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Power Flow Control of a Doubly-Fed Induction Machine Coupled to a Flywheel*

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We consider a doubly-fed induction machine – controlled through the rotor voltage and connected to a variable local load – that acts as an energy-switching device between a local prime mover (a flywheel) and the electrical power network. The control objective is to optimally regulate the power flow, and this is achieved by commuting between different steady-state regimes. We first show that the zero dynamics of the system is only marginally stable; thus, complicating its control via feedback linearization. Instead, we apply the energy-based Interconnection and Damping Assignment Passivity-Based Control technique that does not require stable invertibility. It is shown that the partial differential equation that appears in this method can be circumvented by fixing the desired closed-loop total energy and adding new terms to the interconnection structure. Furthermore, to obtain a globally defined control law we introduce a state-dependent damping term that has the nice interpretation of effectively decoupling the electrical and mechanical parts of the system. This results in a globally convergent controller parameterized by two degrees of freedom, which can be used to implement the power management policy. The controller is simulated and shown to work satisfactorily for various realistic load changes.

Keywords: Doubly-Fed Induction Machine; Passivity-based Control; Port-Hamiltonian Models; Power Flow Control

1. Introduction

Doubly-fed induction machines (DFIMs) have been proposed in the literature, among other applications, for high-performance storage systems [2], wind-turbine generators [11,13] or hybrid engines [3]. The attractiveness of the DFIM stems primarily from its ability to handle large-speed variations around the synchronous speed (see Ref. [15] for an extended literature survey and discussion). In this paper we are interested in the application of DFIM as part of an autonomous energy-switching system that regulates the energy flow between a local prime mover (a flywheel) and the electrical power network, in order to satisfy the demand of a time-varying electrical load.

Most DFIM controllers proposed in the literature are based on vector-control and decoupling [8]. Along these lines, an output feedback algorithm for power control with rigorous stability and robustness results is presented in Ref. [15]. In this paper we propose an

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alternative viewpoint and use the energy-based principles of passivity and control as interconnection [4,7,10,16]. More specifically, we prove that the Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC) technique proposed in Ref. [10] can be easily applied to regulate the dynamic operation of this bidirectional power flow system.

The paper is organized as follows. In Section 2 we introduce the architecture of the system to be controlled and derive its model. Since IDA-PBC concerns the stabilization of equilibrium points, we use the well-known Blondel–Park synchronous dq-coordinates[1] to write the equations in the required form. Then, to render more transparent the application of IDA-PBC, we give the Port-Controlled Hamiltonian (PCH) version of the model. Section 3 discusses the zero dynamics of interest for the kind of task we are trying to solve and show it to be only marginally stable – hampering the application of control schemes relying on stable invertibility, such as feedback linearization or the Standard PBC reported previously [9]. The power management scheme consists of the assignment of suitable fixed points and is introduced in Section 4. The main result of the paper, presented in Section 5, is the proof that IDA-PBC renders each of the desired equilibria globally stable. We start with the solution of the partial differential equation (PDE) that arises in IDA-PBC by direct assignment of the desired energy function and modification of the interconnection structure. Unfortunately, the resulting control law contains a singularity; hence, it is not globally defined. To remove this singularity we introduce a state-dependent damping that, in the spirit of the nested-loop PBC configuration of Chapter 8 in Ref. [9], has the nice interpretation of effectively decoupling the electrical and mechanical parts of the system and Section 6 presents the results of several simulations. Conclusions are stated in Section 7.

Notation. Throughout the paper we use standard notation of electromechanical systems, with λ, v, i, τ, θ, ω denoting flux, voltage, current, torque, angular position and velocity, respectively; while R, L, J_m, B are used for resistance, inductance, inertia and friction parameters, respectively. Self-explanatory sub-indices are introduced also for the signals and parameters of the different subsystems. Finally, to underscore the port interconnection structure of the overall system we usually present the variables in power conjugated couples, i.e. port variables whose product has units of power.

[1]In these coordinates the natural steady-state orbits are transformed into fixed points.

2. The System and its Mathematical Model

Figure 1 shows a DFIM, controlled through the rotor windings port (v_r, i_r), coupled with an energy-storing flywheel with port variables (τ_e, ω), an electrical network modelled by an ideal AC voltage source with port variables (v_n, i_n), and a generic electrical load represented by its impedance Z_l. The main objective of the system is to supply the required power to the load with a high network power factor. Depending on the load demands, the DFIM acts as an energy-switching device between the flywheel and the electrical power network. The control problem is to optimally regulate the power flow. We will show below that this is achieved by commuting between different steady-state regimes.

Network equations are given by Kirchhoff laws

$$i_l = i_n - i_s, \quad v_n = v_s. \tag{1}$$

Figure 2 shows a scheme of a doubly-fed, three-phase induction machine. It contains six energy storage elements with their associated dissipations and six

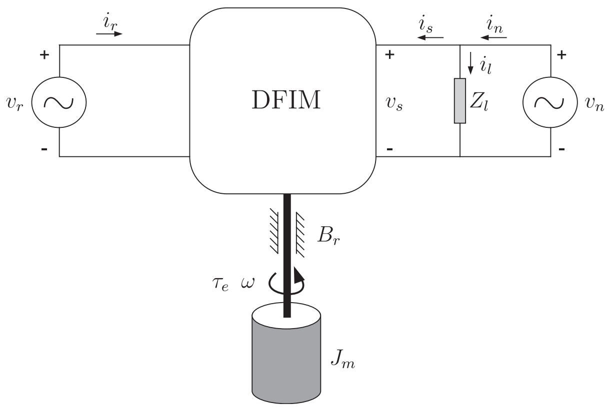

Fig. 1. Doubly-fed induction machine, flywheel, power network and load.

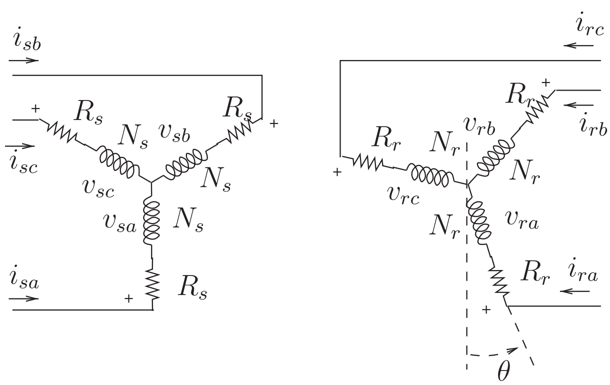

Fig. 2. Basic scheme of the doubly-fed induction machine.