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Identification and multivariable control in state space of a permanent magnet synchronous generator

Identificacion y control multivariable en el estado espacio de un generador síncrono de imanes permanentes

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Abstract

In this paper, a scheme for online identification of multivariable systems (MIMO) and a linear state feedback control is considered. The identification algorithm takes into account the input/output behavior in order to obtain a linear state spaces model that describes adequately the system in discrete time. This representation is obtained by using an online identification method such as the projection algorithm. An optimal linear quadratic regulator is applied in discrete time, where the obtained state feedback control law minimizes the quadratic cost function to calculate the optimal gain matrix. The proposed methodology for identification and multivariable control is applied an evaluated in a wind turbine with a Permanent Magnet Synchronous Generator (PMSG).

***Keywords*:** Control, identification, optimal gain, multivariable, linear model, feedback.

Resumen

En este trabajo, se considera un esquema de identificación en línea de sistemas multivariable (MIMO) y un control lineal por realimentación de estados. El algoritmo de identificación considera el comportamiento de entrada/salida con el fin de obtener un modelo de espacio de estados lineal que describe adecuadamente el sistema en tiempo discreto. Esta representación se obtiene mediante el uso de un método de identificación en línea, tales como el algoritmo de proyección. Un regulador lineal cuadrático óptimo se aplica en tiempo discreto, donde la ley de control por realimentación de estados obtenida, minimiza la función de costo cuadrática para calcular la matriz de ganancia óptima. Se aplica la metodología propuesta para la identificación y el control multivariable, en una turbina eólica con un generador síncrono de imanes permanentes (PMSG).

***Palabras clave*:** Control, identificación, ganancia óptima, multivariable, modelo lineal, retroalimentación.

1. Introduction

With its abundant, inexhaustible potential, its increasingly competitive cost, and environmental advantage, wind energy is one of the best technologies available today to provide a sustainable supply to the world development. Now, the wind energy is an important sustainable energy resource and with this creates the need for increased power production from the wind in adverse conditions, when the wind turbine generator system is coupled to a power system [1]. Recent studies are focused on investigating the system behavior with internal disturbances and variable wind speed that affects the system [2], and other investigations proposing new techniques about the system identification and the control systems in the maximum extracting of energy of the whole system [3].

The systems that use the subspace identification methods (SIMs) have become quite popular in recent years. The SIMs objective is to estimate the state variables or the extended observability matrix directly from the input and output data [4]. The most influential methods are CVA (Canonical Variate Analysis [5]), MOESP (Multivariable Output Error State Space [6]) and N4SID (Numerical Subspace State-Space System Identification [6]). But exist other methods that used the Darma model to estimate the plant parameters in each time with past inputs/outputs values [7].

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Linear system identified with SIMs, are suitable for the application of state space controllers. The investigations around the discrete linear quadratic regulator (DLQR) control are oriented to the convergence of control strategies for discrete-time linear systems in state space based on dynamic programming (DP) and the classical DLQR. The performance of the DP algorithms is evaluated for changes in control targets that are mapped in Q and R weighting matrices [8].

This paper is focused on the mathematical model of a wind generator where the behavior of its variables will be examined. So, a nonlinear multivariable system identification scheme is proposed, based on a linear state space representation to improve the performance of the wind turbine. Lastly, the system's closed loop response is evaluated with the optimal adaptive controllers and the parameters stated by using the identification schemes.

2. Model description

The model of a wind turbine with Permanent Magnet Synchronous Generator (PMSG) is constructed from a number of sub models of the turbine, drive train, synchronous generator and rotor side converter. A general structure of the model is shown in Figure 1 [9,13].

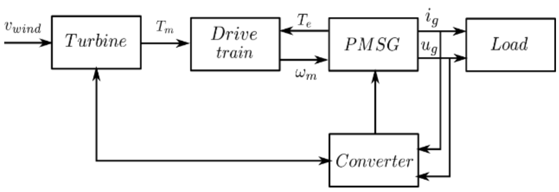

Figure 1 General structure of the wind

2.1 Turbine Model

The main purpose of the wind turbine is to obtain energy from the wind and transform it into electrical energy [9]. The power extracted from the wind is described by (1)

$$P_w = \frac{\pi \rho Ra^2}{2} Cp(\lambda) v^3 \qquad (1)$$

Where, ρ is the air density, Ra is the radius of the area covered by the wind, v is the wind speed and Cp is the performance coefficient in function of the tip speed.
The torque developed from the wind and the Cp approximation is presented in (2) and (3).

$$T_{wt} = \frac{\pi \rho Ra^3}{2} C_p(\lambda) v^2 \qquad (2)$$

$$C_p(\lambda) = 0.22\left(\frac{116}{\lambda} - 5\right) e^{\frac{-12.5}{\lambda}} \qquad (3)$$

A second order approximation, of the coefficient Cp, is calculated employing the least square technique.

$$C_p = a_0 + a_1\lambda + a_2\lambda^2 \qquad (4)$$

The tip speed is (5)

$$\lambda = \frac{\omega_L Ra}{v} \qquad (5)$$

The speed in the generator side is (6), where G is the multiplier coefficient of the gear box.

$$\omega_H = \omega_L G \qquad (6)$$

The torque in the generator side is:

$$T_m = \frac{T_{wt}}{G} \qquad (7)$$

Replacing equations (5) and (4) in (2), the torque in the generator side is represented by the approximation (8)

$$T_m = \frac{d_1 v^2}{G} + \frac{d_2 v \omega_H}{G^2} + \frac{d_3 \omega_H^2}{G^3} \qquad (8)$$

3. Drive train system

Las figuras y tablas deben aparecer lo más cerca posible del lugar de su primera cita, por ejemplo, La figura. 1, en el texto. Las figuras se numerarán con números arábigos, con la leyenda centrada debajo de la figura, en negrita.
The drive train of PMSG consists of five parts, namely, rotor, low speed shaft, gearbox, high-speed shaft and generator. When the study focuses on the interaction between wind farms and AC grids, the drive train can be treated as one-lumped mass model for the sake of time efficiency and acceptable precision. So, the drive train takes the form of the latter one in the paper in which the parameters have been referred to the generator side [10].

$$\begin{cases} \dfrac{d\omega}{dt} = (T_e - T_m - B_m\omega_H)\dfrac{1}{J_H} \\ \dfrac{d\theta}{dt} = \omega_H \end{cases} \qquad (9)$$

ω_H the angular velocity, T_e electrical torque, T_m mechanical torque, B_m is the rotating damping, J_H is the inertia constant and θ the angular position angle.

4. Pmsg modeling

The PMSG has been considered as a system which makes possible to produce electricity from the mechanical energy obtained from the wind.
The dynamic model of the PMSG is derived from the two-phase synchronous reference frame, which the q-axis is 90° ahead of the d-axis with respect to the direction of rotation [1]. By the application of the Park transform and presenting the model as a generator with negative currents; the system is expressed in the coordinates of the rotor

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which makes the design of the driver simpler because their signals are treated as direct current and that reduces the model to two axes.

The system is modeled with the set of equations (10) to (13) where i_{dq} and u_{dq} represent currents and voltages of the stator in the axis q and d respectively [9].

$$\frac{d\theta}{dt} = \omega \tag{10}$$

$$\frac{d\omega}{dt} = \frac{n_p}{J_H}\varphi_m i_q - \frac{T_m}{J_H} \tag{11}$$

$$u_d = -Ri_d + n_p L_s \omega i_q - L_s \frac{di_d}{dt} \tag{12}$$

$$u_q = -Ri_q - n_p L_s \omega_H i_d - L_s \frac{di_d}{dt} + \omega\varphi_m \tag{13}$$

n_p is the number of pole pairs, R is the stator resistance, L_s is the inductance of the stator, φ_m the magnetization flow in the rotor.

The system in state space is represented in (14) to (15) to feed a RL load, L is the inductance of the load, R_L the variable resistance of the load, J_H inertia coefficient at the side of the generator. The state vector is $\boldsymbol{x} = [x_1, x_2, x_3]^T = [i_d, i_q, \omega]^T$, the inputs of the system $\boldsymbol{u} = [u_1, u_2]^T = [R_L, v]^T$ and the rotor speed ω is the output.

$$\frac{dx_1}{dt} = \frac{1}{L+L_s}(-Rx_1 + n_p(L+L_s)x_2x_3 - x_1u_1) \tag{14}$$

$$\frac{dx_2}{dt} = \frac{1}{L+L_s}(-Rx_2 + n_p(L+L_s)x_1x_3 + n_p\varphi_m x_3 - x_2u_1) \tag{15}$$

$$\frac{dx_3}{dt} = \frac{1}{J_H}\left(\eta\left(\frac{d_1}{G}u_2^2 + \frac{d_2}{G^2}u_2x_3 + \frac{d_3}{G^3}x_3^2\right) - n_p\varphi_m x_2\right) \tag{16}$$

$$y = [0 \quad 0 \quad 1]\boldsymbol{x} \tag{17}$$

η is the drive train performance coefficient.

5. Subspace identification method

5.1. Representation of Multivariable Systems

The representation of a multi-variable discrete system with m outputs and r inputs with q as delay operator can be stated in [7]:

$$\boldsymbol{A}(q^{-1})y(k) = \boldsymbol{B}(q^{-1})u(k) \tag{18}$$

where **A** is given by:

$$\boldsymbol{A}(q^{-1}) = \boldsymbol{A}_0 + \boldsymbol{A_1}(q^{-1}) + \cdots + \boldsymbol{A}_{n_1}(q^{-n_1}) \tag{19}$$

and **B** is given by:

$$\boldsymbol{B}(q^{-1}) = \boldsymbol{B_1}(q^{-1}) + \cdots + \boldsymbol{B}_{n_2}(q^{-n_2}) \tag{20}$$

wit$n_1 \geq n_2$h and where $\boldsymbol{A}_i \in \Re^{mxm}$, $\boldsymbol{B}_i \in \Re^{rxr}$, the inputs $\boldsymbol{u} \in \Re^{rx1}$ and the outputs $\boldsymbol{y} \in \Re^{mx1}$ as

$$y(k) = \begin{bmatrix} y_1(k) \\ \vdots \\ y_m(k) \end{bmatrix}, \quad u(k) = \begin{bmatrix} u_1(k) \\ \vdots \\ u_m(k) \end{bmatrix} \tag{21}$$

If $\boldsymbol{A}_o = \boldsymbol{I}$ with **I** the identity matrix, **y** takes the form:

$$\begin{aligned} y(k) = \boldsymbol{B}_1\boldsymbol{u}(k-1) + \cdots + \boldsymbol{B}_{n_2}\boldsymbol{u}(k-n_2) \\ - \boldsymbol{A}_1\boldsymbol{y}(k-1) - \cdots \\ - \boldsymbol{A}_{n_1}\boldsymbol{y}(k-n_1) \end{aligned} \tag{22}$$

where $\boldsymbol{A}_i$ and $\mathbf{B}_i$ are of the form:

$$\begin{aligned} \boldsymbol{A}_i = \begin{bmatrix} a_{1m}^i & \cdots & a_{1m}^i \\ \vdots & \ddots & \vdots \\ a_{m1}^i & \vdots & a_{mm}^i \end{bmatrix} \\ \boldsymbol{B}_i = \begin{bmatrix} b_{1m}^i & \cdots & b_{1m}^i \\ \vdots & \ddots & \vdots \\ b_{m1}^i & \vdots & b_{mm}^i \end{bmatrix} \end{aligned} \tag{23}$$

Equations (22) and (23) can be expressed the output $\boldsymbol{y}_i$ *in* terms of past inputs/outputs as:

$$\begin{aligned} y_i(k) = b_{i1}^1 u_1(k-1) + \cdots + b_{ir}^1 u_r(k-1) + \cdots \\ + b_{i1}^{n_2} u_1(k-n_2) + \cdots + b_{ir}^{n_2} u_r(k \\ - n_2) \\ -a_{i1}^1 y_1(k-1) - \cdots - a_{im}^1 y_m(k-1) - \cdots \\ - a_{i1}^{n_1} y_1(k-n_1) - \cdots - a_{im}^{n_2} y_m(k \\ - n_1) \end{aligned} \tag{24}$$

It appears from the above equation that the DARMA model of the equation (18) can be expressed as [11]:

$$\boldsymbol{y}(k) = \boldsymbol{\theta}^T \phi(k-1); \ \ k \geq 0 \tag{25}$$

where $\boldsymbol{\theta}^T$'s transposed of $\boldsymbol{\theta}$, and $\boldsymbol{\theta}$ has dimension *(mn_1+rn_2) x m* that holds the parameters of $\boldsymbol{A}_i$ and $\mathbf{B}_i$ of the form:

$$\boldsymbol{\theta}^T = [-\boldsymbol{A}_1 \cdots -\boldsymbol{A}_n \boldsymbol{B}_0 \cdots \boldsymbol{B}_{n-1}] \tag{26}$$

and $\phi(k-1)$ is a vector of dimension *(mn_1+rn_2) x 1* that holds the values of past input/output

$$\phi(k-1) = \begin{bmatrix} \boldsymbol{y}(k-1) \\ \vdots \\ \boldsymbol{y}(k-n_2) \\ \boldsymbol{u}(k-1) \\ \vdots \\ \boldsymbol{u}(k-n_1) \end{bmatrix} \tag{27}$$

An state space representation can be obtained from (22) and (27) by selecting $\phi(k-1)$as the state space vector, as follows:

$$\begin{aligned} \phi(k) = E\phi(k-1) + Fu(k) \\ y(k) = M_e\phi(k-1) \end{aligned} \tag{28}$$

being

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$$E=\begin{bmatrix}-\boldsymbol{A}_1 & \cdots & -\boldsymbol{A}_{n_1} & -\boldsymbol{B}_1 & \cdots & \boldsymbol{B}_{n_2}\\ \boldsymbol{I} & 0 & 0 & \cdots & 0 & 0\\ 0 & \ddots & 0 & \cdots & 0 & 0\\ 0 & 0 & 0 & \cdots & 0 & 0\\ 0 & \cdots & 0 & \boldsymbol{I} & 0 & 0\\ 0 & \cdots & 0 & 0 & \ddots & 0\end{bmatrix} \quad (29)$$

and

$$F^T=[0 \quad \cdots \quad 0 \quad \boldsymbol{I} \quad \cdots \quad 0] \quad (30)$$

and

$$M_e=[-\boldsymbol{A}_1 \quad \cdots \quad -\boldsymbol{A}_{n_1} \quad \boldsymbol{B}_1 \quad \cdots \quad \boldsymbol{B}_{n_2}] \quad (31)$$

The PMSG has been considered as a system which makes possible to produce electricity from the mechanical energy obtained from the wind. The PMSG has been considered as a system which makes possible to produce electricity from the mechanical energy obtained from the wind. The PMSG has been considered as a system which makes possible to produce electricity from the mechanical energy obtained from the wind. The PMSG has been considered as a system which makes possible to produce electricity from the mechanical energy obtained from the wind.

5.2. Online Estimation Schemes

The estimated parameters $\hat{\boldsymbol{\theta}}^T(k)$ are calculated in terms of the previous matrix of the estimated parameters $\widehat{\boldsymbol{\theta}}^T(k-1)$ as follows

$$\hat{\boldsymbol{\theta}}(k)=\hat{\boldsymbol{\theta}}(k-1)+\boldsymbol{M}(k-1)\phi(k-1)e(k-1) \quad (32)$$

where $\widehat{\boldsymbol{\theta}}(k)$ is the matrix of parameters estimated in time k, $\boldsymbol{M}(k-1)$ denotes the algorithm gain (possibly a matrix), $\phi(k-1)$is a regression vector composed of past inputs/outputs, and $e(k-1)$ is the error of the form

$$e(k)=\boldsymbol{y}^T(k)-\hat{\boldsymbol{y}}^T(k) \quad (33)$$

where $\hat{\boldsymbol{y}}(k)=\hat{\boldsymbol{\theta}}^T(k-1)\phi(k-1)$is given by

$$\hat{\boldsymbol{y}}(k)=\hat{\boldsymbol{\theta}}^T(k-1)\phi(k-1) \quad (34)$$

5.3. Projection Algorithm

The projection algorithm raises an optimization problem where $\widehat{\boldsymbol{\theta}}(k)$ is being minimised with the $\widehat{\boldsymbol{\theta}}(k-1)$ and $\boldsymbol{y}(k)$ given, such that

$$\boldsymbol{J}=\frac{1}{2}\left\|\hat{\boldsymbol{\theta}}(k)-\hat{\boldsymbol{\theta}}(k-1)\right\|^2 \quad (35)$$

subject to

$$\boldsymbol{y}(k)=\phi^T(k-1)\hat{\boldsymbol{\theta}}(k) \quad (36)$$

The projection algorithm is given by

$$\begin{aligned} e(k)&=\boldsymbol{y}^T(k)-\phi^T(k-1)\hat{\boldsymbol{\theta}}(k)\\ \boldsymbol{M}(k)&=\frac{1}{\phi(k-1)^T\phi(k-1)}\\ \hat{\boldsymbol{\theta}}(k)&=\hat{\boldsymbol{\theta}}(k-1)+\boldsymbol{M}(k)\phi(k-1)e(k)\end{aligned} \quad (37)$$

Least Squares Algorithm

The least squares algorithm is given by

$$\begin{aligned}\boldsymbol{M}(k)&=\frac{P(k-1)}{1+\phi(k-1)^TP(k-1)\phi(k-1)}\\ \hat{\boldsymbol{\theta}}(k)&=\hat{\boldsymbol{\theta}}(k-1)+\boldsymbol{M}(k)\phi(k-1)e(k)\\ P(k)&=P(k-1)-\boldsymbol{M}(k)\phi(k-1)\phi(k-1)^TP(k-1)\end{aligned} \quad (38)$$

5.4. Discrete Linear Quadratic Regulator

The formulation of the DLQR problem in the discrete-time case is analogous to the continuous-time LQR problem. Consider the time-invariant linear system described in (28) where the vector $\phi(k-1)$ represents the variables to be regulated [11]. The DLQR problem is to determine a control sequence $\{u^*(k)\}, k\geq 0$, which minimizes the cost function

$$J(u)=\sum_{k=0}^{\infty}[\phi^T(k-1)Q\phi(k-1)+u^T(k)Ru(k)] \quad (39)$$

where the weighting matrices Q and R are real symmetric and positive definite.
Assume that $(E,F,Q^{1/2}M_e)$ is reachable and observable. Then the solution to the DLQR problem is given by the linear state feedback control law

$$u^*(k)=K^*\phi(k-1)=-[R+F^TP_c^*F]^{-1}F^TP_c^*E\phi(k-1) \quad (40)$$

where P_c^* is the unique, symmetric, and positive-definite solution of the (*discrete-time*) *algebraic Riccati equation*, given by

$$P_c=E^T[P_c-P_c[R+F^TP_c^*F]^{-1}F^TP_c]E+{M_e}^TQM_e \quad (41)$$

As in the continuous-time case, it can be shown that the solution P_c^* can be determined from the eigenvectors of the *Hamiltonian matrix*, which in this case is

$$H=\begin{bmatrix}E+FR^{-1}F^TE^{-T}{M_e}^TQM_e & -FR^{-1}F^TE^{-T}\\ E^{-T}{M_e}^TQM_e & E^{-T}\end{bmatrix} \quad (42)$$

The linear state feedback control law can be extended for reference tracking performance as follows

$$u(k)=-K\phi(k-1)+K_gr(k) \quad (43)$$

being $r(k)$ a reference vector and K_g a steady state matrix gain or reference gain defined by

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$$K_g = (M_e(I - E + FK)^{-1}F)^{\#} \qquad (44)$$

being $(M_e(I - E + FK)^{-1}F)^{\#}$ the pseudoinverse of $(M_e(I - E + FK)^{-1}F)$.

6. Results

The proposed model of PMSG is constructed with MATLAB/Simulink using the parameters of Tables 1, 2 and 3.

Table 1 Wind turbine parameters.

Ra	2,5 m
G	1
J_H	0,5042 kg.m^2
η	1

ρ	1,2259
B_m	0

Tabla 2 Load parameters.

R_L	80 Ω
L	0,08 H

Tabla 3 PMSG parameters.

R	3,3 Ω
L_s	0,04156 H
$Φ_m$	0,48 Wb
n_p	3

This section presents the simulated responses of the system with a variable wind speed from 5m/s to 12 m/s and a time varying load.
The open loop response of the wind turbine is shown in Figure 2.

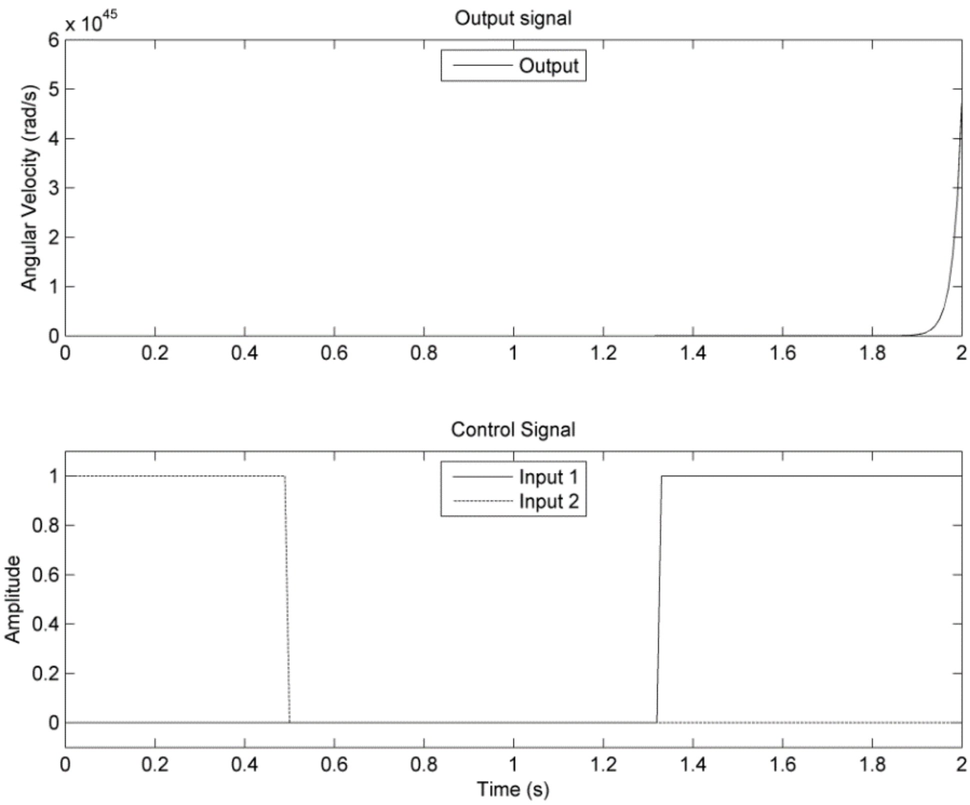

Figure 2 The system's response in open loop.

By applying the online identification scheme, a discrete linear model of the PMSG is obtained. Estimated model is represented in state space as shown in (45)

$$\phi(k) = \begin{bmatrix} 0{,}814 & 0{,}905 & 0{,}127 & 0{,}913 & 0{,}632 & 0{,}097 & 0{,}278 & 0{,}546 & 0{,}957 \\ 1{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1{,}000 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1{,}000 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1{,}000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1{,}000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1{,}000 & 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_1(k) \\ u_2(k) \end{bmatrix} \qquad (45)$$

$$y(k) = [0{,}814 \quad 0{,}905 \quad 0{,}127 \quad 0{,}913 \quad 0{,}632 \quad 0{,}097 \quad 0{,}278 \quad 0{,}546 \quad 0{,}957]\phi(k-1)$$

with

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$$y(k) = \begin{bmatrix} 0{,}7976 & 0{,}5495 & 0{,}5449 & 0{,}4239 & 0{,}4657 & 0{,}3544 & 0{,}5152 & 0{,}2776 & 0{,}2062 \\ 0{,}8779 & 0{,}4747 & 0{,}4902 & 0{,}4603 & 0{,}4686 & 0{,}3088 & 0{,}4560 & 0{,}2497 & 0{,}1855 \end{bmatrix} \quad (46)$$

and

$$K_g = \begin{bmatrix} 0{,}4547 \\ 0{,}4704 \end{bmatrix} \quad (47)$$

being

$$\phi(k-1) = \begin{bmatrix} y(k-1) \\ y(k-2) \\ y(k-3) \\ u_1(k-1) \\ u_2(k-1) \\ u_1(k-2) \\ u_2(k-2) \\ u_1(k-3) \\ u_2(k-3) \end{bmatrix} \quad (48)$$

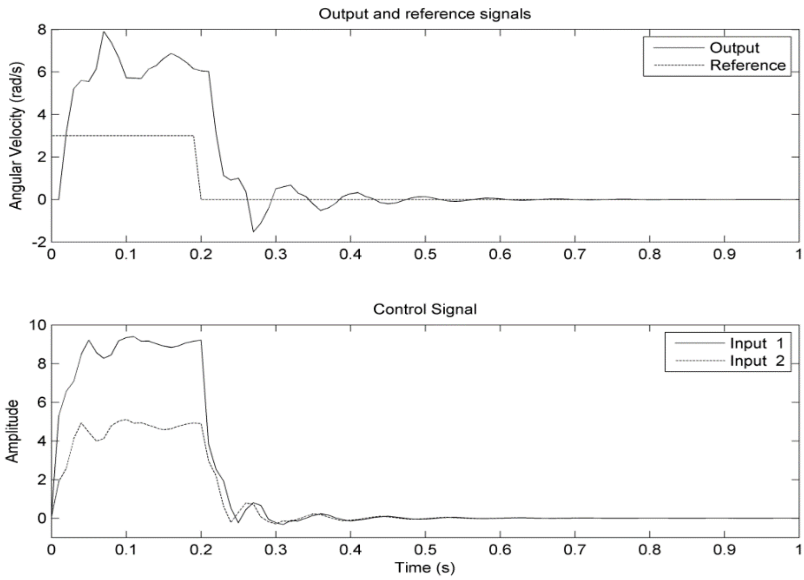

Figure 3 Output and control signal with the *DLQR control* and no reference gain.

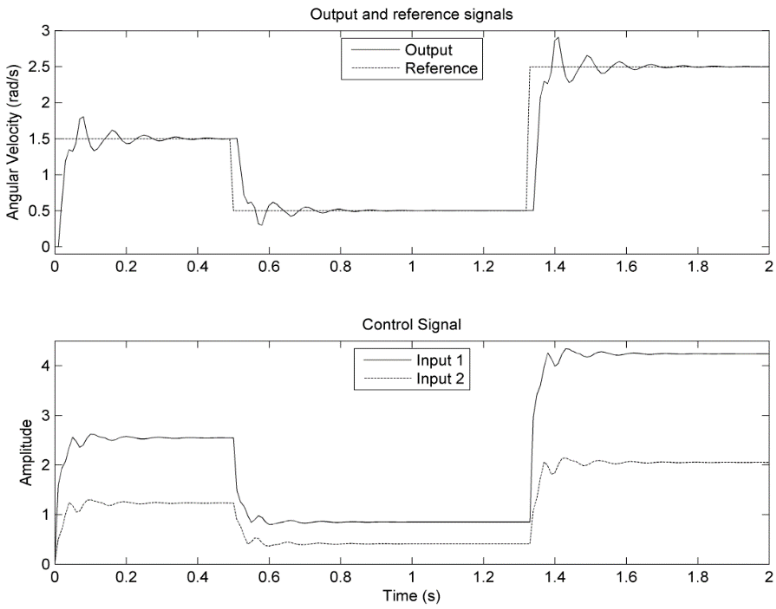

Figure 4 Output and control signals with the *DLQR control* and reference gain.

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Figure 3 shown the system's regulation with the *DLQR control*: K as feedback gain but without K_g as reference gain, the values are the same that is previously used. Output signal has a steady state time around the 0.3s after changing the reference value, an overshoot around the 6 rad/s and an oscillatory response before reaching the steady state.

The system's response using the *DLQR control* is shown in Figure 4 with K as feedback gain and K_g as reference gain, in equations (46) and (47), respectively. In Figure 4, the system has a steady state time around the 0.5 s, an overshoot around the 0.3rad/s and the output signals follows the references.

7. Conclusions

The identification methods of state variables with least squares and projection algorithms, where the observer of states is included, allows a better estimation the linear model in state space of a multivariable discrete system. With a adequate estimation of the system, control strategies can be used where the controller adapts to changes response to any disturbance reference, at each instant time.
The work developed shows that a satisfactory performance of control algorithms depends of the performance of identification algorithms. The steady state time and overshoot of output signal, can be changed depending of the performance of the control algorithms or non-following reference output signal (steady-state error).

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