Nonlinear Observer Design for Load Torque Estimation of Induction Motors

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Abstract. *The paper introduces a design of a nonlinear observer for the estimation of load torque of induction motors based on the output of the stator currents. The observer is built in the synchronous reference frame d-q with three main steps. First, the nonlinear observer for the class of non-affine control systems is reviewed. Second, the induction motor model is written in an appropriate form as a non-affine control system with canonical form for the design of the nonlinear observer. The system state is composed of the stator currents, speed and load torque. Based on the stator currents, the rotor flux leakages are estimated via an open loop and used for the load torque observer. The observer is designed with a constant gain which is calculated by considering the trajectory of the rotor flux leakages. Both the load torque and rotor speed can be estimated by using the proposed observer. Finally, simulation and experiment are carried to validate the effectiveness and robustness of the proposed observer.*

Keywords

Induction motors, non-affine control systems, torque observer.

1. Introduction

Induction motors are widely used in various industrial applications due to their advantages in simplicity, efficiency, ruggedness, and reliability. In the operation and maintenance of the motor, some variables are needed for different purposes, such as the feed-back of controller, the input of energy management system, or condition monitoring systems. To reduce the cost and the complexity of systems, it requires to use as few sensors as possible, especially the mechanical sensors for the measurement of the speed or torque. When it is not possible to install a torque sensor, the torque could be estimated by a dedicated observer which is designed on the basis of the mathematical modeling of the induction motor. As an important variable, the load torque is essential for the operation of induction motors. It can be obtained by utilizing a torque sensor installed on the motor shaft. However, in such a situation, it not only causes an increase of the cost but requires to be invasive and may reduce the reliability of the system. Therefore, the estimation techniques have been extensively proposed to have the knowledge of load torque based on the measurement of electric quantities such as line voltages and currents.

In [1], the authors proposed a method of estimating load torque by using a Luenberger observer, which was inter-connected to a Model Reference Adaptive System (MRAS) based speed estimator in a sensorless Indirect Stator Flux Oriented Controlled (ISFOC) induction motor drive. Subsequently, using the stator voltages and currents, the reference model and adjustable model generate the stator fluxes to produce the errors which are the inputs of an adaptation mechanism to estimate the speed. Based on the estimated speed, stator flux, and measured stator current, the load torque can be estimated. Slip method based torque estimation for three-phase squirrel cages induction motors was adopted in [2]. It is obtained by assuming that the torque is proportional to the ratio of measured slip and the rated one. In [3], a Takagi-Sugeno Adaptive Luenberger Observer and a Takagi-Sugeno Fast Adaptive Luenberger Observer were proposed for the torque and flux estimation of induction motor. The observers require not only stator voltages and currents but the mechanical speed of the motors. An application of extended and unscented Kalman filter algorithms was applied to estimate states and parameters of induction motor including the load torque [4]. The study in [5] showed that the torque could be estimated on the basis of the RMS values of voltages and currents.

In this study, we propose an observer to estimate the load torque in which the system output includes only the stator currents. The principally considerable contribution of the paper is the proposal of observer structure to estimate the load mechanical torque and speed of the induction motor, even in the situation without measuring the rotor position or speed. Moreover, the gain is constant that makes the observer more robust compared to the classically adaptive one.

The remainder of the paper is organized as follows. The selection of observer for non-affine control systems is shown in Sec. 2. In Sec. 3. , the observer for the estimation of load torque in the induction motors is formulated. Subsequently, the simulation and experiment results are presented in Sec. 4. and Sec. 5. , respectively. Finally, Sec. 6. draws the conclusions.

2. Selection of Observer for Non-Affine Control Systems

2.1. The Observability of Nonlinear Systems

The observability analysis is the first necessary step before addressing an algorithm to estimate the state and/or parameter of a physical system, see for example [6], [7] and [8] and the references cited therein. It involves the analysis of the formal sensitivity of the measured output with respect to the variables to be estimated. In this section, the definition and result related to this concept and used for observer design in the next section will be recalled.
Consider the following nonlinear system:

$$\begin{cases} \dot{x} = f(x,u), \\ y = h(x), \end{cases} \tag{1}$$

where $x(t)$ is the state taking values in $\mathbb{R}^n$; $y(t) \in \mathbb{R}^p$ is the measured output, and $u(t)$ is the known external input taking values in $\mathbb{R}^m$.

Definition 1. *A nonlinear system Eq. (1) is called uniformly observable if every admissible input u defined on every interval $[0,T]$ renders the system observable on this interval.*

The class of single output uniformly observable systems is completely characterized by a canonical form [9] and [10].
Assuming that $p = 1$ (the single output case): let u_0 be a fixed element of $\mathbb{R}^m$ and setting $z = T(x)$, where $T_i(x) = L^{i-1}_{f_{u_0}}(h)(x)$, for $i = 1,\ldots,n$.

Theorem 1. *Assuming that $\frac{\partial T}{\partial x}$ is an inversible matrix at a fixed x^0, and system Eq. (1) is uniformly observable. Then T defines a local system of coordinates $z = T(x)$ in which system Eq. (1) takes the form:*

$$\begin{cases} \dot{z}_1(t) = F_1(z_1(t), z_2(t), u(t)), \\ \ldots \\ \dot{z}_k(t) = F_k(z_1(t),\ldots,z_{k+1}(t),u(t)), \\ \ldots \\ \dot{z}_n(t) = F_n(z(t),u(t)), \\ y(t) = z_1(t), \end{cases} \tag{2}$$

Moreover, $\frac{\partial F_k}{\partial z_{k+1}}(z,u) \neq 0$, for every (z,u). Conversely, if system Eq. (1) can be transformed into the above normal form and that $\frac{\partial F_k}{\partial z_{k+1}}(z,u) \neq 0$, for every (z,u), then it is uniformly observable.

2.2. Observer Candidate of the Non-Affine Control System

In Theorem 1 of Sec. 2.1. , the condition has been provided for a nonlinear system, which can be put into the normal form Eq. (2), to be uniformly observable. In addition, the study has been extended to the multi-output case [7]. Subsequently, we consider the following system:

$$\begin{cases} \dot{z} = F(u,z), \\ y = C(z), \end{cases} \tag{3}$$

where $z = (z_1,\ldots,z_q)^T$ is the state, $z_i \in \mathbb{R}^{n_i}$, $n_1 \geq n_2 \geq \ldots \geq n_q$; $n_1 + n_2 + \ldots + n_q = n$;
u are the inputs taking values in a connected and bounded set $U \in \mathbb{R}^m$;
$F(u,z) = (F_1(u,z),\ldots,F_q(u,z))^T$ in which the functions $F_i(u,z)$, $i = 1,\ldots,q-1$, are expressed as: $F_i(u,z) = F_i(u,z_1,\ldots,z_{i+1})$, $z_i \in \mathbb{R}^{n_i}$ with the condition of ranking given by:

$$\text{Rank}\left(\frac{\partial F_i}{\partial z_{i+1}}(u,z)\right) = n_{i+1}, \quad \forall u \in U,\ \forall z. \tag{4}$$

It has been stated that a nonlinear system can be steered by a transformation into the form Eq. (3) by using the uniform observability concept to give a geometric condition.

In what follows, sufficient conditions which allow designing a constant gain observer for the system Eq. (3) will be formulated.

- Global Lipschitz condition:

$$\begin{aligned} &\exists c > 0;\ \forall z, z' \in \mathbb{R}^n,\ \forall u \in U, \\ &||F(u,z) - F(u,z')|| \le c||z - z'||. \end{aligned} \tag{5}$$

- Convex cone condition:

$$\begin{aligned} &\text{for every } k,\ 1 \le k \le q-1, \\ &\text{there exists a } n_k \times n_{k+1} \text{ constant matrix } S_{k,k+1} \\ &\text{such that : for every } (u,z) \in U \times \mathbb{R}^n, \\ &\frac{\partial F_k}{\partial z_{k+1}}(u,z) \in \mathbb{C}(n_k, n_{k+1}; -1; S_{k,k+1}), \end{aligned} \tag{6}$$

where $\mathbb{C}(n_k, n_{k+1}; -1; S_{k,k+1})$ is the convex cone given by $\mathbb{C}(n_k, n_{k+1}; -1; S_{k,k+1}) = \{M \in \mathbb{M}(n_k, n_{k+1}; \mathbb{R});$ *such that* $M^T S_{k,k+1} + S_{k,k+1}^T M < -I_{n_{k+1}}$ in which $\mathbb{M}(n_k, n_{k+1}; \mathbb{R})$ is the space of $n_k \times n_{k+1}$ real matrices.

If the two aforementioned conditions hold, the authors in [7] present a proposition that allows computing the gain of the observer for the system Eq. (3): there exist a symmetric positive define matrix $\mathbf{Q}$, positive constants ρ, η such that for every $(u,z) \in U \times \mathbb{R}^n$, we have:

$$\mathbf{Q}\mathbf{A}(u,z) + \mathbf{A}(u,z)^T\mathbf{Q} - \rho C^T C \le -\eta I, \tag{7}$$

where

$$\mathbf{A}(u,z) = \begin{pmatrix} 0 & \mathbf{A}_{12}(u,z) & \cdots & 0 \\ 0 & 0 & \ddots & \vdots \\ \vdots & \vdots & \ddots & \mathbf{A}_{q-1,q}(u,z) \\ 0 & 0 & 0 & 0 \end{pmatrix}, \tag{8}$$

in which $\mathbf{A}_{k,k+1} = \dfrac{\partial F_k}{\partial z_{k+1}}(u,z)$ are continuous matrices $n_i \times n_{i+1}$ and I is identity matrix of adequate dimension.

Finally, an exponential observer for system Eq. (3) can be described by:

$$\dot{\hat{\mathbf{z}}} = F(u,\hat{z}) + \mathbf{\Delta}_\lambda \mathbf{K}(C\hat{z} - y), \tag{9}$$

where $\mathbf{K} = \mathbf{Q}^{-1}C^T$; $\mathbf{\Delta}_\lambda$ is the diagonal matrix given by:

$$\mathbf{\Delta}_\lambda = \begin{pmatrix} \lambda \mathbf{I}_{n_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda^r \mathbf{I}_{n_q} \end{pmatrix}, \tag{10}$$

in which $\mathbf{I}_{n_k}$ is $n_k \times n_k$ identity matrix, $k = 1, \dots, q$, λ is parameter to be tuned.

In the next section, the model of the induction motor system will be described and put into the triangular form for the observer design.

3. Observer Design

In the sychronous reference frame d-q, the induction motor can be described by [11]

$$\begin{aligned} &\dot{i}_{ds} = -a_{11} i_{ds} + \omega_s i_{qs} + a_{13}\psi_{dr} + a_{14}\omega\psi_{qr} + b v_{ds}, \\ &\dot{i}_{qs} = -\omega_s i_{ds} - a_{11} i_{qs} - a_{14}\psi_{dr} + a_{13}\psi_{qr} + b v_{qs}, \\ &\dot{\psi}_{dr} = a_{31} i_{ds} - a_{33}\psi_{dr} + \omega_{sl}\psi_{qr}, \\ &\dot{\psi}_{qr} = a_{31} i_{qs} - \omega_{sl}\psi_{dr} - a_{33}\psi_{qr}, \\ &\dot{\omega} = a_{51}\left(i_{qs}\psi_{dr} - i_{ds}\psi_{qr}\right) - a_{52}T_m - a_{53}\omega, \\ &\dot{T}_m = 0, \end{aligned} \tag{11}$$

where

$$\begin{aligned} &a_{11} = \frac{1}{T_s\sigma} + \frac{1-\sigma}{T_r\sigma},\ T_s = \frac{L_s}{R_s},\ T_r = \frac{L_r}{R_r}, \\ &a_{13} = \frac{1-\sigma}{L_m T_r \sigma},\ a_{14} = p\frac{1-\sigma}{L_m\sigma},\ b = \frac{1}{\sigma L_s}, \\ &a_{31} = \frac{L_m}{T_r},\ a_{33} = \frac{1}{T_r},\ a_{51} = p\frac{L_m}{J L_r}, \\ &a_{52} = \frac{1}{J},\ a_{53} = \frac{F_v}{J}. \end{aligned} \tag{12}$$

The induction motor system can be therefore written as:

$$\begin{aligned} \dot{\mathbf{X}} &= \mathbf{A}_{20}(X, \hat{\psi}_{dr}, \hat{\psi}_{qr})X + B_2(u, X, \hat{\psi}_{dr}, \hat{\psi}_{qr}) \\ &= F^2(u, X, \hat{\psi}_{dr}, \hat{\psi}_{qr}), \end{aligned} \tag{13}$$

where

$$\mathbf{A}_{20}(X, \hat{\psi}_{dr}, \hat{\psi}_{qr}) = \begin{pmatrix} -a_{11} & \omega_s & a_{14}\psi_{qr} & 0 \\ -\omega_s & -a_{11} & -a_{14}\psi_{dr} & 0 \\ 0 & 0 & -a_{52} & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \tag{14}$$

$$B_2(u, X, \hat{\psi}_{dr}, \hat{\psi}_{qr}) = \begin{pmatrix} b v_{ds} + a_{13}\psi_{dr} \\ b v_{qs} + a_{13}\psi_{qr} \\ a_{51}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right) \\ 0 \end{pmatrix}, \tag{15}$$

X is the state given by:

$$X = \begin{pmatrix} i_{ds} \\ i_{qs} \\ \omega \\ -a_{52}T_m \end{pmatrix}, \tag{16}$$

in which:

$$X_1 = \left[i_{ds}; i_{qs}\right]^T,\ X_2 = \omega,\ X_3 = -a_{53}T_m, \tag{17}$$

u stands for the input given as:

$$u = \left[v_{ds}; v_{qs}\right]^T. \tag{18}$$

The system has the form of an non-affine control system described by:

$$\begin{cases} \dot{X}_1 = F_1(u, X_1, X_2, \hat{\psi}_{dr}, \hat{\psi}_{qr}), \\ \dot{X}_2 = F_2(u, X_1, X_2, X_3, \hat{\psi}_{dr}, \hat{\psi}_{qr}), \\ \dot{X}_3 = 0. \end{cases} \quad (19)$$

Accordingly, the observer having a dynamic structure of the following form can be applied:

$$\dot{\hat{\mathbf{X}}} = F^{(2)}(u, \hat{X}, \hat{\psi}_{dr}, \hat{\psi}_{qr}) + \Delta_{\lambda_2}\mathbf{K}_2(\mathbf{C}_2\hat{X} - y), \quad (20)$$

where, the estimation of rotor flux linkages, $(\hat{\psi}_{dr}, \hat{\psi}_{qr})$, is obtained from the measured stator currents via an open loop according to the following equation:

$$\begin{cases} \dot{\hat{\psi}}_{dr} = a_{31}i_{ds} - a_{33}\hat{\psi}_{dr} + \hat{\omega}_{sl}\hat{\psi}_{qr}, \\ \dot{\hat{\psi}}_{qr} = a_{31}i_{qs} - \hat{\omega}_{sl}\hat{\psi}_{dr} - a_{33}\hat{\psi}_{qr}. \end{cases} \quad (21)$$

$\mathbf{\Delta}_{\lambda_2}$ is the diagonal matrix given by:

$$\mathbf{\Delta}_{\lambda_2} = \begin{pmatrix} \lambda_2 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_2^2 & 0 \\ 0 & 0 & 0 & \lambda_2^3 \end{pmatrix}, \quad (22)$$

where λ_2 is a parameter to be tuned.
$\mathbf{C}_2$ is the output matrix, given by:

$$\mathbf{C}_2 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}. \quad (23)$$

The matrix $\mathbf{K}_2$ is selected such that:

$$(\mathbf{A}_2 + \mathbf{K}_2\mathbf{C}_2)^T\mathbf{Q}_2 + \mathbf{Q}_2^T(\mathbf{A}_2 + \mathbf{K}_2\mathbf{C}_2) \le -\eta_2 I_4, \quad (24)$$

where $\mathbf{Q}_2$ is a symmetric positive definite (S.P.D) matrix , I_4 is 4 x 4 identity matrix, $\eta_2 > 0$. In this study, η_2 is chosen equal to 1.

The matrix $\mathbf{A}_2$ in Eq. (24) is given by:

$$\mathbf{A}_2(\hat{\psi}_{dr}, \hat{\psi}_{qr}) = \begin{pmatrix} O_{2x2} & \frac{\partial F_1}{\partial X_2}(u, X) & O_{2x1} \\ O_{2x2} & O_{2x1} & \frac{\partial F_2}{\partial X_3}(u, X) \\ O_{1x2} & 0 & 0 \end{pmatrix}. \quad (25)$$

Using the equations Eq. (14) and Eq. (19), matrix $\mathbf{A}$ becomes:

$$\mathbf{A}_2(\hat{\psi}_{dr}, \hat{\psi}_{qr}) = \begin{pmatrix} 0 & 0 & a_{14}\hat{\psi}_{qr} & 0 \\ 0 & 0 & -a_{14}\hat{\psi}_{dr} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \quad (26)$$

A trajectory of $[a_{14}\psi_{qr}, -a_{14}\psi_{dr}]^T$, is plotted as in Fig. 1. The trajectory locates on one half plane that the sign of $\frac{\partial F_i^{(2)}}{\partial X_{i+1}}(u, X)$ does not change. Therefore, matrix $\mathbf{A}_2$ is convex by $(\mathbf{A}_{21}, \mathbf{A}_{22})$, which are determined on the basis of two vectors $\vec{OP_1}$ and $\vec{OP_2}$. Once the convex

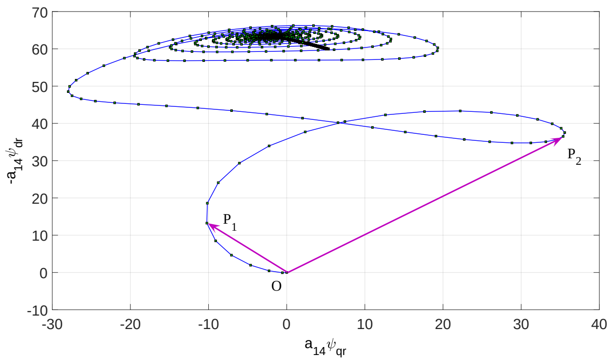

Fig. 1: Rotor flux leakages trajectory.

of matrix $\mathbf{A}_2$ is known, Eq. (24) can be solved by using LMI Solvers of Matlab. Ultimately, gain matrix $\mathbf{K}_2$ is obtained by:

$$\mathbf{K}_2 = \begin{pmatrix} -30 & -10 \\ -10 & -23 \\ -3 & -27 \\ -1 & -9 \end{pmatrix}. \quad (27)$$

Tuning parameter λ_2, we derive: $\lambda_2 = 30$.

4. Simulation Results

In order to illustrate the performances of the observer, simulation of induction motor system and the torque observer are developed in the following conditions:

- The motor is simulated using the parameters given in Appendix A with the model described by Eq. (11) in Sec. 3.
- The input of the model is $u = [v_{ds};\ v_{qs}]^T = [0;\ -319]^T$. It is noted that the line voltages and currents in d-q frame are constant at the steady state. They can be simply obtained from corresponding three-phase instantaneous quantities via the Park' transformation. The angle used for the transformation can be extracted from the line voltages by using a Phase Locked Loop (PLL).
- Steps of torque are applied to the system, including no-load level around 0.5 Nm, 4.6 Nm, and 5.8 Nm.
- Initial conditions for the system are given as $[\psi_{dr}, \psi_{qr}, i_{ds}, i_{qs}, \omega, T_m] = [0, 0, 1, 1, 1, 0.5]$.
- Initial conditions for the flux estimator and the observer are given as $[\hat{\psi}_{dr}, \hat{\psi}_{qr}, \hat{i}_{ds}, \hat{i}_{qs}, \hat{\omega}, \hat{T}_m] = [-1.1, -0.1, 0.5, 0.5, 10, 1.0]$.

Fig. 2 shows the block diagram of the simulation with induction motor model in d-q frame, the estimator of

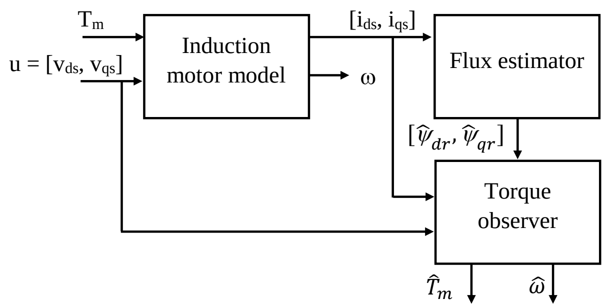

Fig. 2: Simulation diagram of induction motor with torque observer.

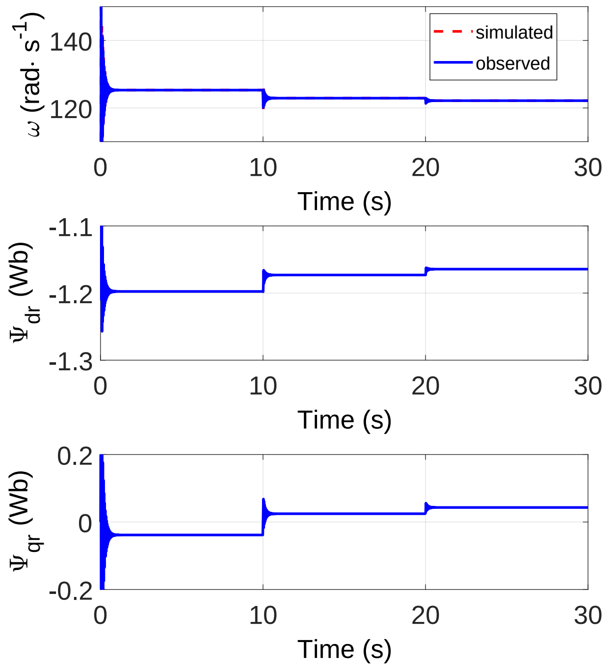

Fig. 3: Estimation of rotor speed (top) and rotor flux leakages (middle and bottom) (simulation).

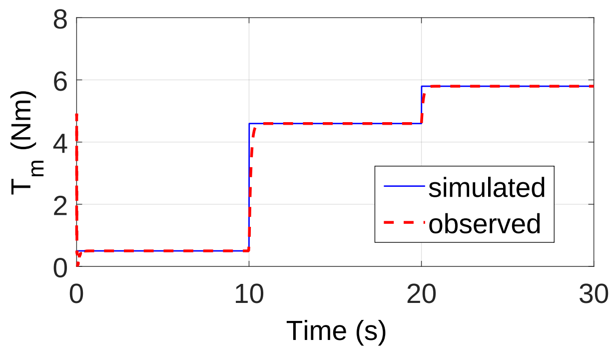

Fig. 4: Observation of torque (simulation).

rotor flux leakages, and the load torque observer. The motor operates with load torque variations at time 10 s and 20 s (Fig. 4). Figure 3 (top) shows that the estimated speed follows their simulated levels. In addition, the rotor flux leakages are stably estimated from the stator currents (Fig. 3 (middle and bottom)). Furthermore, Fig. 4 shows a good agreement between the estimated and simulated torques.

The obtained result demonstrates that the proposed observer has good estimation performance.

5. Experiment Results

In order to validate the proposed observer, the estimation results have to be compared with those given by the experiment tests. The experimental setup, depicted in Fig. 5, is composed of a 1.5 kW induction motor, an inverter, a real-time controller board of dSpace DS1104 and interfaces which allow to measure the currents, the voltages and the torque.

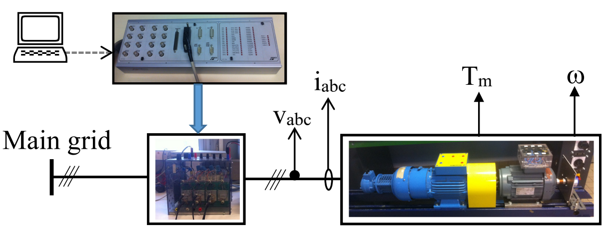

Fig. 5: Experiment setup of induction motor.

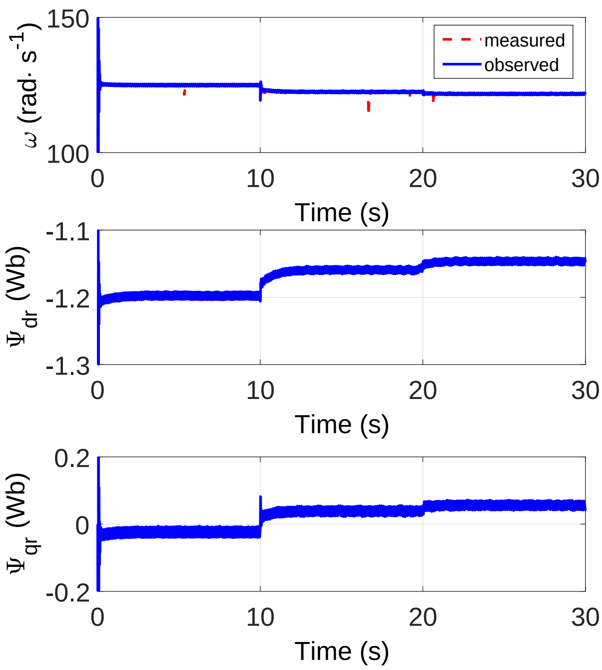

Fig. 6: Estimated speed (top) and rotor flux leakages (middle and bottom)(experiment).

Figure 6 and Fig. 7 show the experiment results for 3-step torque variation. Figure 6 confirms that the estimated rotor speed converges to the real value; and the rotor flux leakages are well estimated and agreed with the simulation results. Moreover, it can be shown

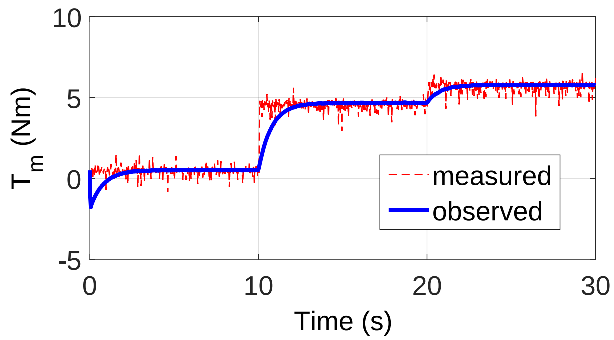

Fig. 7: Observation of torque (experiment).

in Fig. 7 that a great agreement between estimated and measured torques is achieved. The obtained result demonstrates that the proposed observer has a highly satisfactory performance.

6. Conclusion

In this paper, a constant gain observer for the non-affine control systems has been successfully applied to estimation of the load torque in the induction motors. The simulation and experiment results confirm the great performance of the proposed constant gain observer. In the application at steady states, the obtained knowledge of torque can be used as the input of the diagnosis system where the level of torque is required to correctly issue alarm of some types of faults. As future work, the proposed observer structure will be applied to more complex systems using induction machines such as the wind power generation systems.

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Appendix A Induction motor parameters

Tab. 1: Data of induction motor.

Nominal values:		
Rated power	P_n	1500 W
Rated voltage (Y)	V_n	400 V
Rated current (Y/Δ)	I_{sn}	3.35 A
Rated speed	n	1430 rpm
Number of pole pairs	p	2
Power factor	$cos\varphi$	0.77
Number of rotor slots	R	28
Parameters:		
Stator resistance	R_s	3.62 Ω
Rotor resistance	R_r	3.19 Ω
Stator leakage inductance	L_{ls}	0.0184 H
Rotor leakage inductance	L_{lr}	0.0184 H
Magnetizing leakage inductance	L_m	0.3343 H
Total inertia coefficient	J	0.00435 $\text{Nm} \cdot \text{rad}^{-1} \cdot \text{s}^{-2}$