Indonesian Journal of Electrical Engineering and Computer Science
Vol. 28, No. 1, October 2022, pp. 124∼136
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v28.i1.pp124-136

Advanced control with extended Kalman filter and disturbance observer

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Article Info

Article history:

Received Jan 29, 2022
Revised Jun 19, 2022
Accepted Jul 26, 2022

Keywords:

Disturbance observer
Extended Kalman filter
LMIs
Permanent magnet synchronous motors
T-S fuzzy model

ABSTRACT

This paper describes a novel fuzzy tracking control for permanent magnet synchronous motors (PMSM) using an extended Kalman filter (EKF) and disturbance observer (DO). The goal is to create a robust controller able to drive the system's states to track a virtual reference model and provide a low disturbance effect on the synchronous machine. First, the PMSM is represented using a fuzzy model Takagi-Sugeno (T-S) attended by the load torque variation. Next, To simplify the construction of a virtual reference model and nonlinear tracking control, a fuzzy tracking control based on virtual desired variables (VDVs) is proposed. Using this concept, a two-stage design procedure is developed: i) determine the VDVs using the desired output and the load torque, which can be estimated using DO and EKF and ii) calculate the fuzzy controller gains by solving linear matrix inequalities (LMIs). The efficiency of the suggested strategy is eventually shown through simulation results.

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1. INTRODUCTION

During the last years, the high efficiency, power/weight and torque/inertia ratios of permanent magnet synchronous motors (PMSM) have attracted increasing interest in industrial drive applications. Due to the inherent nonlinearities and external disturbances, their analysis and control is a difficult task. Thus, the linear control approach cannot guarantee satisfactory performances. To avoid the difficulties connected with the design of the PMSM controller, many proposals have been developed in the previous three decades, e.g. Direct torque control, adaptive control, neural network control, feedback linearization control, and sliding mode control have been considered respectively in [1]-[5].

Recently, many schemes based on the Takagi-Sugeno (T-S) fuzzy model have been proposed [6]. Using a T-S fuzzy-model-based, a complex dynamic system can be described using an averaged sum of a set of local linear subsystems, thus providing a systematic framework for modelling, analyzing, and controlling nonlinear systems. Using the Lyapunov approach, stability analysis is carried out, where the control issue is formulated into linear matrix inequalities (LMIs) problem [7].

The problem of tracking control of PMSM using the T-S fuzzy model and a novel concept namely virtual desired variables (VDVs) has been studied by many authors [8]–[11]. Based on this notion, the challenge of tracking control can be transformed into a simple stabilization problem which has been discussed in many works using the know parallel distributed compensation (PDC) technique [12]. Moreover, the control law and the reference model can be efficiently designed using generalized kinematics [13].

However, the control of PMSM using T-S fuzzy models and the VDVs concept has been discussed in many works without considering the influence of external disturbances. In practical industrial applications, the PMSM is usually affected by disturbances; their presence diminishes the tracking control performance. Hence, many works have dealt with the T-S fuzzy control of nonlinear systems with disturbances using several techniques, especially those based on H-infinity tracking control [14], [15]. Thus, the first idea is if possible to combine the concept of VDVs with H-infinity performance. In this case, it can design a fuzzy controller that allows benefiting from the first one, the facilitated design of the reference model and the control laws, and from the second one, minimizing the effect of the disturbances on the system. However, this method is not usually effective when disturbances are essential, as in the case of the PMSM system.

This work develops an advanced robust fuzzy tracking scheme for a PMSM. To this end, the PMSM is represented by the T-S fuzzy model. In order to simplify the design of nonlinear control law and a reference model, a fuzzy tracking control based on the set of VDVs is then constructed. Instead of minimizing the effect of the disturbance on the system, the disturbance becomes a part of the reference model to compensate entirely for its effect on the motor. However, the problem here is that the disturbances are usually in an unknown state, or its measure is a difficult task as in the case of considering motor when the load torque is considered an external disturbance. To solve this problem, the load torque is estimated using a disturbance observer and extended Kalman filter, as outlined in Figure 1. The stability of the augmented system is analyzed by Lyapunov's approach, which may be expressed as LMIs problem. An algorithm to calculate the controller gains according to the desired system characteristics is presented and discussed. Matlab/Simulink simulations of the acquired findings demonstrate the great performance of the suggested control approach.

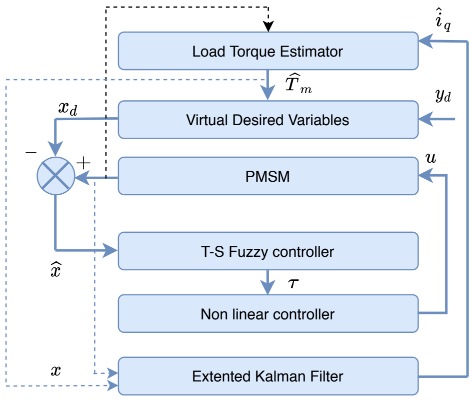

Figure 1. Proposed fuzzy tracking control scheme

2. PMSM MODEL

The following nonlinear system describes the dynamic model of the synchronous motor in the d-q reference frame [16], [17]:

$$\begin{cases} \dot{x}(t) = f(x(t)) + g(x(t))u(t) + \vartheta(x(t)) \\ y(t) = \varphi(x(t)) \end{cases} \tag{1}$$

where:

$$x(t) = \begin{bmatrix} \omega(t) \\ i_q(t) \\ i_d(t) \end{bmatrix}, f(x,t) = \begin{bmatrix} -\frac{f}{J}\omega(t) + \frac{3p\lambda}{2J} i_q(t) \\ -\frac{p\lambda}{L_q}\omega(t) - \frac{R}{L_q} i_q(t) - p\omega(t) i_d(t) \\ p\omega(t) i_q - \frac{R}{L_q} i_d(t) \end{bmatrix}, u(t) = \begin{bmatrix} u_q \\ u_d \end{bmatrix}, g(x(t)) = \begin{bmatrix} 0 & 0 \\ \frac{1}{L_q} & 0 \\ 0 & \frac{1}{L_d} \end{bmatrix}$$

$$\vartheta(x(t)) = \begin{bmatrix} -\frac{1}{J} \\ 0 \\ 0 \end{bmatrix}$$

In which ω is the rotor speed, (i_q, i_d) are the current components in the $q-d$ axis, (u_q, u_d) are the stator voltage components in the $q-d$ axis, L_q and L_d are the stator inductors in the $q-d$ axis, T_m is the load torque (the load torque is an exogenous disturbance). The machine parameters are: the moment of inertia of the rotor J, the number of poles pairs p, the friction coefficient relating to the rotor speed f, the stator winding resistance R, the flux linkage of the permanent magnets λ. In our study, the smooth-air-gap of the PMSM systems are considered, i.e., $L_d = L_q = L$.

3. T-S FUZZY MODEL OF PMSM

In order to represent the motor's nonlinear model as a T-S model with the measurable (speed) parameter as a decision variable. We rewrite (1) in the nonlinear state-space form shown (2):

$$\begin{cases} \dot{x}(t) = A(\omega(t))x(t) + Bu(t) + DT_m(t) \\ y(t) = Cx(t) \end{cases} \tag{2}$$

where:

$$A(\omega(t)) = \begin{bmatrix} -\frac{f}{J} & \frac{3p\lambda}{2J} & 0 \\ -\frac{p\lambda}{L} & -\frac{R}{L} & -p\omega(t) \\ 0 & p\omega(t) & -\frac{R}{L} \end{bmatrix}, B = \begin{bmatrix} 0 & 0 \\ \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}, D = \begin{bmatrix} -\frac{1}{J} \\ 0 \\ 0 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

Note that: $\underline{\omega} \leq \omega(t) \leq \overline{\omega}$ [18], the nonlinear system of (2) could be represented by a T-S model with $r = 2^1$ fuzzy If-Then rules are as follows:

Rule 1: IF $z(t)$ is F_{11} THEN $\dot{x}(t) = A_1x(t) + B_1u(t) + D_1T_m(t)$.

Rule 2: IF $z(t)$ is F_{12} THEN $\dot{x}(t) = A_2x(t) + B_2u(t) + D_2T_m(t)$.

Where $z(t) = \omega(t)$ denotes the premise variable, F_{11} and F_{12} refer to the membership functions which can be described as (3):

$$F_{11}(\omega(t)) = \frac{\omega(t) - \underline{\omega}}{\overline{\omega} - \underline{\omega}}, F_{12}(\omega(t)) = 1 - F_{11}(\omega(t)) \tag{3}$$

the matrices of the local models are given by:

$$A_1 = \begin{bmatrix} -\frac{f}{J} & \frac{3p\lambda}{2J} & 0 \\ -\frac{p\lambda}{L} & -\frac{R}{L} & -p\overline{\omega} \\ 0 & p\overline{\omega} & -\frac{R}{L} \end{bmatrix}, A_2 = \begin{bmatrix} -\frac{f}{J} & \frac{3p\lambda}{2J} & 0 \\ -\frac{p\lambda}{L} & -\frac{R}{L} & -p\underline{\omega} \\ 0 & p\underline{\omega} & -\frac{R}{L} \end{bmatrix}, B_1 = B_2 = \begin{bmatrix} 0 & 0 \\ \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}, D_1 = D_2 = \begin{bmatrix} -\frac{1}{J} \\ 0 \\ 0 \end{bmatrix}$$

based on singleton fuzzifier, the rule of product-inference, and the centre of gravity defuzzifier, the rules (1 and 2) become (4):

$$\dot{x}(t) = \sum_{i=1}^{r} h_i(z(t))(A_ix(t) + B_iu(t) + D_iT_m(t)) \tag{4}$$

where $h_i(z(t)) = \frac{F_{1i}(z(t))}{\sum_{j=1}^{r} F_{1j}(z(t))}$, for all $t > 0, h_i(z(t)) \geq 0$ and $\sum_{i=1}^{r} h_i(z(t)) = 1$.

4. FUZZY TRACKING CONTROLLER DESIGN

The aim of this study is to design a fuzzy controller able to control the system's state $x(t)$ to track a desired set of VDVs $x_d(t)$ and rejecting the impact of disturbance on the motor. The requirements for the feedback tracking control are as follows: $x(t) - x_d(t) \to 0$ as $t \to \infty$ from $y(t) = \varphi(x(t))$, the desired output state $y_d(t) = \varphi(x_d(t))$ is deducted. The tracking error is defined by $\tilde{x}(t) = x(t) - x_d(t)$ and its time derivative is expressed by (5):

$$\dot{\tilde{x}}(t) = \dot{x}(t) - \dot{x}_d(t) \tag{5}$$

from (4) and the concept $\sum_{i=1}^{r} h_i(z(t))(A_i(x(t) - x_d(t))$, (5) will be (6):

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r} h_i(z(t))\{A_i\tilde{x}(t) + B_iu(t) + D_iT_m(t)\} - \dot{x}_d(t) \tag{6}$$

In (6), we present the new variable satisfying the following relationship:

$$\sum_{i=1}^{r} h_i(z(t))B_i\tau(t) = \sum_{i=1}^{r} h_i(z(t))B_iu(t) + \sum_{i=1}^{r} h_i(z(t))A_ix_d(t) - \dot{x}_d(t) \quad (7)$$

where, a new controller $\tau(t)$ will be generated using the PDC method [12]. Using (8) tracking error system (7) becomes:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r} h_i(z(t))A_i\tilde{x}(t) + B_i\tau(t) + D_iT_m(t) \quad (8)$$

The tracking control problem is addressed in the following ways by the PDC controllers:
Rule 1: IF $z(\omega(t))$ is F_{11} THEN $\tau(t) = -K_1\tilde{x}(t)$.
Rule 2: IF $z(\omega(t))$ is F_{12} THEN $\tau(t) = -K_2\tilde{x}(t)$.
The final output of the fuzzy controller is determined by the summation:

$$\tau(t) = -\sum_{i=1}^{r} h_i(z(t))K_i\tilde{x}(t) \quad (9)$$

applying control law (9) to model (8) leads the expression of the closed loop system:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(z(t))h_j(z(t))(A_i - B_iK_j)\tilde{x}(t) \quad (10)$$

letting $G_{ij} = (A_i - B_iK_j)$, in (10) becomes:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(z(t))h_j(z(t))G_{ij}\tilde{x}(t) \quad (11)$$

5. STABILITY ANALYSIS

The objective of this study is to develop a fuzzy state feedback controller in (9), for system (11), able to driving the state of the system to track the desired variables. The gains of the PDC control law (10) are determined using the subsequent theorem [13]. **Theorem** the equilibrium of closed-loop continuous fuzzy system (11) is asymptotically stable if there exist a symmetric matrix $P_c > 0$, a diagonal positive definite matrix D_c and matrices Q_{ij} with: $Q_{ii} = Qii^T$ and $Q_{ji} = Q_{ij}^T$ for $i \neq j$ such that:

$$G_{ii}^TP_c + P_cG_{ii} + D_cP_cD_c^T < 0, i = 1, ..., r \quad (12)$$

$$(\frac{G_{ij} + G_{ji}}{2})^TP_c + P_c(\frac{G_{ij} + G_{ji})}{2}) + Q_{ij} \leq 0, i < j \leq r \quad (13)$$

$$\begin{bmatrix} Q_{11} & . & . & . & Q_{1r} \\ . & . & & & . \\ . & & . & & . \\ . & & & . & . \\ Q_{1r} & . & . & . & Q_{rr} \end{bmatrix} > 0 \quad (14)$$

for $i, j = 1, ..., r$, s.t. the pairs (i, j) such that $h_i(z(t))h_j(z(t)) = 0$,$\forall t$.
The conditions of the previous theorem are related to a problem in the form of LMIs, that can be solved in an efficient way by convex optimization tools. The change of variable $X = P_c^-1$, $K_i = M_iP_c^{-1}$ and the use of congruence in inequalities (12) to (14), the LMIs expressions are given by:

$$\exists X = X^T > 0, \exists Y_{ii} = Y_{ii}^T, \exists Y_{ij} = Y_{ji}^T, M_i$$

$$\begin{bmatrix} XA_i^T + A_iX - B_iM_i - M_i^TB_i^T + Y_{ii} & XD_c^T \\ D_cX & -X \end{bmatrix} < 0, i = 1, ..., r \quad (15)$$

$$XA_i^T + A_iX + XA_j^T + A_jX - B_iM_j - M_j^TB_i^T + 2Y_{ij} \leq 0, i < j = 1, ..., r \quad (16)$$

$$\begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1r} \\ Y_{12} & Y_{22} & \dots & Y_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{1r} & Y_{2r} & \dots & Y_{rr} \end{bmatrix} > 0 \quad (17)$$

we note that the controller gains K_i that guarantees the tracking control is the same that stabilizes the system. The controller performance depends on the best choice of the diagonal matrix D_c. But, there is no specific method for choosing this matrix. Then, we propose here a new algorithm that calculates matrix D_c and the controller gains based on the desired system characteristics. To this end, let us define the desired rise time R_{td} and the desired overshoot O_{vd}. The diagonal matrix is set to be in the following form:

$$\begin{bmatrix} d_c & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & d_c \end{bmatrix} \quad (18)$$

the proposed algorithm is summarized in the following diagram in Figure 2.

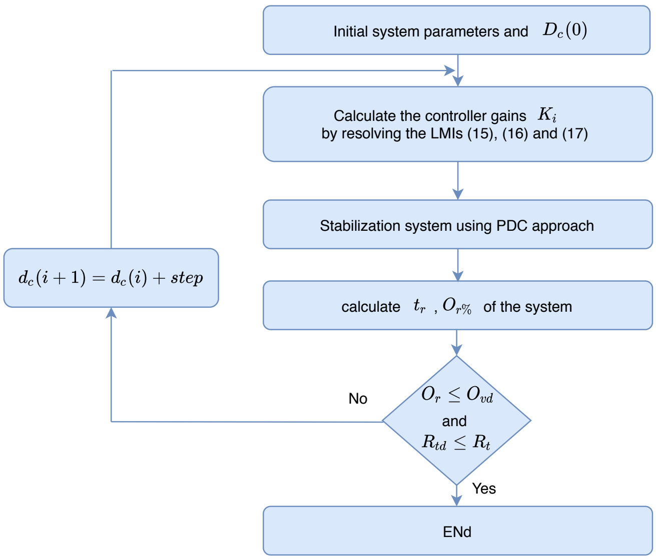

Figure 2. Proposed algorithm to calculate D_c and K_i

6. VDVS AND NONLINEAR CONTROLLER DESIGN

As a way to identify the VDVs $x_d(t)$ and control law $u(t)$ for the PMSM, (8) can be expressed as (19).

$$\sum_{i=1}^{r} h_i(z(t))B_i(u(t) - \tau(t)) = -\sum_{i=1}^{r} h_i(z(t))A_ix_d(t) - \sum_{i=1}^{r} h_i(z(t))D_iT_m(t) + \dot{x}_d(t) \quad (19)$$

Assuming that:

$$g(x) = \sum_{i=1}^{r} h_i(z(t))B_i, A(x) = \sum_{i=1}^{r} h_i(z(t))A_i, \varphi(x) = \sum_{i=1}^{r} h_i(z(t))D_i \quad (20)$$

in (19) can therefore be expressed in the compact form shown (21).

$$g(x)((u(t)-\tau(t)))=A(x)x_d(t)-\varphi(x)T_m(t)+\dot{x}_d(t) \tag{21}$$

Adapting the (21) to the PMSM model, following matrix form is obtained (22).

$$\begin{bmatrix}0 & 0\\ \frac{1}{L} & 0\\ 0 & \frac{1}{L}\end{bmatrix}\begin{bmatrix}u_q(t)-\tau_q(t)\\ u_d(t)-\tau_d(t)\end{bmatrix}=-\begin{bmatrix}-\frac{f}{J} & \frac{3p\lambda}{2J} & 0\\ -\frac{p\psi}{L} & -\frac{R}{L} & -p\omega\\ 0 & p\omega & -\frac{1}{R}\end{bmatrix}\begin{bmatrix}\omega_d\\ i_{qd}\\ i_{dd}\end{bmatrix}-\begin{bmatrix}-\frac{1}{J}\\ 0\\ 0\end{bmatrix}T_m(t)+\frac{d}{dt}\begin{bmatrix}\omega_d\\ i_{qd}\\ i_{dd}\end{bmatrix} \tag{22}$$

$x_d=[\omega_d \quad i_{qd} \quad i_{dd}]^T$ is the vector of the VDVs. From (22), it remains that:

$$\dot{\omega}_d(t)=-\frac{B_f}{J}\omega_d(t)+\frac{3p\lambda}{2J}i_{qd}(t)+\frac{1}{J}T_m(t) \tag{23}$$

which induced that:

$$i_{qd}(t)=-\frac{2J}{3p\lambda}(\dot{\omega}_d(t)+\frac{f}{J}\omega_d(t)+\frac{1}{J}T_m(t)) \tag{24}$$

Noting that a flow model is not necessary for a PMSM. As a consequence, the angle of reference is determined by the position of the rotor. Additionally, because our machine has a smooth poles, the ideal value for its operation is determined when the internal angle is equal to $\frac{\pi}{2}$, which indicates $i_{dd}=0$. As a consequence, we were able to acquire the appropriate state vector shown (25):

$$x_d(y_d,T_m)=\begin{bmatrix}\omega_d\\ i_{qd}\\ i_{dd}\end{bmatrix}=\begin{bmatrix}y_d\\ (\dot{y_d}+\frac{B}{J}y_d+\frac{1}{J}T_m)\frac{2J}{3p\lambda}\\ 0\end{bmatrix} \tag{25}$$

where y_d represent the required speed. From the second and the third expressions of (22), the nonlinear tracking control input is obtained:

$$\begin{cases} u_q(t)=p\lambda\omega_d(t)+Ri_{qd}(t)+L\frac{di_q}{dt}+\tau_q(t)\\ u_d(t)=-pL\omega(t)i_{qd(t)}+\tau_d(t)\end{cases} \tag{26}$$

noting that the reference model obtained in (26) depends on the desired speed and the load torque; this last latter is usually an inaccessible stat or immeasurable, that imposes to look for its estimated. In the following sections, we will show how to get the estimated load torque using both the extended Kalman filter and the disturbance estimator.

7. EXTENTED KALMAN FILTER

R.E. Kalman developed the Kalman filter in 1960. Due to developments in digital computer technology, the Kalman filter is a considerable study of research and application. Kalman filtering has been used in the field of manufacturing [19], navigation [20], aerospace [21], and others [22]-[24]. The EKF is an optimal recursive estimate approach for estimating the states of dynamic nonlinear systems based on the least-squares principle. To determine the conditional mean and covariance of the probability distribution of the state of a nonlinear stochastic system, it is therefore an ideal estimator by measurement noise and uncorrelated Gaussian process. The EKF may be used to estimate state variables since the state models are nonlinear. The back-electric and magnetic field (EMF) is assumed to be a state variable in this way.

7.1. Problem formulation

The following expression is a nonlinear discrete model using white noise:

$$\begin{cases} \dot{x}(k+1)=f(x(k),u(k))+w(k)\\ y(k)=h(x(k))+v(k)\end{cases} \tag{27}$$

where w and v represent the random disturbances. Knowing that v indicates measurement noise, which stands for measurement and sample errors and w refer to the process noise, which represents the parameter errors. The following definitions apply to the noise covariance matrices:

$$Q = cov(w) = E\left\{ww^T\right\}, R = cov(v) = E\left\{vv^T\right\} \tag{28}$$

for the model's linearization process, the partial derivative is adopted to give the discrete state models:

$$F(k) = \left(\frac{\partial f(x(k), u(k))}{\partial x^T(k)}\right)_{x(k)=\hat{x}(k/k)} \tag{29}$$

error covariance matrix estimation:

$$P^-(k+1) = F(k)P(k)F^T(k) + Q \tag{30}$$

where $P^{-1}(k+1)$ represent a matrix of a priori error covariance. Calculating the gain of a Kalman filter:

$$K(k+1) = P^-(k+1)H^T(k)[H(k)P^-(k+1)H^T(k) + R] \tag{31}$$

the state estimation is given by:

$$\hat{x}(k+1) = \hat{x}(k)K(k+1)[y(k+1) - k(\hat{x}(k+1))] \tag{32}$$

updating a matrix of error covariance:

$$P(k+1) = (I - K(k+1)H(k))P^-(k+1) \tag{33}$$

8. EKF FOR THE PMSM

The implementation of EKF for the PMSM requires the discrete motor model, which can be expressed as [19]:

$$x(k+1) = \overbrace{\begin{bmatrix} T_s\frac{3p\lambda}{2J}i_q + (1 - T_s\frac{f}{J})\omega - T_s\frac{1}{J}T_m \\ T_s p\omega i_d + (1 - T_s\frac{R}{L_q})i_q - T_s p\frac{\lambda}{L_q} + T_s\frac{1}{L_q}u_q \\ (1 - T_s\frac{R}{L_d})i_d + T_s p\omega i_q + T_s\frac{1}{L_d}u_d \end{bmatrix}}^{f} \tag{34}$$

define matrix F and H as:

$$\begin{bmatrix} 1 - T_s\frac{f}{J} & T_s\frac{3p\lambda}{2J} & 0 \\ -T_s p(i_d(k) + \frac{\lambda}{L_q}) & 1 - T_s\frac{R}{L_q} & -T_s p\omega(k) \\ T_s p i_q(k) & T_s p\omega(k) & 1 - T_s\frac{R}{L_d} \end{bmatrix} \tag{35}$$

$$h = \begin{bmatrix} \omega(k) \\ i_q(k) \\ i_d(k) \end{bmatrix}, H = \frac{\partial h(k)}{\partial x(k)} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{36}$$

the EKF algorithm for the PMSM is given in Figure 3.

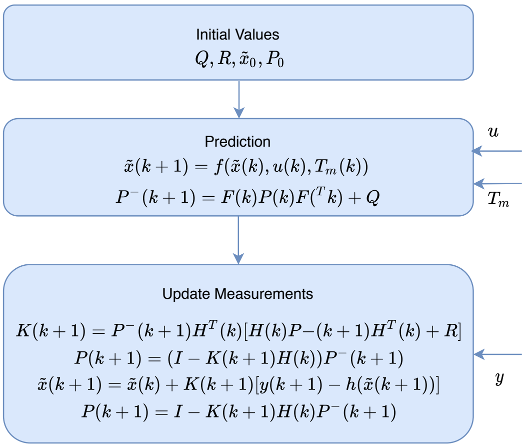

Figure 3. Extended Kalman filter algorithm

9. LOAD TORQUE ESTIMATOR

The reference model obtained in (25) and the EKF algorithm shown in Figure 3 need the load torque state. However, this latter is generally an inaccessible state, or its measure is a difficult task that imposes looking for its estimated value using an approach based on the machine model combined with a proportional-integral controller as illustrated in Figure 4 [25]. The role of this controller is to eliminate the speed tracking error and guarantee the estimated load torque's convergence to the load torque applied to the motor. The PI controller's parameters can be determined using the pole placement technique. To this end, we write the mechanical equation of the PMSM as (37).

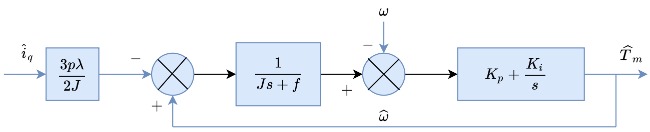

Figure 4. Load torque estimator

$$T_e(t) - T_m(t) = J\frac{d\omega}{dt} + f\omega(t) \tag{37}$$

Where $T_e(t)$ is the electromagnetic torque which can be given by:

$$T_e(t) = \frac{3p\lambda}{2J} i_q(t) \tag{38}$$

which induced that:

$$\widehat{T}_e(t) - \widehat{T}_m(t) = J\frac{d\widehat{\omega}}{dt} + f\widehat{\omega}(t) \tag{39}$$

according to the scheme shown in Figure 4, the (39) combined with a PI controller can be represented by the following matrix form:

$$\begin{bmatrix} \dot{\widehat{\omega}} \\ \dot{\widehat{x}}_c \end{bmatrix} = \begin{bmatrix} -\frac{(f+k_p)}{J} & -\frac{k_I}{J} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \widehat{\omega} \\ \widehat{x}_c \end{bmatrix} + \begin{bmatrix} \frac{3p\lambda}{2J^2} & \frac{k_p}{J} \\ 0 & -1 \end{bmatrix} \begin{bmatrix} I \\ \omega \end{bmatrix} \tag{40}$$

where $x_r(t) = \int(\widehat{\omega}(t) - \omega(t))dt$.
The estimated load torque can be derived as follows:

$$\widehat{T}_m = \begin{bmatrix} k_p & k_I \end{bmatrix} \begin{bmatrix} \widehat{\omega} \\ x_c \end{bmatrix} + \begin{bmatrix} 0 & -k_p \end{bmatrix} \begin{bmatrix} I \\ \omega \end{bmatrix} \tag{41}$$

by identifying with a second-order system, we obtain the following PI parameters:

$$k_p = 2\xi\omega_n J - f, k_I = \omega_n^2 J \tag{42}$$

ξ and ω_n denote the second-order system's of damping ratio and the undimmed natural frequency.

10. SIMULATION RESULTS

In this part, PMSM simulation tests have been conducted to validate the efficacy of the suggested technique. The overall control structure of the PMSM is shown in Figure 5, where the goal is to impose the the PMSM output speed to follow the desired speed. $y_d = \omega_{ref} = 50 rad/sec$ with a load torque $T_m = 8N.m$ applied at $t = 0.5s$.

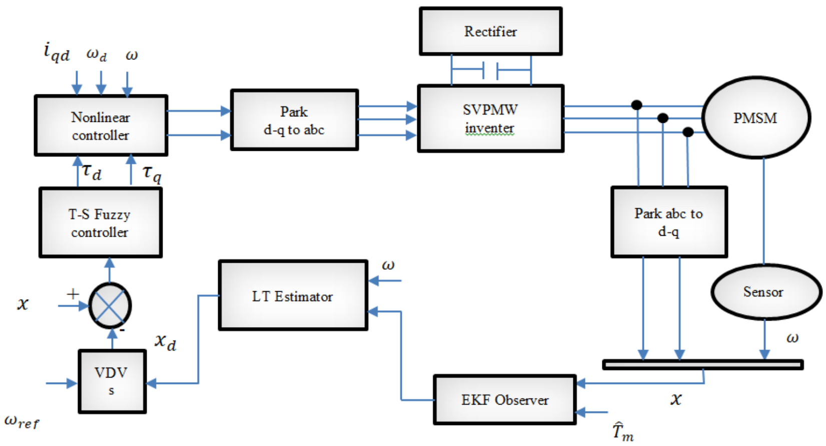

Figure 5. Overall control structure of the PMSM

In order to facilitate the control data and clarify the results, an interface has been designed using Graphic User Interface (GUI); the interface has three figures: The first one is used to enter the different parameters of the motor, the second one is used to determine the best choice of the diagonal matrix D_c. The third one is used to illustrate the simulation results according to the global diagram of the control structure diagram given in Figure 5. The GUI figures are shown in Figure 6 to Figure 8. The obtained controller gains that guarantee overshoot less than $10^{-4}\%$ and time rise less than $t = 0.005s$ are given by:

$$K1 = \begin{bmatrix} 6.9313 & 16.2043 & -0.2969 \\ 0.6946 & -0.2203 & 15.6902 \end{bmatrix}, K2 = \begin{bmatrix} 11.2537 & 14.0795 & -0.1602 \\ 0.0886 & -0.1153 & 12.9561 \end{bmatrix}$$

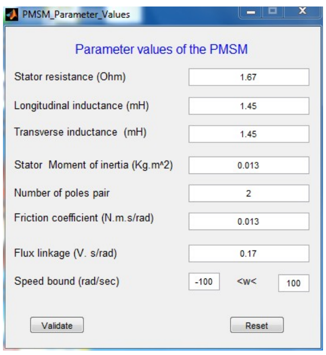

Figure 6. The power curve of 5 MW wind turbine

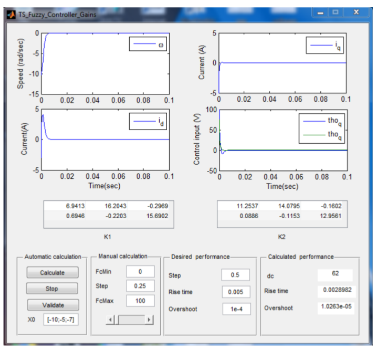

Figure 7. Performance coefficient as a function of Tip Speed Ratio

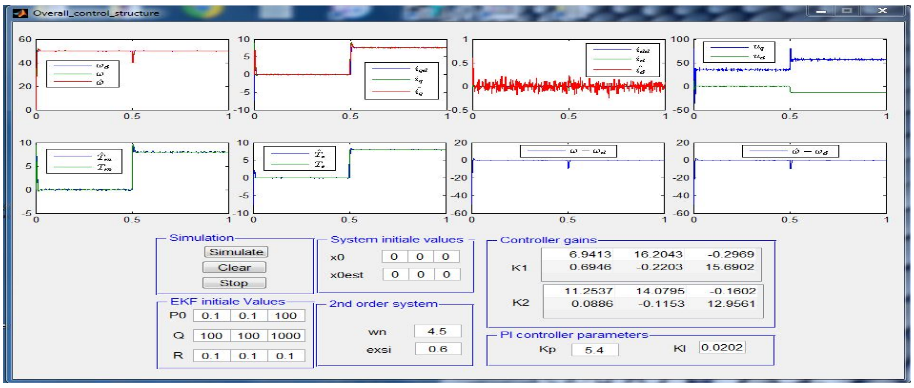

Figure 8. GUI figure to show simulation results

The initial matrices and the EKF are chosen as follows:

$$P_0 = \begin{bmatrix} 0.1 & 0 & 0 \\ 0 & 0.1 & 0 \\ 0 & 0 & 100 \end{bmatrix}, Q = \begin{bmatrix} 100 & 0 & 0 \\ 0 & 100 & 0 \\ 0 & 0 & 1000 \end{bmatrix}, R = \begin{bmatrix} 0.1 & 0 & 0 \\ 0 & 0.1 & 0 \\ 0 & 0 & 0.1 \end{bmatrix}$$

The parameters of the PI controller are chosen as follows: $K_P = 5.4, K_I = 0.0202$. The simulation results of reference speed, actual speed and its estimates, reference q-axes current, actual q-axes current and its estimated, reference d-axes current, d-axes actual current and its estimated and the q-d control voltages are illustrated, respectively, in Figures 9 to 12.

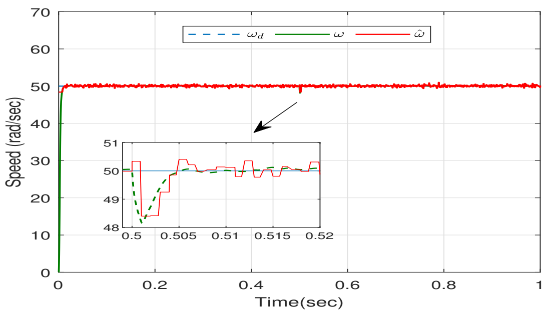

Figure 9. Speed reference, actual rotor speed and its estimate

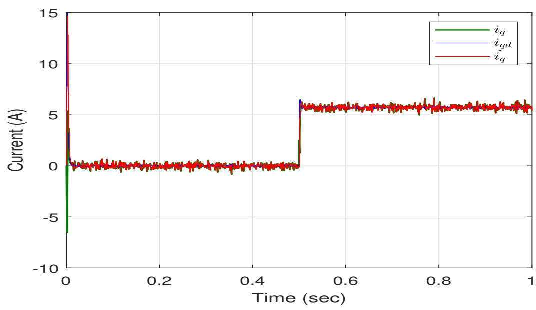

Figure 10. Reference, actual and estimate currents of q-axis

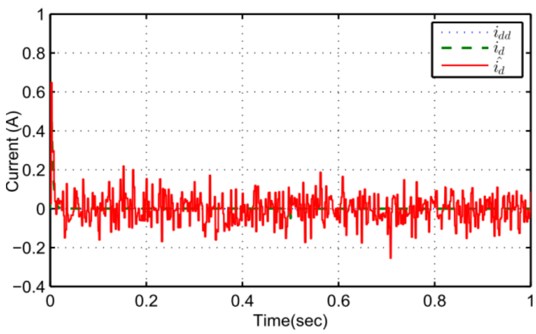

Figure 11. Reference, actual and estimate currents of d-axis

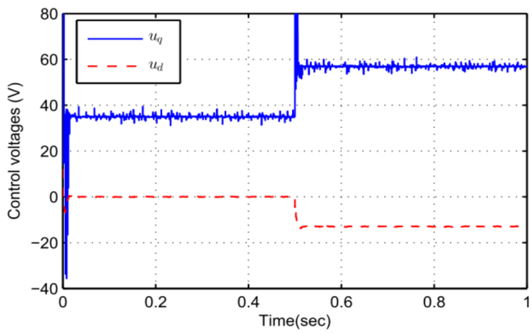

Figure 12. Control input voltages

The simulation results demonstrate that the system is resilient to the disturbance with just a minor deviation during the time the disturbance is applied, the tracking error is obvious but very tiny, and the temporal response of the tracking is extremely low. The simulation results of load torque and its estimated, and the electrometric torque and its estimated are shown in Figure 13 and Figure 14, which demonstrate the good tracking.

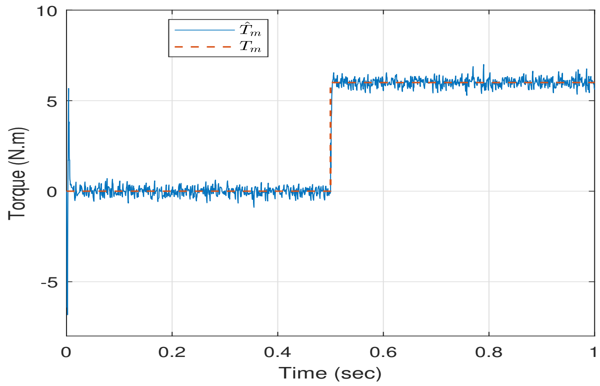

Figure 13. Actual load torque and its estimate

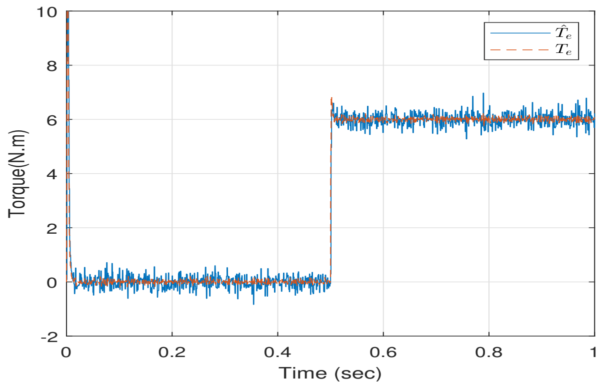

Figure 14. Actual electromagnetic torque and its estimate

11. CONCLUSION

This paper describes a novel fuzzy tracking control strategy for PMSM based on the T-S fuzzy model. Due to this, a fuzzy tracking control based on VDVs and the estimation of the unknown disturbance using an EKF and a DO has been proposed to develop a controller able to reject a completely unknown disturbance. Using Lyapunov's approach, sufficient requirements for stability are determined. VDVs concepts have been utilized to simplify the construction of the reference model and control laws. A PMSM controller has achieved successful testing. The outcomes demonstrate that the suggested fuzzy tracking control approach may deliver the controlled system's intended performances.

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