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Sensorless Exact Input-Output Linearization Control of the Induction Machine, Based on Parallel Stator Resistance and Speed MRAS Observer, with a Flux Sliding Mode Observer

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Abstract: This paper presents an exact input-output linearization control scheme for rotor speed and rotor flux control of induction motor drive. In this scheme the motor model, is described in the fixed stator frame, and it is linearized, using exact input-output linearization technique, allowing a decoupled control of rotor flux and torque. To avoid the use of mechanical sensor, the rotor speed estimation is made by an observer using a specific MRAS (Model reference adaptive system) technique; this observer is designed to perform simultaneous estimation of stator resistance and rotor speed. In order to estimate rotor flux, a sliding mode observer is proposed in this paper. Simulation results are realized and presented to validate and to prove the effectiveness of the proposed Sensorless control.

Keywords: Input-output linearization, Induction Motor Drive, MRAS observer, Sliding Mode.

1. Introduction

Induction motors are widely used in industry especially in variable speed applications. An induction motor is simple in operation, rugged, maintenance free and generally less expensive than other machines.

However, its model is complicated for various reasons. The dynamic behavior of the motor is described by a fifth-order highly coupled and nonlinear dynamical system, the rotor electric variables (fluxes and currents) are practically not measured; and some of its physical parameters may vary significantly while operating the motor (stator and mainly rotor resistance, due to heating, magnetizing induction due to saturation);

Those difficulties have whetted the curiosity of scientists and researcher in laboratories, in the last few years, Evidenced by the growing number of publications that discuss the subject. Different control strategies were developed, like Field Oriented Control (FOC) proposed by Blaschke [1], and Direct Torque Control (DTC) have been extensively reported and discussed in the literature [1]-[4] to achieve a decoupled control of induction motor.

In vector control the torque and flux are decoupled by a suitable decoupling network. Then the flux component and the torque are controlled independently and respectively by stator direct-axis current and stator quadratic-axis current to control the induction motor (IM) as a separately excited DC motor.

A disadvantage of the FOC is that the method assumes that the magnitude of the rotor flux is regulated to a constant value. Therefore, the rotor speed is only asymptotically decoupled from the rotor flux. To improve the I.M control performances others technique were conceived like the sliding mode control, it is characterized by simplicity of design and attractive robustness properties. Its major drawback is the chattering phenomenon [5]-[8].

By contrast, the passivity based control [9,10], doesn't cancel all the nonlinearity but ensure system stability, but its experimental implementation is still difficult.

Backstepping control approach [11]-[15], is more recent. Its present form is due to Krstic, Kanellakopoulos and Kokotovic. This control technique offers good performance in both steady state and transient operations.

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Among technique that we find in the literature, there is the exact input-output linearization technique [16]-[23] used in this work. The technique of input-output linearization based on the differential geometry allows by a diffeomorphic transformation and a state feedback to uncouple and linearize the model put under canonical and then controlled using linear control techniques. This technique has the advantage of being able to separately control flux and torque even in mode of variation of flux. This method cancels the nonlinear terms in the plant model which fails when the physical parameters varies.

These control techniques can not guarantee good performances without the use of suitable state observer. Among the observation technique used, there are the sliding mode techniques used in this work to estimate flux, and MRAS technique, used, in particular, in Sensorless IM drives at the first time by Schauder (1992). MRAS is interesting since it leads to relatively easy to implement system with high speed adaptation [24]-[27].

In this work we propose a new structure of MRAS Observer, allowing simultaneous observation of stator resistance and rotor speed.

This article is organized into three main sections, in the first one we design the exact input-output linearization control, in the second one we present the flux sliding mode observer, the last one we present the design of the parallel MRAS observer of stator resistance and rotor speed.

Simulation results, given at the end, illustrate the good performance of this combination of control method and observation techniques.

2. Input-Output Linearization of the Induction Machine

In order to reduce the complexity of the three phase model and then simplify the control design, an equivalent two phase representation is chosen. Under the assumptions of linearity of the magnetic circuit and neglecting iron losses, a two phase IM model in the fixed stator, reference frame (α , β) can be described as:

$$\begin{cases} \dfrac{d\Phi_{r\alpha}}{dt} = \lambda_r.(L_m.i_{s\alpha} - \Phi_{r\alpha}) \ - p.\Omega.\Phi_{r\beta} \\ \dfrac{d\Phi_{r\beta}}{dt} = \lambda_r.(L_m.i_{s\beta} - \Phi_{r\beta}) \ + p.\Omega.\Phi_{r\alpha} \\ \dfrac{di_{s\alpha}}{dt} = -\gamma.i_{s\alpha} + k.\lambda_r.\Phi_{r\alpha} + k.p.\Omega.\Phi_{r\beta} + \delta.v_{s\alpha} \\ \dfrac{di_{s\beta}}{dt} = -\gamma.i_{s\beta} - k.p.\Omega.\Phi_{r\alpha} + k.\lambda_r.\Phi_{r\beta} + \delta.v_{s\beta} \\ \dfrac{d\Omega}{dt} = \dfrac{\mu}{J}.\left(\Phi_{r\alpha}.i_{s\beta} - \Phi_{r\beta}.i_{s\alpha}\right) - \dfrac{f}{J}.\Omega - \dfrac{T_L}{J} \end{cases}$$

Where:

$$\sigma = 1 - \frac{L_m^{\ 2}}{L_r.L_s} \ ; \quad k = \frac{L_m}{\sigma L_s L_r} ; \quad T_r = \frac{L_r}{R_r} \ ; \quad \lambda_r = \frac{R_r}{L_r} ; \ \gamma = \frac{1}{\sigma L_s}\left(R_s + \frac{R_r.L_m^{\ 2}}{L_r^{\ 2}}\right) \ ; \quad \mu = p\frac{L_m}{L_r} \ ;$$

$$\delta = \frac{1}{\sigma.L_s}$$

We saw that the dynamic equations of the induction machine are non-linear, what make the control difficult to conceive. However, with some transformations, the nonlinear system can be converted into the corresponding linear system. Feedback linearization is one of the approaches for the nonlinear control design [18], [19]. The fundamental idea is to apply linear control techniques for the nonlinear system. It has been used to solve a lot of practical control problems in industry by transforming a nonlinear system dynamics into a fully or partly linear one. The simplest form of feedback linearization is to cancel the nonlinearities of a nonlinear system so that the closed-loop dynamics is in a linear form.

The structure of the proposed I.M control is represented below, in Figure 1.
The induction motor model (1) is put in the following form:

$$\begin{cases} \dot{x} = f(x) + g(x) \\ y = h(x) \end{cases}$$

Where:

$$x = \left[\Phi_{r\alpha}, \Phi_{r\beta}, i_{s\alpha}, i_{s\beta}, \Omega\right]^T$$

$$f(x) = \begin{bmatrix} -\lambda_r.\Phi_{r\alpha} - p.\Omega.\Phi_{r\beta} + \lambda_r.L_m.i_{s\alpha} \\ p.\Omega.\Phi_{r\alpha} - \lambda_r.\Phi_{r\beta} + \lambda_r.L_m.i_{s\beta} \\ k.\lambda_r.\Phi_{r\alpha} + k.p.\Omega.\Phi_{r\beta} - \gamma.i_{s\alpha} \\ -k.p.\Omega.\Phi_{r\alpha} + k.\lambda_r.\Phi_{r\beta} - \gamma.i_{s\beta} \\ \frac{\mu}{J}.\left(\Phi_{r\alpha}.i_{s\beta} - \Phi_{r\beta}.i_{s\alpha}\right) - \frac{f}{J}.\Omega - \frac{T_L}{J} \end{bmatrix}$$

$$g(x) = \begin{bmatrix} 0 & 0 & 0 & \delta.u_\alpha & 0 \\ 0 & 0 & \delta.u_\alpha & 0 & 0 \end{bmatrix}^T$$

Having two control variables u_α *and* u_β, it is possible to decompose the model into two independent systems and then control separately two outputs. We choose as the outputs, the electromagnetic torque Te and the rotor flux modulus $\Phi_r^{\ 2}$.

$$h(x) = \begin{bmatrix} T_e \\ \Phi_r^{\ 2} \end{bmatrix} = \begin{bmatrix} \mu.\left(\Phi_{r\alpha}.i_{s\beta} - \Phi_{r\beta}.i_{s\alpha}\right) \\ \Phi_{r\alpha}^{\ 2} + \Phi_{r\beta}^{\ 2} \end{bmatrix}$$

In order to be able to impose arbitrary dynamics on every output $y_1 = T_e$ and $y_2 = \Phi_r^{\ 2}$, we mast find a differential relation linear between the output y_1 and y_2 and input of command u_α and u_β, it is necessary to find a return of state, in a way that the system in closed buckle is linear and decoupled. Thus, it is necessary to derive the output function $h_1(x)$ and $h_2(x)$ respectively r_1 and r_2 (corresponding relative degrees) time, until create differential equations where intervene the commands (u_α, u_β).

This linearization operation is possible in case where the total relative degree $r = r_1 + r_2$ is lower or equal to the order of the system n (r ≤ n), so the system is controllable.
By successive derivation we can write:

$$\begin{cases} \dfrac{dy_1^{r_1}}{dt} = L_f^{\,r_1}.h_1(x) + \sum_{j=1}^{2} L_{g_j}.L_f^{\,r_1-1}.h_1(x).u_j \\ \dfrac{dy_2^{r_2}}{dt} = L_f^{\,r_2}.h_2(x) + \sum_{j=1}^{2} L_{g_j}.L_f^{\,r_2-1}.h_2(x).u_j \end{cases}$$

$L_f h$ is h lie derivation in direction of the vector field $f_{(.)}$ such as:

$$\begin{cases} L_f h(x) = dh.f = \sum_i^n \frac{\partial h(x)}{\partial x_i}.f_i(x) \\ f(x) = \left(f_1(x), f_2(x), ...f_n(x)\right) \end{cases}$$

And $r = [r_1, r_2]$ is the relative degree which has to satisfy the following conditions:

$$* L_{g_j} L_f^{\,k}.h_i(x) = 0 \qquad for \quad \begin{cases} 1 \le j \le 2, \\ 1 \le i \le 2, \; k < r_i - 1, \end{cases}$$

$$* L_{g_j} L_f^{\,r_i - 1}.h_i(x) \ne 0 \qquad for \quad \begin{cases} 1 \le j \le 2, \\ 1 \le i \le 2, \end{cases}$$

Also let us define the matrix of decoupling:

$$D(x) = \begin{bmatrix} L_{g_1} L_f^{\,r_1 - 1}.h_1(x) & L_{g_2} L_f^{\,r_1 - 1}.h_1(x) \\ L_{g_1} L_f^{\,r_2 - 1}.h_2(x) & L_{g_2} L_f^{\,r_2 - 1}.h_2(x) \end{bmatrix}$$

We can then write the system of equation (3) under the following matrix form:

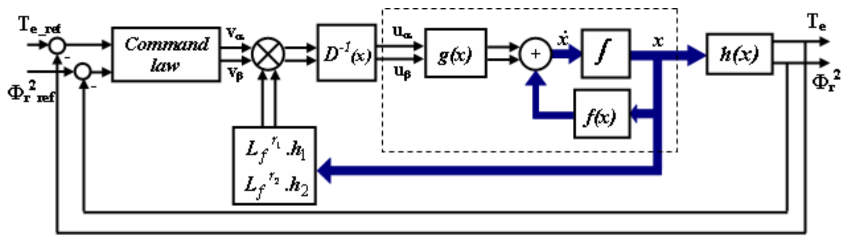

Figure 1. Structure of the nonlinear control (input-output linearization)

$$\begin{bmatrix} h_1^{(r_1)}(x) \\ h_2^{(r_2)}(x) \end{bmatrix} = \begin{bmatrix} L_f^{\,r_1}.h_1 \\ L_f^{\,r_2}.h_2 \end{bmatrix} + D(x).\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

A. For the first output: torque Te

Consider the machine model defined by (2) and determine the order of derivative for which the first variable to be set (the electromagnetic torque) is explicitly affected by the controls u_α and u_β.

By successive derivations, the relative degree r_1 associated with the torque of the MAS is equal 1:

$$\frac{dy_1}{dt} = \frac{dT_e}{dt} = L_f h_1(x) + L_{g_1} L^0{}_f h_1(x).u_\alpha + L_{g_2} L^0{}_f h_1(x).u_\beta$$
$$L_f h_1(x) = \mu.\left(\Phi'_{r\alpha}.i_{s\beta} + \Phi_{r\alpha}.i'_{s\beta} - \Phi'_{r\beta}.i_{s\alpha} - \Phi_{r\beta}.i'_{s\alpha}\right)$$

Then we get this expression:

$$L_f h_1(x) = A_1.\left(\Phi_{r\alpha}.i_{s\beta} - \Phi_{r\beta}.i_{s\alpha}\right) + A_2.\left(\Phi_{r\alpha}.i_{s\alpha} + \Phi_{r\beta}.i_{s\beta}\right) + A_3.\left(\Phi_{r\alpha}{}^2 + \Phi_{r\beta}{}^2\right)$$

Where:

$$\begin{cases} A_1 = -\mu.(\lambda_r + \gamma) \\ A_2 = -p.\Omega.\mu \\ A_3 = k.A_2 \end{cases}$$

And:

$$\begin{cases} L_{g_1} L^0{}_f h_1(x) = -p.k.\Phi_{r\beta} \\ L_{g_2} L^0{}_f h_1(x) = p.k.\Phi_{r\alpha} \end{cases}$$

B. For the second output: square of rotor flux $\Phi_r{}^2$.

In the same way as previously, the relative degree r_2, associated with the second output, is equal 2. Then after the second derivation we get:

$$\frac{d^2 y_2}{dt^2} = L^2{}_f h_2(x) + L_{g_1} L^1{}_f h_2(x).u_\alpha + L_{g_2} L^1{}_f h_2(x).u_\beta$$

Where:

$$L_f h_2(x) = -2.\lambda_r.\left(\Phi_{r\alpha}{}^2 + \Phi_{r\beta}{}^2\right) + 2.L_m.\lambda_r.\left(\Phi_{r\alpha}.i_{s\alpha} + \Phi_{r\beta}.i_{s\beta}\right)$$

$$\Rightarrow L^2{}_f h_2(x) = B_1.\left(i_{s\alpha}{}^2 + i_{s\beta}{}^2\right) + B_2.\left(\Phi_{r\alpha}.i_{s\beta} - \Phi_{r\beta}.i_{s\alpha}\right) + B_3.\left(\Phi_{r\alpha}.i_{s\alpha} + \Phi_{r\beta}.i_{s\beta}\right) + B_4.\left(\Phi_{r\alpha}{}^2 + \Phi_{r\beta}{}^2\right)$$

Where:

$$\begin{cases} B_1 = 2.(L_m.\lambda_r)^2 \quad , \quad B_2 = 2.p.\Omega.L_m.\lambda_r \\ B_3 = -6.L_m.\lambda_r{}^2 - 2.\gamma.L_m.\lambda_r \quad , \quad B_4 = 4.\lambda_r{}^2 + 2.k.L_m.\lambda_r{}^2 \end{cases}$$

$$\begin{cases} L_{g_1} L^1{}_f h_2(x) = 2.k.R_r.\Phi_{r\alpha} \\ L_{g_2} L^1{}_f h_2(x) = 2.k.R_r.\Phi_{r\beta} \end{cases}$$

C. Feedback law

The matrix form of the system equations (4) allows as deducting the return of nonlinear state $u = \alpha(x) + \beta(x).v$ that give to the system a linear input/output behavior:

By putting:

$$\begin{cases} \alpha(x) = -D^{-1}(x).\begin{bmatrix} L_f{}^{r_1}.h_1 \\ L_f{}^{r_2}.h_2 \end{bmatrix} \\ \beta(x) = D^{-1}(x) \end{cases}$$

The input of the resulting linear system is defined as follow:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = D^{-1}(x)\left(\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} - \begin{bmatrix} L_f{}^{r_1}.h_1 \\ L_f{}^{r_2}.h_2 \end{bmatrix}\right)$$

Where:

v_α and v_β : are the new inputs controls.