \vec{V}^t \right) q, \quad (10)$$

with:  $\tilde{\Omega}_n$ : torsional rotation speed of gear  $n$ ,  $1 \leq n \leq 2$ ,  $I_n$ : inertia tensor of gear  $n$ ,  $k(t)$ : time varying mesh stiffness,  $\vec{V}$ : constant structure vector depending on the gear geometry  $\vec{V} = [R_{b1} \cos(\beta) \quad R_{b2} \cos(\beta)]^t \in \mathbb{R}^2$ , where  $R_{b1}$ ,  $R_{b2}$  are, respectively, the base radii of the pinion and the wheel,  $\beta$  is the helix angle of the gear, and  $q = [\theta_1 \quad \theta_2]^t \in \mathbb{R}^2$  is a torsional vector whose coordinates are the two degrees of freedom of the gear element. Therefore, equation (8) gives:

$$\frac{d}{dt}\left(\frac{\partial E_c}{\partial \dot{q}}\right) - \frac{\partial E_c}{\partial q} = M\ddot{q}, \quad (11)$$

$$\frac{\partial E_p}{\partial q} = K(t)q, \quad (12)$$

where  $M = \text{diag}(I_1, I_2)$  represents the mass matrix, and  $K(t) = k(t) \vec{V} \vec{V}^t$  is the stiffness matrix of the gear element which depends explicitly on the time, see [2].

Using (11) and (12), the global equation of motion of the mechanical model can be rewritten as:

$$M\ddot{q} + C\dot{q} + K(t)q = F(t), \quad (13)$$

where  $C$  is the damping and  $F(t) \in \mathbb{R}^2$  is the external forces (motor and load torque). The introduction of the damping  $C$  is always tricky so a simple Rayleigh model has been considered, that is a constant matrix expressed as a linear combination of the mass and mean stiffness matrices:

$$C = \gamma_1 M + \gamma_2 K_{av}, \quad (14)$$

where the parameters  $\gamma_1$  and  $\gamma_2$  are proportionality constants and  $K_{av}$  is the average of  $K$ . Finally, the state space representation of the gear element can be written as follows:

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -M^{-1}K_e & & & \\ & -M^{-1}C_e & & \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -M^{-1}F \end{bmatrix} \quad (15)$$

with  $F$  the external forces.

### C. Gear-motor Coupling

The last step of modeling consists of coupling the electrical variables of the asynchronous motor with the mechanical ones in the same states vector  $[i_{ds} \quad i_{qs} \quad \phi_{dr} \quad \phi_{qr} \quad \omega_m \quad q \quad \dot{q}]^t \in \mathbb{R}^9$ . The principle of this coupling is to substitute firstly, the electromagnetic torque, given by (7), in the mechanical system (i.e., the gear rotates with the motor torque given by the asynchronous machine) and secondly, the gear vibrations (whose dynamics are described by the equation of  $\theta_1$ ) in the mechanical rotation speed of the asynchronous motor. So, the representation of the electro-mechanical model becomes:

$$\dot{x}(t) = f(t, x), \quad (16)$$

where  $x = [i_{ds} \quad i_{qs} \quad \phi_{dr} \quad \phi_{qr} \quad \omega_m \quad \theta_1 \quad \theta_2 \quad \dot{\theta}_1 \quad \dot{\theta}_2]^t$  is the state of the global electro-mechanical model (composed of the currents, fluxes, mechanical speed rotation of the asynchronous motor and the two torsional displacements and their velocities for the mechanical part) and the drift  $f$  is given by:

$$\begin{pmatrix} ai_{ds} + \omega_s i_{qs} + c\phi_{dr} + d(p\omega_m + \dot{\theta}_1)\phi_{qr} + \frac{1}{\sigma L_s} v_{ds}, \\ -\omega_s i_{ds} + ai_{qs} - d(p\omega_m + \dot{\theta}_1)\phi_{dr} + c\phi_{qr} + \frac{1}{\sigma L_s} v_{qs}, \\ ei_{ds} + f\phi_{dr} + (\omega_s - (p\omega_m + \dot{\theta}_1))\phi_{qr}, \\ ei_{qs} - (\omega_s - (p\omega_m + \dot{\theta}_1))\phi_{dr} + f\phi_{qr}, \\ \frac{1}{4}[C_{em} - C_r - f_1\omega_m], \\ \theta_1, \\ \dot{\theta}_2, \\ \frac{1}{I_1}[-K_{11}\theta_1 - K_{12}\theta_2 - C_{11}\dot{\theta}_1 - C_{12}\dot{\theta}_2 + C_{em}], \\ \frac{1}{I_2}[-K_{21}\theta_1 - K_{22}\theta_2 - C_{21}\dot{\theta}_1 - C_{22}\dot{\theta}_2 - C_r], \end{pmatrix} \quad (17)$$

where  $K_{ij}$  (respectively,  $C_{ij}$ ),  $1 \leq i, j \leq 2$  are the stiffness (respectively, damping) matrix coefficients.

Recall that  $K_{ij}$  depend explicitly on the time, thus equation (17) shows that the electro-mechanical system is a time-variant system. As explained in the introduction, developing the gear transmission model is a problem that has attracted a lot of attention. Once a dynamical model is obtained, another important problem is its supervision and the possible faults detection. within this context, the interest of this work is

two fold: firstly, it allow us to study the global system by coupling the electrical and the mechanical parts, and secondly, it supervise the dynamic behavior of the global system using the observers. Moreover, it proposes some good choices for the time constants, the constant parameters and the observers gain that take into account the slow and fast dynamics of the motor-gear system. Since the global electromechanical system is a non linear control-affine system, see (17), Sliding Mode Observers will be applied to monitor the dynamic behavior of the global system.

### III. MONITORING OF THE ELECTRO-MECHANICAL SYSTEM (MOTOR-GEAR) BASED ON OBSERVERS

We will next briefly recall the notion of observability and the principle of the Sliding Mode Observers and then, we will present the observer design.

#### A. Observability of the electro-mechanical system

The observability allows us to reconstruct the state vector from the measured outputs of a system and we next recall how to check it. Consider a non linear system of the form:

$$\begin{cases} \dot{\zeta}(t) = f(\zeta(t)), \\ y(t) = h(\zeta(t)), \end{cases} \quad (18)$$

where  $\zeta \in \mathbb{R}^n$  represents the state vector,  $y \in \mathbb{R}^m$  is the output vector (the measurements), and the vector field  $f$  and the functions  $h_i$ ,  $1 \leq i \leq m$  are supposed  $C^\infty$ -smooth.

Assume that all outputs  $h_i$ , for  $1 \leq i \leq m$ , are independent and compute their successive time-derivatives:

$$\begin{aligned} y_i^0(t) &= h_i(\zeta(t)) = L_f^0 h_i(\zeta(t)) = y_i(t), \\ y_i^j(t) &= L_f^j h_i(\zeta(t)) = L_f(L_f^{j-1} h_i(\zeta(t))) \\ &= \frac{\partial L_f^{j-1} h_i(\zeta(t))}{\partial \zeta} f(\zeta(t)), \end{aligned}$$

where  $j \geq 1$ ,  $1 \leq i \leq m$ , and  $L_f^j h_i(\zeta(t))$  is the Lie derivative of order  $j$  of the smooth function  $h_i$ . The observability space of system (18) is given by  $O = \text{span} \{ dL_f^j h_i, 1 \leq i \leq m, j \geq 0 \}$ . System (18) is locally observable at  $\zeta_0$  if  $\dim O(\zeta_0)$  is maximal and equal to  $n$ , the state space dimension [13].

For the electro-mechanical system, two current sensors are placed in order to measure the system currents ( $y_1 = h_1 = i_{ds}$ ,  $y_2 = h_2 = i_{qs}$ ), a tachymeter to measure the motor speed ( $y_3 = h_3 = \omega_m$ ) and two rotary encoders (see Fig. 1) are used to obtain the systems displacements ( $y_4 = h_4 = \theta_1$  and  $y_5 = h_5 = \theta_2$ ).

Via a straight forward computation, we obtain:

$$\begin{aligned} \dot{y}_1 &= L_f y_1 = a i_{ds} + b i_{qs} + c \phi_{dr} + d(p\omega_m + \dot{\theta}_1) \phi_{qr} + \frac{v_{ds}}{\sigma L_s}, \\ \dot{y}_2 &= L_f y_2 = -b i_{ds} + a i_{qs} - d(p\omega_m + \dot{\theta}_1) \phi_{dr} + c \phi_{qr} + \frac{v_{qs}}{\sigma L_s}, \\ \dot{y}_4 &= L_f y_4 = \dot{\theta}_1, \\ \dot{y}_5 &= L_f y_5 = \dot{\theta}_2. \end{aligned}$$

Since the determinant of the following matrix

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a & w_s & c & d(p\omega_m + \dot{\theta}_1) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -w_s & a & -d(p\omega_m + \dot{\theta}_1) & c & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

equals  $-c^2 - (d\dot{\theta}_1)^2 - 2pd^2\dot{\theta}_1\omega_m - (dp\omega_m)^2$  and does not vanish for any values of  $\dot{\theta}_1$  and  $\omega_m$ , it follows that the observability space is always of constant rank and given by  $O = \text{span}\{dh_i, 1 \leq i \leq 5, \text{ and } dL_f h_i, i \in \llbracket 1, 5 \rrbracket \setminus 3\}$ , and, therefore, all components of the state vector are observable and can be reconstructed by an observer.

#### B. Some recalls on observer design

An observer is a dynamic system that estimate the unmeasured states of the system from only its measured outputs and has many important applications (see, [11] for a problem similar to that considered in this paper). In [14],[15], observers construction problem for linear dynamic system is applied, respectively, for fault detection of a drying blower system and for a vehicule rollor warning system. For nonlinear systems [16], the available results depend on the problem and its applications. Nevertheless, the extended Kalman filter is the standard nonlinear observer (see, e.g., [17], [18], [19] for some applications). It provides an accurate and quick estimation for the desired variables using all available measurements. The output injection method (see, e.g., [20], [21]) is proposed for limited classes of nonlinear systems and can ensure the global asymptotic stability of the error dynamics. The extended Luenberger [22] and high gain observers [23] are used for many applications in order to monitor the nonlinear systems. The simplicity of their implementation is the main advantage of these observers. Sliding Mode Observers design breaks up into two parts: the first one is a mathematical replica of the real system and the second one is a built signal (called corrective term) representing the difference between the outputs of the plant and the estimated outputs. In the case of Luenberger observer, this signal is send back linearly into the observer which poses a problem in presence of uncertain parameters or unknown signals. This situation makes the Luenberger observers incapable to force the error of the output estimation to zero and to ensure the convergence of the estimated states to the real states. The principal of the Sliding Mode Observers (SMO) is to constraint the dynamics of the system (corresponding in our case to the observation errors) to converge to a surface  $s$  called sliding surface by using the discontinuous function *sign*. SMO are very advantageous by their capacity to a) obtain a convergence of the outputs estimation error in finite time b) assure the convergence of the estimated states to the real ones c) reconstruct the disturbances within the system d) guarantee, under some well chosen parameters and conditions, a good robustness [24]. SMO are applied for to monitor the linear or nonlinear systems and developed for many electrical and mechanical applications (see, e.g., [25],[26]).

In [27], a conventional SMO for linear and nonlinear system is developed, it is based on a change of coordinates leading to a state vector that contains explicitly the outputs of the system. Despite their robustness and accuracy, classic SMO have a major problem that is the chattering effect caused by the discontinuous function. Many solutions are proposed to solve this issue, among them the high order sliding mode observers (HOSMO). Most HOSMO use the concept of homogeneity (see *e.g.*, [28],[29], and [30]) based on the differentiation algorithms. In this context, Levant [31] proposed a robust exact differentiator. It estimates the derivatives from order 1 to order  $n - 1$  (where  $n$  is the system order) assuming that the  $n$ th order derivative is known. As we have seen, observers can be used to identify the unknown system parameters but also to diagnose (*i.e.*, to detect the possible faults) and finally, as in our case, to monitor the dynamic behavior of the system.

### C. Observer Design of the electro-mechanical system

In this section we present the implementation of the observer to supervise the dynamic behavior of the coupled torsional model. The monitoring is realized, when the asynchronous motor is on steady state in order to simplify the analysis and avoiding perturbations due to the boundary layer [32]. We apply a differentiator to estimate the state variables from the four system outputs (see Section III A). It is well known that the super twisting differentiators [27] have good properties with respect to sensibility perturbation but their accuracy is degraded if the signal is perturbed by a noise, contrary to the linear observers that have good performances with respect to the measurement noise but they are sensible to perturbations. In [30], [33], a novel second order sliding mode differentiator with a variable exponent is proposed in order to make trade off between accuracy and noise sensibility. Following [30], [33], we explain the differentiator design, then, we will apply it to the electro-mechanical system. Consider the following second order system:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = u, \\ y_m = x_{1m} = x_1 + w, \end{cases} \quad (19)$$

where  $x(t) \in \mathbb{R}^2$  is the state of the system,  $u(t) \in \mathbb{R}$  is the unknown input,  $y(t) \in \mathbb{R}$  represents the output of the system and  $w$  refers to measurement noise. The proposed differentiator of system (19) is designed as follows:

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 + k_1 \mu |e_1|^\alpha \text{sign}(e_1), \\ \dot{\hat{x}}_2 = k_2 \alpha \mu^2 |e_1|^{2\alpha-1} \text{sign}(e_1), \\ \hat{y}_m = \hat{x}_{1m}, \\ e_1 = y_m - \hat{y}_{m1} = x_{1m} - \hat{x}_{1m}, \end{cases} \quad (20)$$

where  $e_1$  is the output estimation error,  $\alpha$  is the variable exponent depending on the estimation error  $e_1$ ,  $k_i$ ,  $1 \leq i \leq 2$ , are constants chosen such that the eigenvalues of the estimation error are stable, and  $\mu$  is a positive constant suitably chosen to cancel the effect of the perturbation and to preserve the homogeneity for a fixed  $\alpha$ .

In this paper, we will study two cases: we suppose, first, that the parameter  $\alpha$  is constant, and, second, we let  $\alpha$

vary between 0.5 (corresponding to the exact differentiator) and 1 (case of linear observers), see [34] for the methodologies for adaptive observer. This variation is obtained by a low-pass filter of noisy output frequencies  $|y_{mhf}|$  expressed as follows:

$$\begin{cases} \dot{\hat{x}}_3 = -\tau \hat{x}_3 + \tau |y_{mhf}|, \\ \alpha = 0.5 \left( 1 + \frac{\hat{x}_3}{\hat{x}_3 + \epsilon} \right), \end{cases} \quad (21)$$

where  $\tau$  is a constant parameter chosen small with respect to the dynamic system to fix the filtered output sufficiently low and  $\epsilon$  is a constant parameter that should be greater than 1 to ensure that  $\alpha$  remains in  $[0.5, 1]$  when  $x_3$  is equal to zero. This parameter is linked to the precision of the differentiator.

The differentiator explained above is applied for the electro-mechanical system. In order to obtain the estimated states of the transmission gear model, we apply four differentiators: the first two for the electrical part (the asynchronous motor) and the last ones for the mechanical part (the gear element). For the asynchronous motor, we denote  $z_1 = i_{ds}$ ,  $z_2 = \frac{di_{ds}}{dt}$ ,  $z_3 = i_{qs}$ ,  $z_4 = \frac{di_{qs}}{dt}$ , the differentiator is applied to estimate the derivative of the currents. This estimation with fixed gain  $\alpha$  is obtained by the following equations where for simplicity of notation, we write  $[\cdot]^\alpha$  instead of  $|e_i|^\alpha \text{sign}(e_i)$ .

$$\begin{cases} \dot{\hat{z}}_1 = \hat{z}_2 + k_1 \mu_1 [\cdot]^\alpha, \\ \dot{\hat{z}}_2 = k_2 \alpha_1 \mu_1^2 [\cdot]^{2\alpha_1-1}, \\ e_1 = z_1 - \hat{z}_1, \end{cases} \quad \text{and} \quad \begin{cases} \dot{\hat{z}}_3 = \hat{z}_4 + k_1 \mu_1 [\cdot]^\alpha, \\ \dot{\hat{z}}_4 = k_2 \alpha_1 \mu_1^2 [\cdot]^{2\alpha_1-1}, \\ e_2 = z_3 - \hat{z}_3. \end{cases}$$

The estimated fluxes are deduced under the assumption that  $\dot{e}_1$  and  $\dot{e}_2$  tend to zero (see [35]). Thus, the two fluxes expressed in the  $(dq)$ -frame can be written as below:

$$\begin{bmatrix} \phi_{dr} \\ \phi_{qr} \end{bmatrix} = D \begin{bmatrix} \hat{z}_2 + k_1 \mu_1 [\cdot]^\alpha - a i_{ds} - \omega_s i_{qs} - \frac{1}{L_s \sigma} v_{ds} \\ \hat{z}_4 + k_1 \mu_1 [\cdot]^\alpha + \omega_s i_{ds} - a i_{qs} - \frac{1}{L_s \sigma} v_{qs} \end{bmatrix},$$

with,  $D = \begin{bmatrix} c & d(p\omega_m + \dot{\theta}_1) \\ -d(p\omega_m + \dot{\theta}_1) & c \end{bmatrix}^{-1}$  which is always invertible (due to the observability property).

The differentiator applied for the gear element aims to estimate the displacements derivative  $\dot{\theta}_1$  and  $\dot{\theta}_2$ . Denote  $z_5 = \theta_1$ ,  $z_6 = \dot{\theta}_1$ ,  $z_7 = \theta_2$  and  $z_8 = \dot{\theta}_2$ , the differentiator equations associated to the mechanical part are the flowing:

$$\begin{cases} \dot{\hat{z}}_5 = \hat{z}_6 + k_3 \mu_2 [\cdot]^\alpha, \\ \dot{\hat{z}}_6 = k_4 \alpha_2 \mu_2^2 [\cdot]^{2\alpha_2-1}, \\ e_3 = z_5 - \hat{z}_5, \end{cases} \quad \text{and} \quad \begin{cases} \dot{\hat{z}}_7 = \hat{z}_8 + k_3 \mu_2 [\cdot]^\alpha, \\ \dot{\hat{z}}_8 = k_4 \alpha_2 \mu_2^2 [\cdot]^{2\alpha_2-1}, \\ e_4 = z_7 - \hat{z}_7. \end{cases}$$

In order to vary the gains  $\alpha_1$  and  $\alpha_2$ , (21) will be applied for the four proposed differentiators described above. With the help of these differentiators, we are thus able to recover all states of the system (the motor-gear model) and, consequently, monitoring the dynamics behavior of the gear.

## IV. SIMULATION AND RESULTS

In this section, the simulations results of the electromechanical system controlled by the proposed differentiator are presented. The designed system was implemented in Matlab Simulink environment where an ode1 (*Euler*) is used with a fixed step size equal to  $10^{-6}$ . White noises blocks, from Matlab library, are used and considered as sensors noises. The

TABLE I: Motor parameters

Stator resistance $R_s$ ( $\Omega$ )	9.163
Rotor resistance $R_r$ ( $\Omega$ )	5.398
Stator inductance $L_s$ (H)	0.115
Rotor inductance $L_r$ (H)	0.0943
Magnetizing inductance $L_m$ (H)	0.0943
Number of pole-pairs $p$	1

TABLE II: Gears parameters

Module (mm)	4
Tooth number of Pinion	21
Tooth number of wheel	31
Face width (mm)	10
Pressure angle (deg)	20

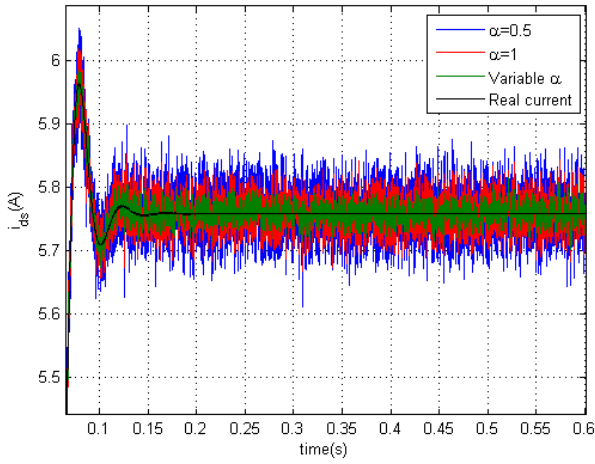
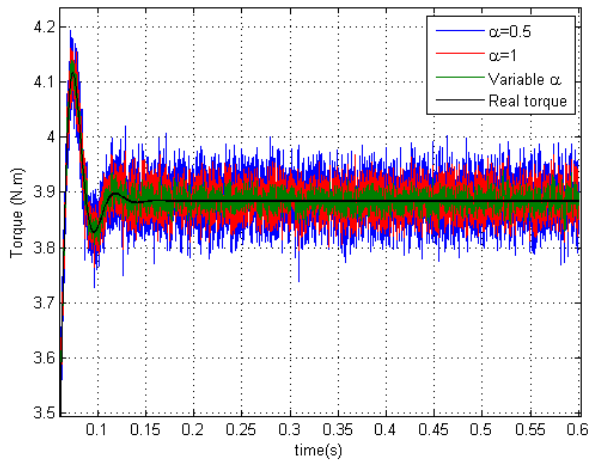
Fig. 3: Real and estimated current  $i_{ds}$ 

Fig. 4: Real and estimated electromagnetic torque

asynchronous motor and spur gear parameters are given in tables I and II, respectively. The first two simulations were realized with fixed gains  $\alpha_i$ ,  $1 \leq i \leq 2$ , while the second one was simulated with variable  $\alpha_i$ .

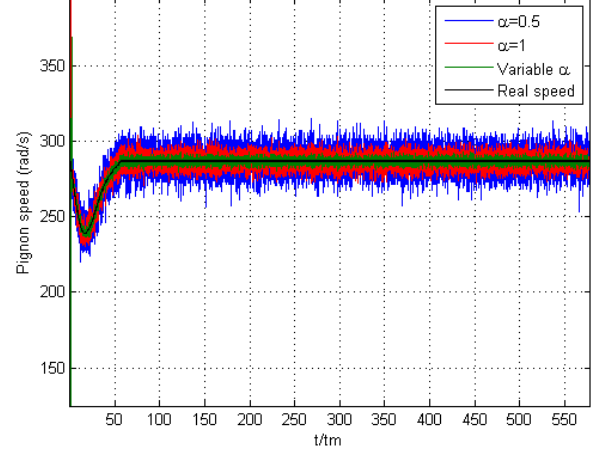
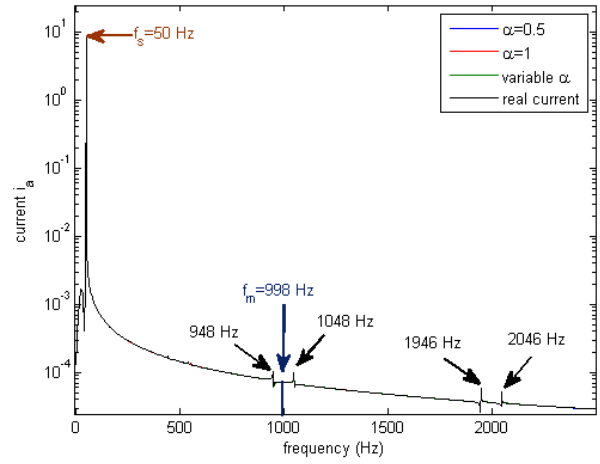
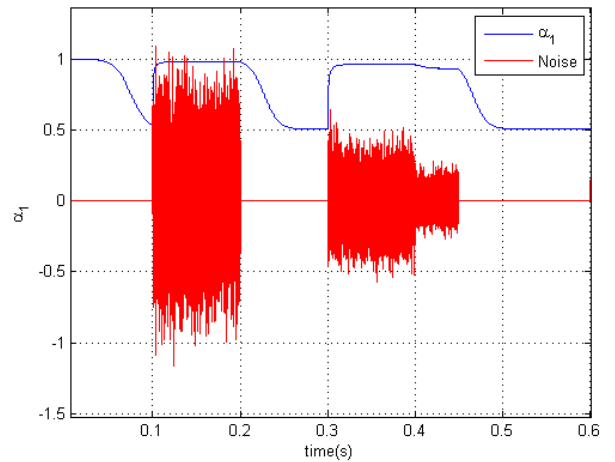


Fig. 5: Real and estimated speed of the pinion

Fig. 6: Spectrum of the first phase current  $i_a$ Fig. 7: Electrical noise and gain  $\alpha_1$ 

In order to compare the performances of the proposed differentiators, first, we fix  $\alpha_i = 0.5$ ,  $1 \leq i \leq 2$  (corresponding



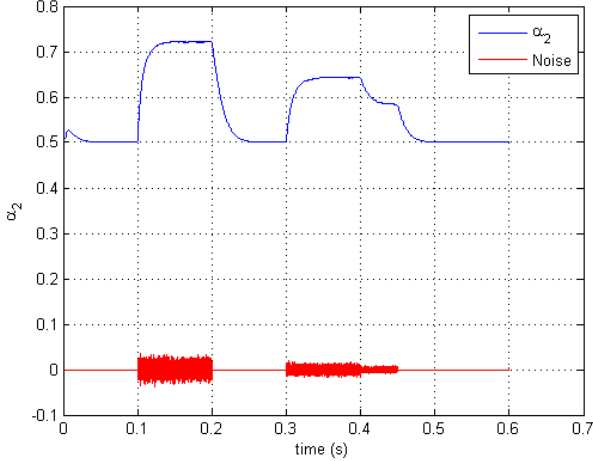


Fig. 8: Mechanical noise and gain  $\alpha_2$

to the Levant's differentiator) and second, we put  $\alpha_i = 1$ ,  $1 \leq i \leq 2$  (corresponding to the linear differentiator). Recall that, when  $\alpha_i$  is allowed to vary, 0.5 and 1 are respectively the minimal and the maximal possible value that  $\alpha_i$  can take. Finally, the case when  $\alpha$  varies according to (21) is considered.

Fig. 3-5 show that, in all cases of  $\alpha_i$ , the estimated quantities converge in finite time to the real states of the system. Fig. 3 and 4 present the electrical quantities which are, respectively, the current  $i_{ds}$  of the asynchronous machine expressed in the  $(dq)$ -frame and the electromagnetic torque  $C_{em}$  of the motor. In these figures, we can see that the differentiator with variable gains  $\alpha_i$ ,  $1 \leq i \leq 2$  have good proprieties compared to those for which  $\alpha$  is fixed ( $\alpha_i = 0.5$ , respectively,  $\alpha_i = 1$ ,  $1 \leq i \leq 2$ ). In fact, when white noises are introduced, from Fig. 3 and 4, it is clear that the differentiator with a variable  $\alpha$  gives more precise convergence (notice that the noises interval is reduced with respect to the constant cases). For the mechanical part, Fig.5 displays the pinon speed rotation and confirm the good performances of the differentiators associated to the gear element with variable  $\alpha$ . Fig 6 represents the frequency spectrum of the current  $i_a$ . This current is obtained by multiplying the  $i_{ds}$  and  $i_{qs}$  by the inverse matrix of  $T_{2/3}$ . This figure shows the perfect convergence of the proposed differentiators. We obtain an error of the order of  $10^{-4}$  that justifying that the curves given by different values of  $\alpha$  coincide in Fig. 6. On the other hand, Fig. 6 illustrates the influence of the mechanical quantities on the electrical ones. In fact, this figure shows firstly, a peak at the electrical supply frequency  $f_s = 50Hz$  and secondly, two peaks at the frequency meshing  $f_m \pm f_s$  and its harmonics  $if_m$ ,  $i = \{1, 2, 3, ect.,\}$ . For example, in our case, we have  $f_m = 998Hz$  and  $f_s = 50Hz$ , so the two peaks are obtained at a)  $948Hz$  and b)  $1048Hz$ . These frequencies are retrieved in the three cases of differentiators.

Moreover, since the mechanical element is slower than the electrical one, the added noise is different: we use a noise of order of  $10^{-7}$  for the electrical differentiator while for the mechanical one the added noise is of order of  $10^{-10}$ . The following noises division of the mechanical and electrical dif-

ferentiators depends on the effect of variable  $\alpha$ . In Fig. 7 and Fig. 8, the added noise is multiplied : a) by 0 for  $t \in [0, 0.1s]$ ,  $[0.2, 0.3s]$  and  $[0.45, 0.6s]$ , b) by 1 for  $t \in [0.1, 0.2s]$ , c) by  $\frac{1}{2}$  for  $t \in [0.3, 0.4s]$ , and, d) by  $\frac{1}{4}$  for  $t \in [0.4, 0.45s]$ , which guarantees that  $\alpha$  tends to 1 when the noise is the most important (approaching the linear differentiator) and is 0.5 when the noise is absent. On the other hand, as the electrical evolution is faster than the mechanical one, the choice of the differentiator parameters, such as the time constants ( $\tau$ ,  $\epsilon$ ) and  $\mu_i$ ,  $i = 1 \leq i \leq 2$ , is not obvious. The values of  $\mu_i$ ,  $i = 1 \leq i \leq 2$ , are crucial to cancel the perturbation effect. In fact, for the first differentiator, the choice of  $\mu_1$  that guarantees the cancellation of the electrical perturbation is  $\mu_1 = 5 \times 10^3$ . For the gear system, we have to cancel the mechanical perturbation and to this end, we choose  $\mu_2 = 10^5$ . The parameter  $\tau$  should be as small as possible and its role is to fix the output sensors sufficiently low with respect the dynamic system (here, we take  $\tau_1 = 80$  and  $\tau_2 = 100$ ).

## V. CONCLUSION AND PERSPECTIVES

In this paper, the modeling of an electro-mechanical system has been presented. The electromagnetic torque produced by the asynchronous machine with regarding the gear perturbed rotational speed is considered as an input of the gear subsystem leading to a global electro-mechanical system. In order to supervise the behavior of all components of the system, the observers (differentiators) via sliding mode technique are developed and different simulations have been presented. These results show the effect of the noise on the exponent gain  $\alpha_i$  and on the performances of differentiators. Our on going work, will focus on the faults detection of gear transmission using the supervision based on observers and will implement the electro-mechanical model with six degrees of freedom of the motor-gear system (here only two were considered).

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