Electrical Power and Energy Systems 45 (2013) 303–312

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

On the passivity-based power control of a doubly-fed induction machine

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ARTICLE INFO

Article history:
Received 5 September 2011
Received in revised form 24 August 2012
Accepted 29 August 2012
Available online 23 October 2012

Keywords:
Double-fed induction machines
Passivity-based control
Power regulation

ABSTRACT

In this paper the stator-side power regulation control problem of DFIM is approached. It is shown how a passivity-based controller can deal with this problem establishing a viable solution from both a dynamic performance perspective and a practical implementation point of view. The evaluation of the presented scheme is carried out by considering typical operation conditions, namely: active power generation with demanded or delivered reactive power. Special interest is given to the rigorous establishment of the stability properties of the closed-loop system, which allows for achieving remarkable dynamic responses, in terms of convergence rates as well as the region of attraction of the equilibrium point defined by a given operation regime. From a practical viewpoint, the usefulness of the scheme is concluded by realizing that the requirements imposed concerning the structural features of both the generator by itself and the power converter required for its operation, can be fulfilled by commercially available off-the-shelf devices.

1. Introduction

Doubly-fed induction machines (DFIMs) have become a fundamental element in several applications related with efficient methods for electric energy generation. This fact is due, on the one hand, to the high performance that can be achieved with this kind of devices under variable-speed operation and, on the other hand, to the possibility for feeding directly the rotor windings using high efficient power converters, which makes feasible to carry out the energy conversion process using only a small fraction of the energy managed by the whole power system [1–3].

Motivated by these remarkable features, DFIM has been deeply studied and several useful properties are currently well-known, for example, that if the model is represented in a line-voltage vector-oriented reference frame, then the controller design can be carried out in a simpler and more robust way, since the stator active and reactive power can be controlled in a decoupled way while the coordinate transformation for representing the model in the aforementioned reference frame is parameter-independent [4].

Starting with the pioneering work of [1], currently several controllers have been proposed in the literature, specially in applications related with wind generation, e.g. [5,6]. Unfortunately, in most of these contributions both the design and/or the performance analysis rely on the application of classical linear control techniques [8,9], simplifying model assumptions (either considering linearized models [7], negligible some of the machine parameters [10] or using reduced order models [11]) or by implementing non-robust open-loop integration methods for estimation of unmeasurable variables (e.g. stator fluxes [12]), while (to the best of the authors' knowledge) only a few references can be found, where a rigorous complete stability analysis is presented, being the results presented in [13,14] some illustrative examples.

The purpose of this paper is to contribute to the proposition of control schemes for DFIM that can deal with the stator-side power regulation control problem with rigorously established stability properties. The motivation for contributing in this way to the solution of this problem lies in the conviction that better structured control schemes leads to the achievement of higher performances. To this aim, in this paper it is shown that the controller presented by the authors in [15], where it was considered the case of having an isolated load, can be directly implemented to solve the power control problem, in the sense that some constant reference for the stator-side active and reactive powers can be reached asymptotically. This objective is achieved by identifying, for some given power reference, the corresponding values for stator and rotor currents and mechanical speed that must be achieved and showing that the considered control scheme indeed states a stabilization

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[1] On sabbatical leave at LSS-SUPELEC, France, supported by SUPELEC, DGAPA-UNAM (IN111211), II-FI-UNAM (Grant 1111) and Université Paris-Sud XI.

[2] Arnau Dòria-Cerezo was partially supported by the Spanish government research project DPI2010-15110.

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http://dx.doi.org/10.1016/j.ijepes.2012.08.067

mechanism for this operation conditions, provided the mechanical torque delivered to the generator is constant.

The usefulness of the controller scheme is evaluated assuming the more typical operation conditions for the DFIM, i.e. active power is always fed into the grid (for different values of stator power factor) while it is allowed both to deliver or demand reactive power to/from the grid. This different scenarios are considered by letting the constant mechanical torque to take different values. The achieved stability and performance properties of the closed-loop system are illustrated, first, under an stringent scenario, where the generator is at standstill at the beginning of the experiments, and, second, under a more practical situation, where the operation departs from non-zero initial conditions. The attractiveness of the control scheme is concluded from two different perspectives, namely: From the dynamic point of view, due to the stability properties and performance exhibited by the closed-loop system, and from a practical viewpoint, since the magnitude of all the system variables correspond to commercially available off-the-shelf experimental setups (including both the generator and the power converter).

The rest of the paper is organized as follows: In Section 2, the considered model for the DFIM is presented, together with the control problem formulation and its solvability analysis. The proposed controller is developed in Section 3 while its evaluation is carried out in Section 4. Section 5 is devoted to state some concluding remarks.

2. Problem formulation

In this section the considered model for the DFIM is presented to later on state the approached control problem and the conditions under which it is solvable.

2.1. DFIM model

Under the assumption of linear magnetic circuits and balanced operating conditions, the equivalent two-phase model of the symmetrical DFIM, represented in a rotating *dq* reference frame fixed to the stator voltage vector, is given by [4]

$$\frac{di_s}{dt} = -\omega_s \mathbf{J} i_s - \omega\beta\mathbf{J}\lambda_r - \gamma i_s + \alpha\beta\lambda_r + \frac{\beta L_r}{L_{sr}} u_s - \beta u_r \tag{1}$$

$$\dot{\lambda}_r = -(\omega_s - \omega)\mathbf{J}\lambda_r + \alpha L_{sr} i_s - \alpha\lambda_r + u_r \tag{2}$$

$$J\dot{\omega} = \frac{L_{sr}}{L_r} i_s^T \mathbf{J}\lambda_r - B\omega + T_m \tag{3}$$

where ω_s is the rotation speed for the reference frame, ω is the rotor speed, $i_s = [i_{s1}, i_{s2}]^T$ are the stator currents, $\lambda_r = [\lambda_{r1}, \lambda_{r2}]^T$ are the rotor fluxes, u_s and u_r are the stator and rotor voltages, respectively, while the all positive parameters are given by

$$\alpha = \frac{R_r}{L_r}; \quad \beta = \frac{L_{sr}}{\mu}; \quad \gamma = \frac{1}{\mu}\left(\frac{R_s L_r^2 + R_r L_{sr}^2}{L_r}\right)$$

with $\mu = L_s L_r - L_{sr}^2$ and

$$\mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} = -\mathbf{J}^T$$

Here L_s, L_r are stator and rotor proper inductances, L_{sr} is the mutual inductance, R_s, R_r are the winding resistances, J is the inertia coefficient, B is the damping coefficient and T_m is the applied mechanical torque.

Considering the flux vector $\lambda = \mathcal{L}_e i$ with $\lambda = \left[\lambda_s^T, \lambda_r^T\right]^T$ and $i = \left[i_s^T, i_r^T\right]^T$, where λ_s are the stator fluxes and i_r the rotor currents, while

$$\mathcal{L}_e = \begin{bmatrix} L_s\mathbf{I}_2 & L_{sr}\mathbf{I}_2 \\ L_{sr}\mathbf{I}_2 & L_r\mathbf{I}_2 \end{bmatrix}; \quad \mathbf{I}_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{4}$$

model (1)–(3) can be equivalently written as

$$\dot{\lambda}_s = -\omega_s L_s \mathbf{J} i_s - \omega_s L_{sr} \mathbf{J} i_r - R_s i_s + u_s \tag{5}$$

$$\dot{\lambda}_r = -(\omega_s - \omega) L_{sr} \mathbf{J} i_s - (\omega_s - \omega) L_r \mathbf{J} i_r - R_r i_r + u_r \tag{6}$$

$$J\dot{\omega} = L_{sr} i_s^T \mathbf{J} i_r - B\omega + T_m \tag{7}$$

Remark 1. Under generator operation of the DFIM, T_m is the torque delivered to the machine by a controlled primary mover while $T_g = L_{sr} i_s^T \mathbf{J} i_r$ is torque produced by the machine itself. In this paper it is considered that T_m is constant, assumption that is not restrictive since usually the primary mover is equipped with a speed controller [16].

Remark 2. From a controller design perspective, one advantage exhibited by the DFIM is that the complete state vector is measurable, i.e. mechanical speed and both stator and rotor currents can be used to structure of the control scheme.

2.2. Power control problem

From the generated power viewpoint, model (5)–(7) exhibits the following structure if it is assumed that the stator terminals are connected to an infinite bus with voltage magnitude U and frequency determined by ω_s. Active ($\mathcal{P}$) and reactive ($\mathcal{Q}$) power at the stator side are given by

$$\mathcal{P}_{ab} = I_s^T V_s; \quad \mathcal{Q}_{ab} = -I_s^T \mathbf{J} V_s$$

where I_s and V_s are the vectors of stator currents and voltages, respectively, in the natural *ab* reference frame for the induction machine.[3] In the *dq* reference frame considered for representing the machine model, these expressions take the form

$$\mathcal{P} = U i_{s1}; \quad \mathcal{Q} = -U i_{s2} \tag{8}$$

which clearly exhibit the advantage of the representation, since control of the active and reactive power can be carried out by controlling each of the components of the stator current vector i_s.

Taking into account the information presented above, the control problem solved in this paper can be stated as.

Consider the DFIM model given by (5)–(7). Assume that

- **A.1** The mechanical speed and both stator and rotor currents are available for measurement.
- **A.2** The torque delivered by the prime mover is constant and known.
- **A.3** The model parameters are known.
- **A.4** Stator voltages have fixed frequency and amplitude, i.e. stator windings are directly connected to the line grid.

Under these conditions, design a control law for the rotor voltages $u_r = u_r(i_s, i_r, \omega)$ such that

$$\lim_{t\to\infty} \mathcal{P} = \mathcal{P}_{\star}; \quad \lim_{t\to\infty} \mathcal{Q} = \mathcal{Q}_{\star}$$

with the desired power defined by $\mathcal{P}_{\star}$, $\mathcal{Q}_{\star}$, guaranteeing internal stability.

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[3] In the *ab* reference frame the stator variables are represented in a fixed reference frame while the rotor variables are expressed with respect to a reference frame that rotates at an angular speed given by ω [4].