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Modeling, simulation and control of a doubly-fed induction machine

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The Hamiltonian model and control of a doubly-fed induction machine is discussed. The geometric properties of the Hamiltonian formalism allow us to develop control algorithms which assure stability and good performance. Experimental results in good accordance with the control goals are presented.

1 The doubly-fed induction machine

Doubly-fed induction machines (DFIMs) have been proposed in the literature, among other applications, for high-performance storage systems, wind turbine generators or hybrid engines (see [1] for and extended literature survey and discussion). The attractiveness of the DFIM stems primarily from its ability to handle large-speed variations around the synchronous speed. Furthermore, this induction machine require an small power electronic equipment for control purposes (instead of the classical induction machines). The DFIM is a three-phase induction machine whit both stator and rotor windings accessible, and the rotor side is used for control.

A DFIM can be used as a generator or motor. In this work we present a controller for a motor mode, and the goals are to regulate the mechanical speed while keeping the power factor close to one.

Under the assumption that the machine is symmetric (all windings are equal), the cross inductances are smooth, sinusoidal functions of θ (rotor position), and the three-phase system is balanced, this mathematical transformation can be used to decouple variables (reduce the system dimension) and to facilitate the solution of equations with time-varying coefficients. Then, the original θ-depending model is simplified, and also, for control purposes, the *dq*, or Park, transformation [2] allows to describe a tracking problem as a regulation one, which can be solved with IDA-PBC (Interconnection and Damping Assignment–Passivity-based Control) techniques [3].

2 Port-Hamiltonian model of a DFIM

As discussed in [4] (and references therein) a large class of physical systems of interest in control applications can be modelled in the general form of Port-controlled Hamiltonian systems (PCHS). An explicit PCHS has the form

$$\left\{ \begin{array}{lcl} \dot{x} &=& (J(x) - R(x))\partial_x H(x) + g(x)u \\ y &=& g^T(x)(\partial_x H(x))^T \end{array} \right. \tag{1}$$

where $x \in \mathbb{R}^n$ is the vector state, or Hamiltonian variables, $y \in \mathbb{R}^m$ are the port variables, $H(x) : \mathbb{R}^n \mapsto \mathbb{R}$ is the Hamiltonian function (or energy function), $J(x) \in \mathbb{R}^{n\times n}$ is the interconnection matrix ($J(x) = -J(x)^T$), $R(x) \in \mathbb{R}^{n\times n}$ is the dissipation matrix ($R(x) = R^T \geq 0$) and $g(x) \in \mathbb{R}^{n\times m}$ is the external port connection matrix.

The *dq* model of a DFIM can be written as a PCHS (1), with the Hamiltonian variables $x^T = (\lambda_s^T, \lambda_r^T, J_m\omega) \in \mathbb{R}^5$, where λ_s, λ_r are the stator and rotor fluxes, ω is the mechanical speed, J_m is the inertia of the rotating parts, and

$$J(x) = \begin{bmatrix} -\omega_s L_s J_2 & -\omega_s L_{sr} J_2 & O_{2\times 1} \\ -\omega_s L_{sr} J_2 & -(\omega_s - \omega) L_r J_2 & L_{sr} J_2 i_s \\ O_{1\times 2} & L_{sr} i_s^T J_2 & 0 \end{bmatrix}, R(x) = \begin{bmatrix} R_s I_2 & O_{2\times 2} & O_{2\times 1} \\ O_{2\times 2} & R_r I_2 & O_{2\times 1} \\ O_{1\times 2} & O_{1\times 2} & B_r \end{bmatrix}, J_2 = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}, \tag{2}$$

where L are inductances and R are resistances (lower indices s and r refer to stator and rotor, respectively), B_r is the mechanical damping, $i_s, i_r \in \mathbb{R}^2$ are the stator and rotor currents and I_2 a 2×2 identity matrix. The port variables are $u^T = [v_s^T, v_r^T, \tau_L]$ and the interconnection matrix g is a 5×5 identity matrix. Furthermore

$$\begin{bmatrix} \lambda_s \\ \lambda_r \end{bmatrix} = \mathcal{L} \begin{bmatrix} i_s \\ i_r \end{bmatrix} = \begin{bmatrix} L_s I_2 & L_{sr} I_2 \\ L_{sr} I_2 & L_r I_2 \end{bmatrix} \begin{bmatrix} i_s \\ i_r \end{bmatrix}, \quad H = \frac{1}{2}[\lambda_s^T, \lambda_r^T]\mathcal{L} \begin{bmatrix} \lambda_s \\ \lambda_r \end{bmatrix} + \frac{1}{2} J_m \omega^2. \tag{3}$$

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3 Port-Hamiltonian control of a DFIM

Most DFIM controllers proposed in the literature are based on vector control and decoupling [5]. Vector control contains an inner-loop which requires the reconstruction of the magnetic flux variables (which are not directly measurable).

Passivity-based Control (PBC) [6] uses the fact that passive nonlinear systems are described by an storage function (which is a proper Lyapunov function). The control design main goal is then to reshape the original energy function by means of the controller. Based on PBC, the IDA-PBC technique, which uses the passive properties of port-Hamiltonian Systems, was presented in [3].

In [7] it is shown that the standard procedure using IDA-PBC can be applied for controlling the DFIM, treating the mechanical system as a cascaded subsystem. Using the SIDA-PBC (Simultaneous IDA-PBC) approach [8], it is possible to shape the energy function of the complete system, resulting in a controller with improved power flow regulation performance. Further improvements of the basic IDA-PBC [1] allow to design a controller with reduced parameter dependence [9]. The new controller is more robust than the previous ones based on basic (S)IDA-PBC. The main advantages with respect to classical vector control are:

- The stator flux is not required. This dispenses with the estimation of a critical variable which will be used to construct the rotating reference.
- The rotating reference is referred to the stator voltage, which, as discussed in the previous item, is easier to obtain than the stator flux oriented reference. The computations depend only on a measured variables.
- The reference inputs of the new controller are directly the stator currents (which are the outputs of the electrical subsystem), whereas the references of the inner-loop of vector control are rotor currents.
- No assumption is made on the smallness of rotor resistances.

Experimental results [9] are presented in Fig. 1. In this case the mechanical speed (Fig. 1a) is regulated with a good power factor (Fig. 1b), *i.e.* voltage and current are nearly in phase.

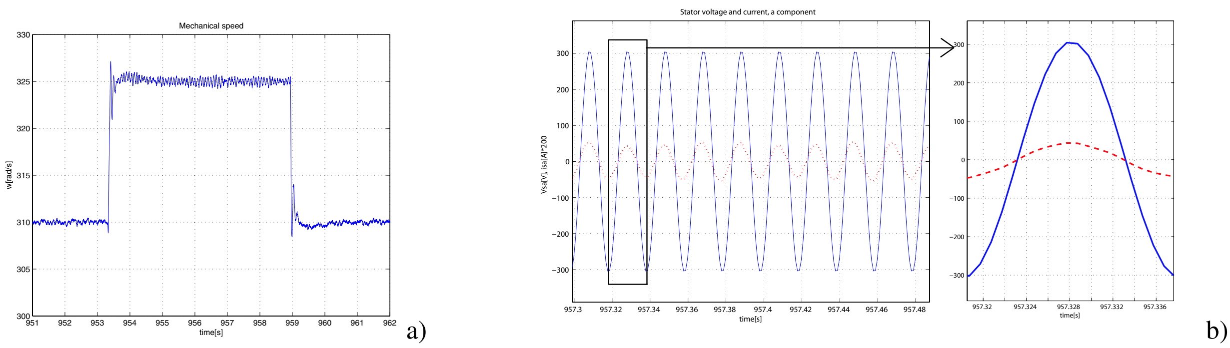

Fig. 1 Experimental results. a) Mechanical speed, ω, b) stator voltage an current (V_{sa}, i_{sa}).

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