

Flatness Based Nonlinear Sensorless Control of Induction Motor Systems

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ABSTRACT

This paper deals with the flatness-based approach for sensorless control of the induction motor systems. Two main features of the proposed flatness based control are worth to be mentioned. Firstly, the simplicity of implementation of the flatness approach as a nonlinear feedback linearization control technique. Secondly, when the chosen flat outputs involve non available state variable measurements a nonlinear observer is used to estimate them. The main advantage of the used observer is its ability to exploit the properties of the system nonlinearities. The simulation results are presented to illustrate the effectiveness of the proposed approach for sensorless control of the considered induction motor.

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1. INTRODUCTION

Induction motors are suitable electromechanical systems for a large spectrum of industrial applications. This is due to their high reliability, relatively low cost, and modest maintenance requirements. However, induction motors are known as multivariable nonlinear time-varying systems. Thus makes their control so difficult, mainly in variable speed applications [1].

A control literature review shows that a variety of solutions has been proposed for the control of induction motor systems. In the linear case, one has to mention the scalar control which is the first scheme proposed for this task. It is easy to implement but it does not provide good performance [2], [3]. The second well-known scheme is the vector control technique called also field oriented control (FOC) proposed by Blaschke [4]. The main disadvantage of this later control technique is the inherent coupling of the torque and the flux and the sensitivity against rotor resistance variations. In addition, the placement of the speed sensor on the motor rotor shaft reduces its robustness and reliability. In [3] a review of direct torque control (DTC) strategies is presented to overcome the FOC limitations. However the DTC technique presents the disadvantage of large flux and torque ripples. Consequently, this has opened a new and interesting area for academic research and industrial applications for nonlinear control techniques.

Among nonlinear control techniques, one has to mention the input-output feedback linearization technique initiated and developed by Isidori [5]. This method implements the differential geometry theory to transform a nonlinear system into a linear one and after that it applies a method of linear system control theory [6], [7], [8], [9]. The sliding mode control is characterized by its simplicity of design and attractive robustness properties [10]. Its major drawback is the chattering phenomenon [11], [12], [13]. Backstepping control presents the ability to guarantee the global stabilization of system and offers good performance, even

in the presence of parameter variations, however the choice of an appropriate Lyapunov function at each step is still a difficult problem [14], [15], [16], [17].

A relatively new method based on the flatness properties of a system, the flatness based control, is closely related to the ability to linearize a nonlinear system by an appropriate choice of a dynamic state feedback [18]. This type of method, in addition to its simplicity of implementation and input-output decoupling, it permits to directly estimate each system variable as a function of the chosen system outputs, called flat outputs, and a finite number of their time derivatives [19], [20], [21], [22].

All these control techniques and others assume that all state variables of the considered system are available for on line measurements. However in the practical case, only a few state variables of the machine system are available for on line measurement because of technical and/or economic constraints of the considered application. In order to perform advanced sensorless control techniques there is a great need of a reliable and accurate estimation of the unmeasurable key state variables of the machine. To this end a state observer may be used. Several solutions are presented in the literature including linearization techniques, adaptive or non adaptive high gain and sliding mode observers [2], [10], [17], [23].

In this paper we focus our attention on the application of a flatness based sensorless control of induction motor by using a circle criterion based nonlinear observer, designed in the previous paper [24], for the estimation of unavailable state measurements. The main advantage of this type of observer is the direct handling of the system nonlinearities with less restriction than linearization and high gain observer based approaches [25], [26]. The paper is organized as follows: In the second section we present the basic concepts of the notion of differential flatness control. The application of flatness control to considered nonlinear induction motor model is presented in the third section. The circle criterion based nonlinear observer is presented in the fourth section and finally in the fifth section we present simulation results and comments. A conclusion ends the paper.

2. BASIC CONCEPTS OF FLATNESS

In this section, we provide a brief introduction to the notion of differential flatness and its application in dynamical system control. The property of flatness of a system is closely related to the general ability to linearize a nonlinear system by an appropriate choice of a dynamic state feedback [18]. Roughly speaking, the flatness is a structural property of a class of nonlinear systems, for which all system variables can be written in terms of a set of specific variables (the so-called flat outputs) and a finite number of their time derivatives [19], [20], [21], [22].

Let us consider the following general nonlinear system:

$$\dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)) \quad (1)$$

$$\mathbf{y}(t) = \mathbf{h}(\mathbf{x}(t)) \quad (2)$$

Where $\mathbf{x}(t)$ is the state vector of the considered system, $\mathbf{u}(t)$ and $\mathbf{y}(t)$ are the input control and the output measurements, respectively. The functions $\mathbf{f}(\cdot)$ and $\mathbf{h}(\cdot)$ are assumed to be smooth with respect to their arguments.

The nonlinear system (1)-(2) is said to be (differentially) flat if and only if there exists an output vector $\mathbf{z}(t)$, called flat or linearizing output, such that:

- The flat output $\mathbf{z}(t)$ and a finite number of its time derivatives $\dot{\mathbf{z}}(t), \ddot{\mathbf{z}}(t), \dots, \mathbf{z}^{(n)}(t)$ are independent,
- The number of independent components of the flat output is equal to the number of independent inputs,
- Every system state and inputs variables may be expressed as a function of the flat output and of a finite number of its time derivatives as:

$$\mathbf{x}(t) = \phi(\mathbf{z}(t), \dot{\mathbf{z}}(t), \dots, \mathbf{z}^{(n-1)}(t)) \quad (3)$$

$$\mathbf{u}(t) = \psi(\mathbf{z}(t), \dot{\mathbf{z}}(t), \dots, \mathbf{z}^{(n)}(t)) \quad (4)$$

The functions $\phi(\cdot)$ and $\psi(\cdot)$ are assumed to be smooth.

The choice of the flat output is not very restrictive condition in the case of real systems. It can be a physical variable as a position, a velocity, a current, a voltage ... etc. In the case of flat outputs that are

unavailable for on line measurements, a state observer can be designed to estimate them. The main advantage of the differential flatness is that the differentiation of the chosen flat output, up to order n yields the necessary information to reconstruct the state and input trajectories of the considered system with the help of the relations (3) and (4).

The differentiation of the flat output results in the following canonical system model called Brunovsky form.

$$\begin{aligned} z(t) &= z_1(t) \\ \dot{z}_1(t) &= z_2(t) \\ \dot{z}_2(t) &= z_3(t) \\ &\dots = \dots \\ \dot{z}_n(t) &= \eta(z_1(t), z_2(t), \dots, z_n(t), u(t)) \end{aligned} \quad (5)$$

Solving $\dot{z}_n(t) = \eta(z_1(t), \dots, z_n(t), u(t)) = v$ results in:

$$u(t) = \psi(z(t), \dot{z}(t), \dots, z^{(n+1)}(t), v) \quad (6)$$

Here v represents the reference trajectory for the higher time derivative of the flat output.

The implementation of the control law in relation (4) defines the exact feedforward linearizing technique whereas the control law in relation (6) defines the exact feedback linearizing technique [20], [21].

Given a reference trajectory $z_r(t)$ for the flat output $z(t)$ and its time derivatives, one can define a tracking error as:

$$e_i(t) = z_i(t) - z_r(t), \quad i = 1, 2, \dots, n \quad (7)$$

In these conditions, the tracking error dynamics are defined as:

$$\begin{aligned} \dot{e}_i(t) &= \dot{z}_i(t) - \dot{z}_r(t) \\ &= z_{(i+1)}(t) - z_r^{(i)}(t) \end{aligned} \quad (8)$$

And:

$$\dot{e}_n(t) = \eta(z_1(t), \dots, z_n(t), u(t)) - z_r^{(n)}(t) \quad (9)$$

If the implementation of the determined control law does not match the desired performance of the considered system, one can introduce an error term as PID-like feedback stabilization and compute the new input v as the following [20], [21]:

$$v = z_r^{(n)}(t) + \Lambda(\bar{e}) \quad (10)$$

$$\text{With } \Lambda(\bar{e}) = \sum_{i=0}^{n-1} K_i e^{(i)} \quad (11)$$

The relation (10) can be written as:

$$e^{(n)} - \sum_{i=0}^{n-1} K_i e^{(i)} = 0 \quad (12)$$

The coefficients K_i are chosen such that the resulting characteristic polynomial, relation (12), is Hurwitz. In these conditions error dynamics converge exponentially to zero and all system variables and their time derivatives converge exponentially to their reference values [20], [21], [22].

3. FLATNESS BASED INDUCTION MOTOR CONTROL

Induction motor is known as a complex nonlinear system in which time-varying parameters entail additional difficulty for its control. Different structures of the induction motor nonlinear model are investigated and discussed in [27]. In this paper, the considered induction motor model has stator current, rotor flux and rotor angular velocity as selected state variables as in [24]:

$$\frac{d}{dt} i_{sd} = -\gamma i_{sd} + \frac{\beta}{T_r} \varphi_{rd} + \beta \omega_r \varphi_{rq} + \frac{1}{\sigma l_s} u_{sd} \quad (13)$$

$$\frac{d}{dt} i_{sq} = -\gamma i_{sq} - \beta \omega_r \varphi_{rd} + \frac{\beta}{T_r} \varphi_{rq} + \frac{1}{\sigma l_s} u_{sq} \quad (14)$$

$$\frac{d}{dt} \varphi_{rd} = \frac{m}{T_r} i_{sd} - \frac{1}{T_r} \varphi_{rd} - \omega_r \varphi_{rq} \quad (15)$$

$$\frac{d}{dt} \varphi_{rq} = \frac{m}{T_r} i_{sq} + \omega_r \varphi_{rd} - \frac{1}{T_r} \varphi_{rq} \quad (16)$$

$$\frac{d}{dt} \omega_r = \alpha(\varphi_{rd} i_{sq} - \varphi_{rq} i_{sd}) - k_f \omega_r - k_l T_l \quad (17)$$

Where $\alpha = \frac{n_p^2 m}{J l_r}$, $\beta = \frac{1}{m} \left(\frac{1-\sigma}{\sigma} \right)$, $\sigma = 1 - \frac{m^2}{l_s l_r}$, $\gamma = \frac{1}{\sigma} \left(\frac{1}{T_s} + \frac{1-\sigma}{T_r} \right)$, $k_f = \frac{f_r}{J}$, $k_l = \frac{n_p}{J}$, and $\omega_r = n_p \Omega_r$

The indexes s and r refer to the stator and the rotor components respectively and the indexes d and q refer to the direct and quadrature components of the fixed stator reference frame respectively (Park's vector components). i and u are the current and the voltage vector, φ is the flux vector, l is the inductance, m is the mutual inductance. T_s and T_r are the stator and the rotor time constant respectively. ω_r is the rotor angular velocity, f_r is the friction coefficient, J is the moment of inertia coefficient, n_p is the number of pair poles, Ω_r is the rotor mechanical speed and finally T_l is the mechanical load torque.

The considered induction motor system model has only the stator current and voltage components as state variables that are available for on line measurements. In this paper we consider only the nonlinearity introduced by the variation of the rotor angular velocity. In order to take into account the effect of the time-varying parameters, as stator (rotor) resistance, one has to introduce an additional equation relating to the considered parameter variation.

In order to implement the flatness based control for our induction motor system we select the rotor angular velocity and the rotor flux as system outputs:

$$z_1(t) = \omega_r(t) \quad (18)$$

$$z_2(t) = \varphi_r(t) \quad (19)$$

A first differentiation of the two selected outputs results in:

$$\begin{aligned} \dot{z}_1 &= \dot{\omega}_r \\ &= \alpha(\varphi_{rd} i_{sq} - \varphi_{rq} i_{sd}) - k_f \omega_r - k_l T_l \end{aligned} \quad (20)$$

$$\begin{aligned} \dot{z}_2 &= \dot{\varphi}_r(t) \\ &= \frac{m}{T_r} (\varphi_{rd} i_{sd} + \varphi_{rq} i_{sq}) - \frac{1}{T_r} \varphi_r \end{aligned} \quad (21)$$

Relation (21) is obtained after a few mathematical operations and simplification using the model relations (13)-(17). Equations (20) and (21) describe the mechanical part and the flux dynamics part of the induction motor system respectively. One can see the coupling effects between the two parts of the system. Nonlinear feedback theory based on flatness concepts is used to eliminate this coupling relationship. To this end let V_1 and V_2 two new control inputs defined as:

$$V_1 = \varphi_{rd} \dot{i}_{sq} - \varphi_{rq} \dot{i}_{sd} \quad (22)$$

$$V_2 = \frac{1}{\varphi_r} (\varphi_{rd} \dot{i}_{sd} + \varphi_{rq} \dot{i}_{sq}) \quad (23)$$

Equations (20) and (21) as functions of the new control inputs can be rewritten as:

$$\dot{\omega}_r = \alpha V_1 - k_f \omega_r - k_l T_l \quad (24)$$

$$\dot{\varphi}_r = \frac{m}{T_r} V_2 - \frac{1}{T_r} \varphi_r \quad (25)$$

From relations (24) and (25) one can express the new control inputs V_1 and V_2 as functions of the outputs ω_r and φ_r as the following:

$$V_1 = \frac{1}{\alpha} (\dot{\omega}_r + k_f \omega_r + k_l T_l) \quad (26)$$

$$V_2 = \frac{1}{m} (T_r \dot{\varphi}_r + \varphi_r) \quad (27)$$

And from equations (22) and (23) one can write the induction motor state variables, i.e. the stator currents i_{sd} and i_{sq} , in terms of the new inputs V_1 and V_2 , and hence in terms of the chosen outputs as:

$$i_{sdf} = -\frac{\varphi_{rq}}{\varphi_r^2} V_1 + \frac{\varphi_{rd}}{\varphi_r} V_2 \quad (28)$$

$$i_{sqf} = \frac{\varphi_{rd}}{\varphi_r^2} V_1 + \frac{\varphi_{rq}}{\varphi_r} V_2 \quad (29)$$

A second differentiation of the chosen outputs, using the Lie derivatives, leads to the appearance of the control inputs, for the first time. The control inputs can then be express as a function of the chosen outputs and a finite number of their time derivative as:

$$\begin{pmatrix} u_{dsf} \\ u_{qsf} \end{pmatrix} = A^{-1}(x) \left[\begin{pmatrix} \ddot{z}_1 \\ \ddot{z}_2 \end{pmatrix} - \begin{pmatrix} B_1(x) \\ B_2(x) \end{pmatrix} \right] \quad (30)$$

With
$$A(x) = \begin{bmatrix} -\frac{\alpha}{p\sigma_s} \varphi_{qr} & \frac{\alpha}{p\sigma_s} \varphi_{dr} \\ -\frac{2m}{\sigma_s T_r} \varphi_{dr} & -\frac{2m}{\sigma_s T_r} \varphi_{qr} \end{bmatrix},$$

$$B_1(x) = \frac{pm}{Jl_r} \left(\gamma + \frac{1}{T_r} + \frac{f_r}{J} \right) (\varphi_{dr} \dot{i}_{ds} - \varphi_{qr} \dot{i}_{qs}) - \frac{p^2 m \beta}{Jl_r} \varphi_r^2 - \frac{p^2 m}{Jl_r} \omega_r (\varphi_{dr} \dot{i}_{ds} + \varphi_{qr} \dot{i}_{qs})$$

$$B_2(x) = \frac{2m}{T_r} \left(\gamma + \frac{3}{T_r} \right) (\varphi_{dr} i_{ds} + \varphi_{qr} i_{qs}) - \frac{2pm}{T_r} \omega_r (\varphi_{qr} i_{ds} - \varphi_{dr} i_{qs}) + \frac{4 + 2m\beta}{T_r^2} \varphi_r^2 + \frac{2m^2}{T_r^2} i_s^2$$

The matrix $A(x)$ represents the system input-output decoupling term. Equations (28)-(30) show that the induction motor system is a flat system and the selected outputs are flat. Relation (30) represents the input control to be applied to induction motor system to fit the desired performance. If this type of input control does not provide the desired performance of the considered induction motor system one can add a correcting term as a PID-like which takes into account a tracking error as in relations (10)-(12).

In general, control algorithms assume that all state variables involved in are available for on line measurements. However, in the practical case, only a few state variables of the considered system are available for on line measurements. In this case, one has to design a state observer to estimate unmeasured state variables. In this paper we use the circle criterion based nonlinear observer designed in the previous paper [24]. In the following we recall briefly the essential ingredients, for detail see reference [24] and references herein.

4. NONLINEAR OBSERVER DESIGN

In contrast of the linearization based and high-gain approaches which attempt to eliminate or to dominate the system nonlinearity effects, circle-criterion approach exploits the properties of system nonlinearities to design nonlinear observer [24]. In its basic form, introduced by Arcak and Kokotovic [28], the approach is applicable to a class of nonlinear systems that can be decomposed into linear and nonlinear parts as the following [28], [29], [30]:

$$\dot{x}(t) = Ax(t) + \phi[u(t), y(t)] + Gf[H.x(t)] \quad (31)$$

$$y(t) = Cx(t) \quad (32)$$

Where A , G , H , and C are known constant matrices with appropriate dimensions. The pair (A, C) is assumed to be observable. The term $\phi[u(t), y(t)]$ is an arbitrary real-valued vector that depends only on the system inputs $u(t)$ and outputs $y(t)$. The nonlinear part of the system is modelled by the term $f[H.x(t)]$ which is a time-varying function verifying the following sector property [29]:

$$f(z, t) : R^p \times [0 + \infty[\rightarrow R^p \text{ is said to belong to the sector } [0 + \infty[\text{ if } z^T f(z, t) \geq 0.$$

Theorem [28], [29]: Consider a nonlinear system of the form (31)-(32) with the nonlinear part satisfying the sector property. If there exist symmetric and positive definite matrix $P \in R^{n \times n}$, $Q \in R^{n \times n}$ and a set of row vectors $K \in R^p$ such that the following linear matrix inequalities (LMI) hold:

$$(A - LC)^T P + P(A - LC) + Q \leq 0 \quad (33)$$

$$PG + (H - KC)^T = 0 \quad (34)$$

Then a nonlinear observer can be designed as:

$$\dot{\hat{x}}(t) = A\hat{x}(t) + \phi[u(t), y(t)] + L[y(t) - \hat{y}(t)] + G f[H\hat{x}(t) + K(y(t) - \hat{y}(t))] \quad (35)$$

$$\hat{y}(t) = C\hat{x}(t) \quad (36)$$

Where $\hat{x}(t)$ is the estimate of the state vector $x(t)$ of the considered nonlinear system. A detailed proof of the theorem is presented in [24].

Note that the nonlinear observer design refers to the selection of the gain matrices \mathbf{L} and \mathbf{K} satisfying the LMI conditions (33)-(34). One can see that the induction motor model structure, relations (30)-(31) and the observer dynamics, relations (35)-(36), can be considered as linear systems controlled by a time-varying nonlinearity function satisfying the sector property. Circle criterion establishes that a feedback interconnection of a linear system and a time-varying nonlinearity satisfying the sector property is globally uniformly asymptotically stable [28], [29]. In [30], the author has investigated the study of bounded state nonlinear systems. Such systems constitute a large class that includes electric machine systems in which the magnetic flux is a bounded state variable due to the effect of the magnetic material saturation property.

5. SIMULATION RESULTS AND COMMENTS

In order to point out the performance of the proposed flatness based sensorless control, an induction motor system with characteristics presented in Table 1 is considered. In this simulation experiments, a two level inverter based SPWM (Sinusoidal Pulse Width Modulation) technique feeds the induction motor system.

Table 1. Characteristics of the considered induction motor

Symbol	Quantity	Numerical Value
P	Power	1.5 KW
f	Supply frequency	50 Hz
U	Supply voltage	220 V
n_p	Number of pair poles	2
R_s	Stator resistance	4.850 Ω
R_r	Rotor resistance	3.805 Ω
l_s	Stator inductance	0.274 H
l_r	Rotor inductance	0.274 H
m	Mutual inductance	0.258 H
ω_r	Rotor angular speed	297.25 rad/s
J	Inertia coefficient	0.031 kg^2 / s
f_r	Friction coefficient	0.00114 N.s/rad
T_l	Load torque	5 N.m

The simulation experiments consist of the following steps.

1. Resolve the LMI conditions to determine the matrices gain of the observer, and simulate the observer dynamics to estimate the chosen flat outputs.
2. Implemente the flatness based control as a function of the estimated flat outputs.

In order to implement the first step of the simulation experiments and to perform circle criterion based nonlinear observer, taking into account the numerical values of the different physical parameters of the machine, the nonlinear induction motor model is written in the standard form, relations (31)-(32). To this end, nonlinearities of the model are expressed as $\omega_r \varphi_{rd} = (\omega_r \varphi_{rd} + \rho \omega_r) - \rho \omega_r$ to verify the following equivalent sector property:

$$\frac{\partial}{\partial \omega_r} (\omega_r \varphi_{rd} + \rho \omega_r) = \varphi_{rd} + \rho \geq 0 \quad \text{with} \quad \|\varphi_{rd}\| \leq 2 \quad \text{and} \quad \rho = 2.$$

After that the LMI conditions, relations (33)-(34), are resolved using an adequate LMI tool such as the LMI tool-box of the Matlab software. The obtained observer gain matrices \mathbf{L} and \mathbf{K}_i are the following:

$$\mathbf{L} = \begin{bmatrix} -1.6749 & 0.1188 \\ 0.1188 & -1.6749 \\ -0.7172 & -0.1075 \\ -0.1075 & -0.7172 \\ 1.6201 & -1.6201 \end{bmatrix}$$

$$\mathbf{K}_1 = [-1.6037 \quad -0.738], \quad \mathbf{K}_2 = [0.7381 \quad 1.6037], \quad \mathbf{K}_3 = [0.3948 \quad -0.9193], \quad \mathbf{K}_4 = [-0.9193 \quad 0.3948]$$

The corresponding Lyapunov matrix for the feasibility test of the LMI is:

$$\mathbf{P} = \begin{bmatrix} 0.1550 & -0.0710 & 0.0514 & 0.1486 & 0.0274 \\ -0.0710 & 0.1550 & 0.1486 & 0.0514 & -0.0274 \\ 0.0514 & 0.1486 & 5.6010 & 0.4659 & -0.0505 \\ 0.1486 & 0.0514 & 0.4659 & 5.6010 & 0.0505 \\ 0.0274 & -0.0274 & -0.0505 & 0.0505 & 0.0173 \end{bmatrix}$$

Here $\mathbf{Q} = \varepsilon \mathbf{I}_5$ with $\varepsilon = 0.04$ and \mathbf{I}_5 is a unit matrix of fifth order.

Injecting the obtained numerical values of the observer gain matrices in the observer expression, relation (35)-(36), the estimated state variables of the induction machine, including the chosen flat outputs, are generated.

Figure 1 and Figure 2 present the estimated flat outputs and their time derivatives. One can verify that in the transient state the first time derivative is a pulse and in steady state the second time derivative is null. Thus confirm the mathematical aspect. The system state variables and control inputs are expressed as functions of the estimated flat outputs. The obtained control law, as function of the flat outputs, is presented in Figure 3. One can see that it presents a sinusoidal shape. Thus reduce the induced harmonics effect.

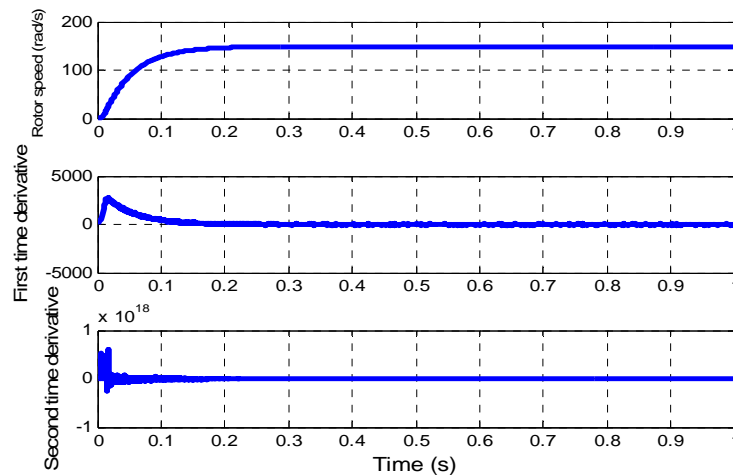


Figure 1. Rotor speed flat output and its time derivatives

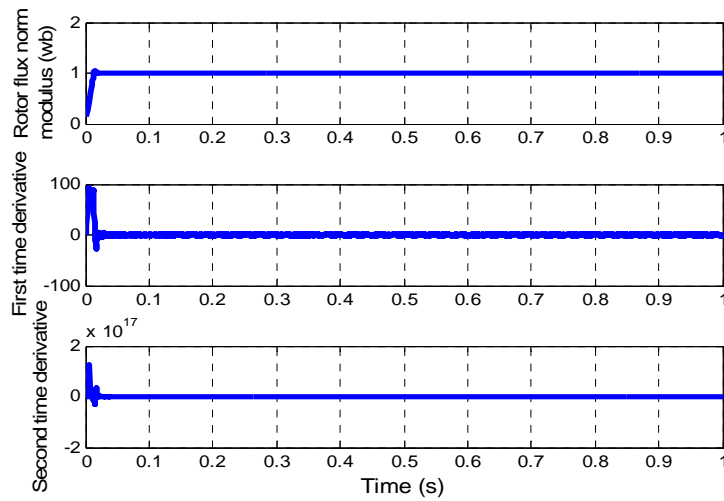


Figure 2. Rotor flux norm modulus flat output and its time derivatives

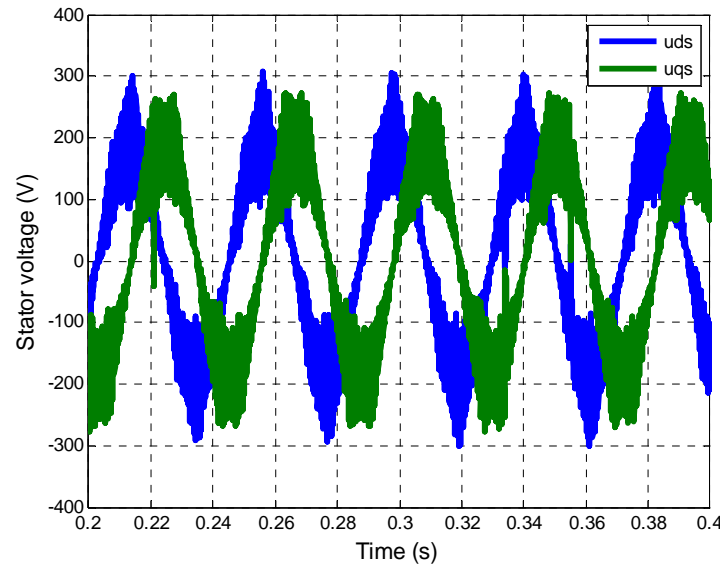


Figure 3. Stator voltage control flat inputs

The next step of simulation consists in applying the obtained control signal to the two level inverter fed induction motor system and varying the load torque from no load value to the value $T_l = 5 \text{ N.m}$ introduced at time $t = 1$ second and return to no load value at time $t = 2$ second. After that the rotor angular velocity is reversed from the reference value of $\omega_{ref} = 150 \text{ rad/s}$ to $\omega_{ref} = -150 \text{ rad/s}$ at time $t = 2.5$

second and a load $T_l = -5 \text{ N.m}$ is introduced at time $t = 3$ second and return to no load at time $t = 4$ second.

Figure 4 and Figure 5 present the electromechanical torque and the rotor angular velocity variations respectively, with respect to the simulation tests. One can see that the estimated torque follows the reference load torque. The observed disturbance at time $t = 2.5$ second is due to the reversed sense of the rotor speed. Notice that in this case, the rotor angular velocity which is a chosen flat output follows its reference value in the corresponding range of load variations.

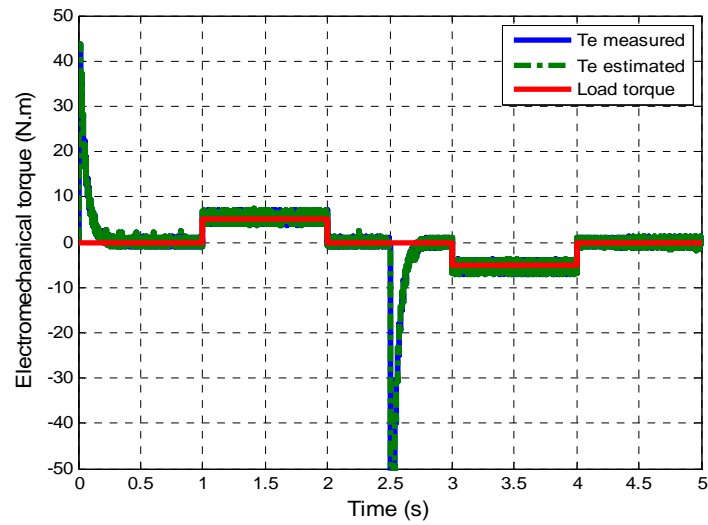


Figure 4. Load torque, measured and observed electromechanical torque

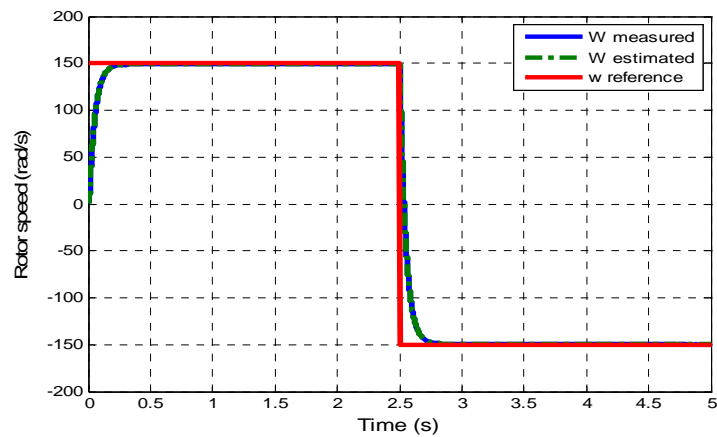


Figure 5. Measured and observed rotor velocity evolution according to load variations

Figure 6 presents the variations of the rotor flux modulus. One can see, after a transient time, the flux reaches its reference value. A little disturbance appears at the instant of reversing the rotor speed. A roughly smooth curve is then obtained because there is no variation according to the introduced load torque.

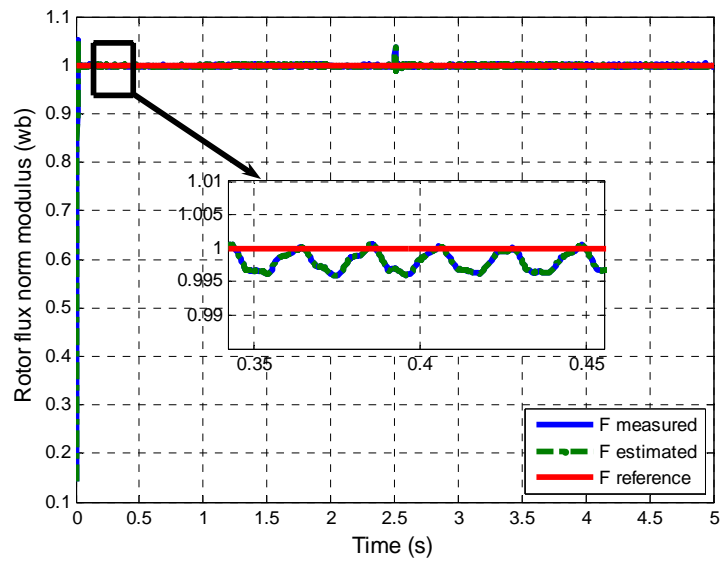


Figure 6. Measured and estimated rotor flux norm modulus

Figure 7 and Figure 8 present the stator current components respectively. One can see that the stator current components follow the variations of the electromechanical torque. A smashed curve is obtained due to variations of load torque.

Analysis of the different figures shows that proposed flatness based nonlinear sensorless control of induction motor system performs the desired control strategy and all state and input variables can be expressed as functions of the chosen flat outputs.

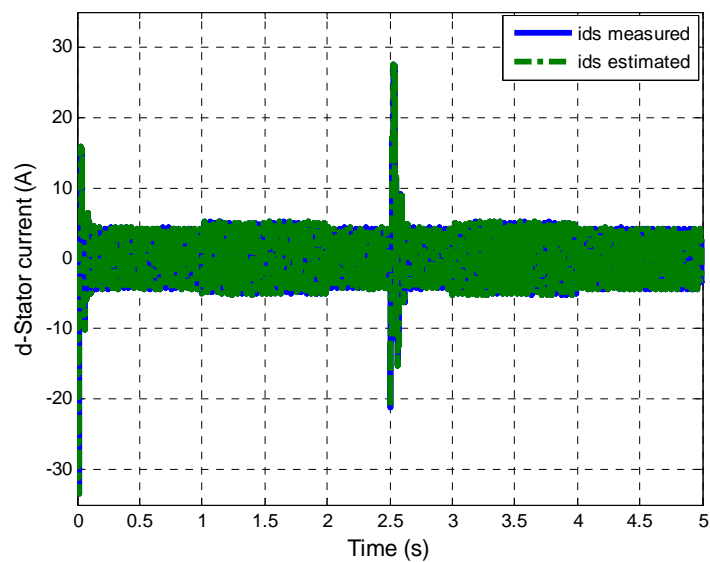


Figure 7. Measured and estimated d- stator current components.

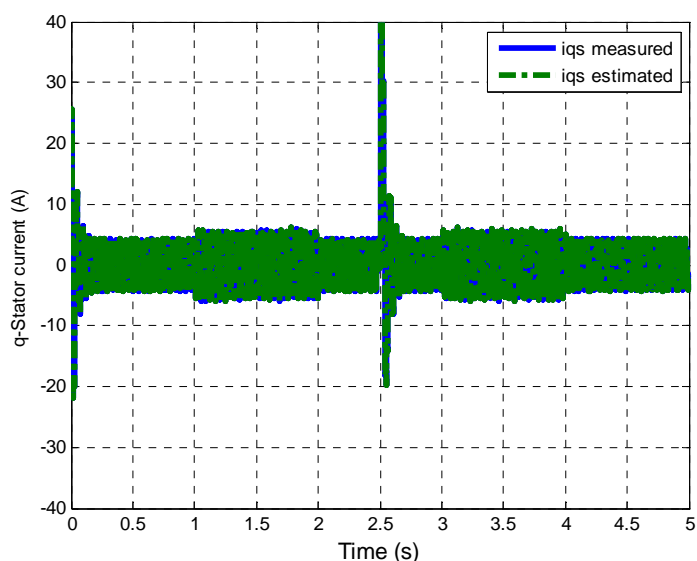


Figure 8. Measured and estimated q-stator current components

6. CONCLUSIONS

In this paper flatness based approach for nonlinear sensorless control of the induction motor system has been presented by using a circle-criterion based nonlinear observer to estimate the chosen flat outputs. Decoupling is achieved between the two selected outputs (speed and flux) with the help of the system flatness properties. The used nonlinear observer has contributed effectively to estimate the unmeasurable state variables that are essential for the nonlinear control. Simulation results show that this control strategy assures a perfect linearization regardless trajectory profiles physically imposed on the induction machine system.

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