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Stability by assigning structures by applying the multivariable subspace identification algorithm for a wind system with a DFIG

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ABSTRACT

In this paper, a controller for a doubly fed induction generator (DFIG) connected to a wind system is proposed. This control assigning its own structures as an optimal control method, the electric model in the DFIG state space is also shown, for which it is expected to estimate a linear model through the subspace technique and thus to design the controller. It will be possible to show that a structure assignment controller is undoubtedly a good option for the control of multivariable systems. The results of the output signals will be analyzed when applying the controller, assigning their own structures, which will allow us to observe that the response and disturbance times are below two tenths of a second.

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1. INTRODUCTION

The need to reduce emissions of greenhouse gases, which cause global warming and pollute the atmosphere, has led researchers to look for new non-polluting ways to generate energy, such as wind power. Within this branch of generation, one of the most widely used generators is the double-fed induction generator (DFIG), shown in Figure 1, which has the capacity to continue generating when disconnected from the main electrical grid. This alternative has grown in the last decades due to the technical advance that has allowed the decrease of the investment costs and the increase of the generation capacity per kWh. Although it must be borne in mind that the use of wind as a primary source in the generation of electrical energy can bring disadvantages, since the wind speed is variable every hour of the day or season of the year during the generation periods, this causes a limiting when connecting the turbine to the network where optimal performance in terms of efficiency is not achieved [1]-[4].

Because the power flux between the generator and the grid does not remain constant due to wind disturbances, which leads to variations in voltage and frequency, which are variables that must remain in fixed values imposed by the network to which it is connected. Therefore, in recent years we have been working with DFIGs, which can work at variable speeds avoiding the mechanical stress of the machine and allowing an increase in the energy captured; they also have a back-to-back converter that allows regulation of the voltage and frequency, the flow of reactive power to the network and keeps the voltage at the generator terminals constant. In comparison with the asynchronous generator in general, the DFIG has a more complex configuration [5]-[8].

Bearing in mind that the main disadvantage of wind turbines is the fluctuation of wind speed, a control system is required that makes their efficiency reach an optimum point of performance. The control systems ensure that the operation of the system is correct as long as it works under normal conditions or disturbances occur, and the control implemented must guarantee greater efficiency in terms of generating electrical energy by discarding the speed of the turbine and adapting the speed from the rotor to variations in wind speed in order to achieve a greater amount of energy generated. Currently, there are different control schemes such as the proportional integral (PI) controller, linear quadratic gaussian (LQG) controller, robust H-infinity controller, discrete linear quadratic regulator (DLQR) controller, and optimal control. One of the most used schemes in generation systems is the PI controller where algorithms are applied that optimize the generator performance, although it has the disadvantage of not receiving as much energy as possible from the wind.

In this paper, the optimal multivariable control of the DFIG is proposed, using its own structure assignment through the multivariable output error state space (MOESP) algorithm. The document is organized as: section two is about the control of multivariable systems and how to identify them from their inputs and outputs. Section three describes the model in the state space for the DFIG and finally section four shows the results obtained from the implementation of the controller by assigning its own structures.

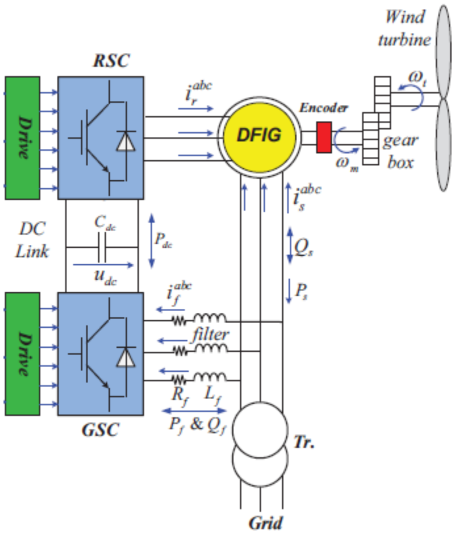

Figure 1. Wind generation system with a double-fed generator [9]

2. METHOD
2.1. Multivariable control

In this subsection of the document we will talk about the characteristics of a multivariable system control, and how they can be identified from their inputs and outputs. Figure 2 defines the general structure of a controller, where the control law is defined taking into account the accumulated one for the error of the control signal [10]. The error of the control signal is defined as:

$$e(k) = r(k) - y(k) \tag{1}$$

With which the extended system will be defined by:

$$\begin{bmatrix} x(k+1) \\ e(k+1) \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & I \end{bmatrix} \begin{bmatrix} x(k) \\ e(k) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(k) + \begin{bmatrix} 0 \\ I \end{bmatrix} r(k) \tag{2}$$

$$y(k) = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x(k) \\ e(k) \end{bmatrix} \tag{3}$$

Where the control signal is calculated as:

$$u(k) = -\begin{bmatrix} K & K_i \end{bmatrix} \begin{bmatrix} x(k) \\ e(k) \end{bmatrix} \tag{4}$$

Here, K and K_i are constant matrices, which vary according to the control algorithm applied to the system studied using from the (1) to the (4).

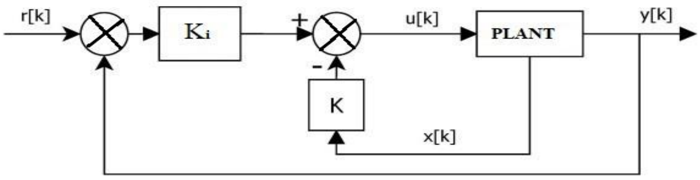

Figure 2. Block diagram of studied structure [10]

2.2. Assignment of structures

In recent years the assignment of structures has been applied in different types of multivariable control systems, as it is a robust control technique and a high performance. Said technique can be applied using state feedback or feedback of the output by means of a gain. The method of allocation of structures basically steps:

– Choice of a set (or sets) of possible eigenvalues (or poles) in closed-loop.
– Calculate the subspaces of eigenvectors for the generation of eigenvectors in closed-loop.
– Select some specific vectors of the subspaces according to design techniques.
– Calculate the control law for the election of the own structure.

The multivariable output error state space (MOESP) method allows determining a well-conditioned solution for the problem of assigning eigenvalues by state feedback. The solution obtained is such that the sensitivity of the eigenvalues assigned to the perturbations in the system and the gain matrices are minimized [11]. The objective function for optimizing the sensitivity of the eigenvalue in general can be expressed by means of the (5).

$$J_o = \eta(R) = \frac{\sigma_1(R)}{\sigma_n(R)} \quad (5)$$

Where σ_1 is the largest singular value of the right eigenvector array of R and σ_n is the smallest singular value of the right eigenvector array of R. The formulation of the problem of the technique of allocation of own structures, is based on finding the law of control by feedback of states [12] (6) to (12).

$$u(k) = -Kx(k) \quad (6)$$

Given the eigenvalues $\Lambda = diag(\lambda_1, \lambda_2, \ldots, \lambda_n)$ and the array of eigenvectors R, there is a K such that:

$$(A + BK)R = R\Lambda \quad (7)$$

Just if:

$$U_1^T(AR - R\Lambda) = 0 \quad (8)$$

Where:

$$B = [U_0 \quad U_1][Z^T \quad 0]^T \quad (9)$$

With $U = [U_0 \quad U_1]$ orthogonal and Z non-singular. Therefore, the profit matrix K is explicitly defined by:

$$K = Z^{-1}U_0^T(R\Lambda R^{-1} - A) \quad (10)$$

The law of control by feedback states can be extended by a reference as (11).

$$u(k) = -Kx(k) + K_i e(k) \quad (11)$$

Where K_i is the steady-state gain or reference gain defined by:

$$K_i = C(I - A + BK)^{-1}B \quad (12)$$

Where $C(I - A + BK)^{-1}B$ the matrix pseudoinverse.

2.3. Identification by subspaces

The linear model of the system can be obtained by applying a subspace approach such as the orthogonal decomposition (ORT) method or the MOESP method of the system around an operating point [13] (13) to (18).

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) + Du(k) \end{aligned} \tag{13}$$

Where the input-output data is assumed to be $\{u(t), y(t), t = 0,1,\dots,N+2k-2\}$ and are given with N large enough and $k > n$. Based on the input-output data [14], the input matrix passed from the Hankel blocks and and future entry are respectively defined as:

$$U_p = \begin{bmatrix} u(0) & u(1) & \cdots & u(N-1) \\ u(1) & u(2) & \cdots & u(N) \\ \vdots & \vdots & \ddots & \vdots \\ u(k-1) & u(k) & \cdots & u(N+k-2) \end{bmatrix} \tag{14}$$

$$U_f = \begin{bmatrix} u(k) & u(k+1) & \cdots & u(k+N-1) \\ u(k+1) & u(k+2) & \cdots & u(k+N) \\ \vdots & \vdots & \ddots & \vdots \\ u(2k-1) & u(2k) & \cdots & u(N+2k-2) \end{bmatrix} \tag{15}$$

In the same way, the past and future of the exit is defined y_p, y_f. The extended observability matrix of order i, where $i = k-1$, the inferior triangular Toeplitz matrix, and the ratio of the decomposition LQ are defined respectively as:

$$\Gamma_i = [C^T \quad (CA)^T \quad \dots \quad (CA^{i-1})^T]^T \tag{16}$$

$$H_i = \begin{bmatrix} D & 0 & \cdots & 0 \\ CB & D & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{i-2}B & CA^{i-3}B & \cdots & D \end{bmatrix} \tag{17}$$

$$\begin{bmatrix} U_f \\ U_p \\ y_p \\ y_f \end{bmatrix} = \begin{bmatrix} L_{11} & 0 & 0 & 0 \\ L_{21} & L_{22} & 0 & 0 \\ L_{31} & L_{32} & L_{33} & 0 \\ L_{41} & L_{42} & L_{43} & L_{44} \end{bmatrix} \begin{bmatrix} Q_1^T \\ Q_2^T \\ Q_3^T \\ Q_4^T \end{bmatrix} \tag{18}$$

Now, we show the MOESP algorithm, estimation of a multivariable system: first, to build data matrices U_p, U_y, y_p, y_f. Second, to perform factoring LQ from the (18). Third, to perform singular value decomposition (SVD) to the work matrix $G = [L_{42} L_{43}]$, with $G = [\hat{U} \quad \overline{U}] \begin{bmatrix} \hat{S} & 0 \\ 0 & \overline{S} \end{bmatrix} \begin{bmatrix} \hat{V} \\ \overline{V} \end{bmatrix} \cong \hat{U}\hat{S}\hat{V}^T$. Forth, to calculate the estimates of A and C from (16) $\Gamma_i = \hat{U}\hat{S}^{1/2}$. Finally, fifth, to calculate the estimates of B and D from (17), $\overline{U}^T L_{41} L_{11}^{-1} = \overline{U}^T H_i$.

2.4. Generator model

The DFIG doubly fed induction generator is the one that is most commonly installed in many wind farms. In comparison with the asynchronous generator in general, the DFIG has a more complex configuration [15]. The DFIG is based on a principle of the induction generator and incorporates two groups of similar multi-phase coils of power that have independent means of excitation. The DFIG transforms the power of the input turbine into electrical energy. The power produced in the stator is always positive [10]. The Figure 3 shows the equivalent circuit of a DFIG in the reference frame that rotates at the synchronous angular velocity ω_1 [16]-[19]. From Figure 3 we have the stator and rotor flows are given by (19) to (22).

$$\begin{cases} \Psi_s = L_s I_s + L_m I_r \\ \Psi_r = L_m I_s + L_r I_r \end{cases} \tag{19}$$

Where L_s, L_r, L_m, are the self-inductances of the stator, rotor and mutual respectively. The stator and rotor voltages V_s and V_r are expressed as:

$$\begin{cases} V_s = R_s I_s + \frac{d\Psi_s}{dt} + j\omega_1 \Psi_s \\ V_r = R_r I_r + \frac{dr}{dt} + j(\omega_1 - \omega_r)\Psi_r \end{cases} \quad (20)$$

Being I_s and I_r the stator and rotor currents, R_s and $R_r$are the resistances of the windings, ω_r is the angular velocity of the rotor and $\omega_r = \omega_1 - \omega_s$, the angular velocity of glid [19]-[21]. The DIFG uses the stator voltage orientation (SVO) scheme as described in the reference [22]-[25], which allows rewriting the voltage (21) in the rotor in the synchronous reference frame dq as:

$$\begin{cases} V_{rd} = V'_{rd} + \frac{L_m}{L_s}\left(V_s - \frac{R_s}{L_s}\Psi_{sd} + \omega_r \Psi_{sq}\right) \\ V_{rq} = V'_{rq} - \frac{L_m}{L_s}\left(\frac{R_s}{L_s}\Psi_{sq} + \omega_r \Psi_{sd}\right) \end{cases} \quad (21)$$

The system representing the state space is presented as:

$$\begin{aligned} \frac{dI_{rd}}{dt} &= \frac{1}{\sigma L_r}\left(V'_{rd} - R'_r I_{rd} + \omega_s \sigma L_r L_{rq}\right) \\ \frac{dI_{rq}}{dt} &= \frac{1}{\sigma L_r}\left(V'_{rq} - R'_r I_{rq} - \omega_s \sigma L_r L_{rd}\right) \end{aligned} \quad (22)$$

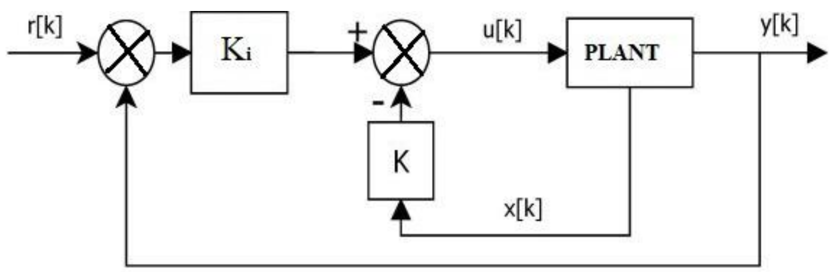

Figure 3. Equivalent circuit of the DFIG in the frame of reference with speed [19]

3. RESULTS AND DISCUSSIONS

For the model presented in the previous section, the outputs of the system are the currents in the rotor on the axis d and on the axis q, that is, a system of two inputs and one output (23) and (24). The Figure 4 shows the behavior of the open-loop outputs before the inputs presented in the Figure 5.

$$y = \begin{bmatrix} 1 & 1 \end{bmatrix} \begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} \quad (23)$$

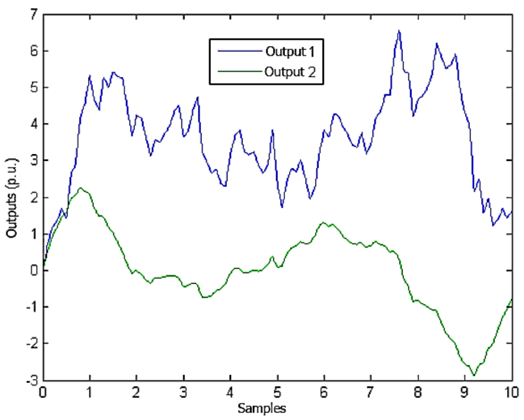

Figure 4. System response in open loop (source: author)

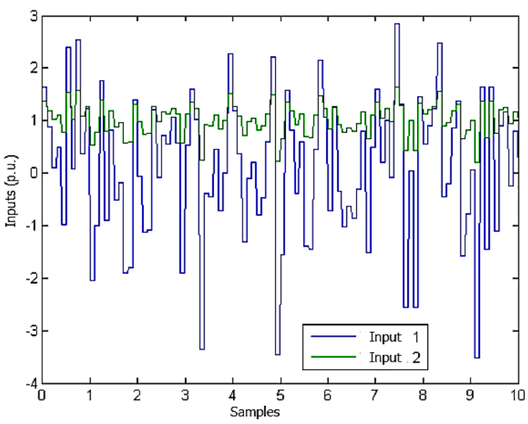

Figure 5. System inputs (source: author)

Knowing the inputs and outputs of the system, the identification of the same is applied through the algorithm proposed in section 2, with which the following system is obtained.

$$A = \begin{bmatrix} 0.9992 & 0.0112 \\ -0.0129 & 0.9992 \end{bmatrix}; \tag{24}$$

$$B = \begin{bmatrix} -0.0566 & 0.0620 \\ -0.1034 & -0.0494 \end{bmatrix}; \tag{25}$$

$$C = \begin{bmatrix} -0.2080 & -0.2871 \\ 0.3077 & -0.1940 \end{bmatrix}; \tag{26}$$

$$D = \begin{bmatrix} 0.0467 & -0.2088 \\ 0.0014 & -0.0063 \end{bmatrix}; \tag{27}$$

With the previous estimated model, a controller is designed by assigning its own structures for the multivariable system. The following figures show the responses of the I_{rd} and I_{rq} streams when applying the driver to the system (see Figure 6 and Figure 7). Now, when analyzing the results of the output signals when applying the controller by assigning own structures, it can be concluded that the models respond in an approximate time of 0.2 s to reach the reference and a disturbance time 0.2 s.

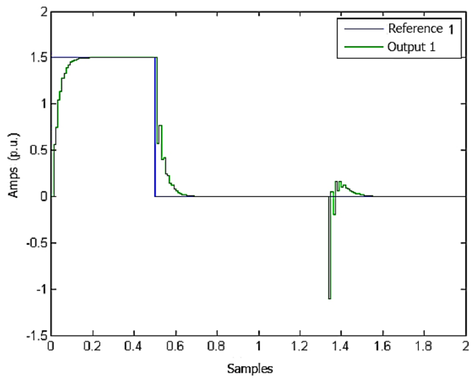

Figure 6. Current response I_{rd} (source: author)

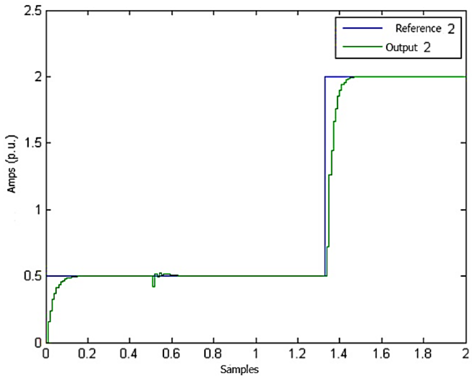

Figure 7. Current response I_{rq} (source: author)

4. CONCLUSION

This work proposed a controller for allocation of structures for the doubly fed induction generator DFIG, based on the identification of the multivariable system through a MOESP subspace method, for this estimation it is required that the input/output data of the plant be as variable as possible and thus know the behavior of the plant before any internal or external disturbance, to be adopted by the identified system.

Once the system was identified, the controller was designed with which the results were obtained that allowed us to observe how the I_{rd} and I_{rq} outputs reach the reference levels in very short times and with very low oscillations. Once the system was identified, the controller was designed with which the results were obtained that allowed us to observe how the I_{rd} and I_{rq} outputs reach the reference levels in very short times and with very low oscillations. Therefore, it is concluded that the controller by assignment of structures is a good option for the control of multivariable systems. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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