Chapter 6

Conclusions

The work developed for this Ph.D. thesis has contributed some new results to the port Hamiltonian modeling and control framework, and has applied them, together with previously known results, to a complex system made of a doubly-fed induction machine (DFIM) and a back-to-back (B2B) power converter. An energy management strategy for the coupled system has also been formulated in port Hamiltonian terms. The validation of all the results has been carried out both in simulation and in experiment.

6.1 Chapter summary

Chapter 1 describes the flywheel energy storage system, composed of a doubly-fed induction machine (DFIM), coupled to a flywheel and controlled through the rotor side by a back-to-back (B2B) converter. This system is able to store kinetic energy in the flywheel and to give it back to the electrical subsystem in case that a local load requires more power than the grid can give.

Dynamical equations of the system, DFIM and B2B, are presented, tacking special account of the coordinate transformations (the dq or Blondel-Park transformation) for the electrical machine. A power flow management is studied so that the main goals of the system can be achieved. This power strategy is split into three operating modes: generator, motor and stand-by. However, stability cannot be ensured, without further analysis, when the power flow strategy that switches the operating modes is in place. If the switching is replaced by a smooth, sufficiently slow, transition from one operating point to the other, we can invoke total stability arguments to prove that stability is preserved under some additional uniformity assumptions.

The main contributions of this Chapter are:

- Power flow management of the flywheel energy storage system in the port Hamiltonian framework.

In Chapter 2 the energy based modeling framework, with special emphasis in the electromechanical domain, is revised. Port Hamiltonian systems (PHS) and, more generally, Dirac structures, are presented by means of several examples. Variable structure systems (illustrated by power converters) are also studied. From the classical PHS framework a generalized Fourier expansion (GSSA), truncated to the relevant terms, is described again in a PHS framework.

The port-Hamiltonian modeling paradigm has been illustrated for a complex system, made of subsystems from the electrical and mechanical domains: a DFIM controlled by a B2B converter. Each subsystem has some particularities which show the power and adaptability of the port Hamiltonian approach. In particular, how to deal with variable structure system in the PHS framework has been demonstrated with electronic power converters, and the apparition of state-space dependent interconnection matrices has been exemplified for a rotating induction machine in synchronous coordinates. For both subsystems, the selection of suitable coordinate transformations, GSSA and the dq-transformation, has been necessary to design controllers with the IDA-PBC technique (see Chapter 4). The PHS models of both subsystems have been coupled together, and introduced in the 20sim modeling and simulation software [1]. The simulations have been run in closed loop with controllers designed in Chapter 4. The description of the whole system as a network of interconnected subsystems which exchange power in a preserving way has proved itself useful both from the modeling and the control specification and design points of view.

The main contributions of this Chapter are:

- Port-controlled Hamiltonian model of the doubly-fed induction machine.
- Port-controlled Hamiltonian model of the back-to-back converter.
- Port-controlled Hamiltonian model of the interconnection of the DFIM and the B2B by means of the dq-transformation.

In Chapter 3 the theory of passivity-based control is reviewed. The Hamiltonian description allows to interpret easily the dissipation and energy functions of the system, which play an important role in the passivity-based approach to control . In this framework the Interconnection and Damping Assignment-Passivity–based Control (IDA-PBC) technique is presented. The methodology consist in assigning a new desired PHS (adding damping terms and re-shaping the energy function), which has an stable equilibrium point at the desired coordinates. This procedure leads to the need to solve the so-called *matching equation*.

Along this Chapter we presented a new approach, the Simultaneous IDA-PBC, which increases the solvability of the matching equation. The main contribution is the design of the interconnection and damping matrices (J and R) of the closed-loop system together, which allows new solutions to the problem. In this way we enlarge the class of systems that can be stabilized using IDA-PBC and, furthermore, through the consideration of a broader set of desired damping matrices, we provide the designer with more tuning knobs to improve performance. An academic example shows the possibilities of the SIDA-PBC.

An important gap in the IDA-PBC technique is found when designing robust controllers. Our first approach to this problem is the study of a dynamical extension, which implies an integral action in the controller, while keeping at the same time the Hamiltonian structure of the closed-loop system. However, our present understanding of the problem permits only to solve the case of passive outputs (or relative degree one outputs).

For higher relative degree outputs we developed a modification of the IDA-PBC method which makes the controller robust with respect to uncertain parameters appearing in the

[1]See `http://www.20sim.com`

components of the vector field corresponding. Carefully selection of the interconnection and damping matrices allows the dependence of the controller in uncertain parameters to be removed. This new approach has been applied to a simple toy model, for which a robust controller has been designed and simulated. Extending this idea, namely to improve robustness of IDA-PBC controllers via structure modification, to underactuated systems and to relax the conditions under which this technique can be applied will be the object of future research. The use of integral controllers in the IDA-PBC framework for higher order relative degree outputs as a means of improving robustness is also under study.

The main contributions of this Chapter are:

- The Simultaneous IDA-PBC (SIDA) approach, an extension of the IDA-PBC methodology which enlarges the class of solvable problem controls and enriches the set of control laws.
- Discussion on the dynamical extension keeping the PHS structure.
- A methodology for designing more robust IDA-PBC controllers.

Chapter 4 presents several controllers for the DFIM and the B2B converter.

The most used methodology to control the DFIM is Vector Control. In subsection 4.1.1 this technique has been shortly reviewed. In subsection 4.1.1 we have been able to solve the standard IDA-PBC equations for the DFIM by assigning the desired Hamiltonian and introducing a variable damping to eliminate the resulting singularity. The controller obtained is globally convergent and decouples the mechanical and electrical subsystems in the interconnection matrix. Further improvements are described in subsection 4.1.3. The SIDA-PBC idea has also been applied, thus avoiding the classical nested-loop control configuration prevalent in electromechanical systems. We have been able to improve the mechanical response of a DFIM, working both as a motor and a generator. The DFIM control study finalizes in subsection 4.1.4, where a particularly simple controller for the DFIM has been presented. It consists of a feedback linearizing term and a PI around stator currents. This controller has been obtained applying the robust approach of the IDA-PBC methodology. We prove also that the scheme is globally asymptotically stable for all values of the proportional gain and sufficiently small integral gains. A region where large PI gains can be applied, preserving stability, is also identified. As no stator flux estimation is required, the algorithm scheme is simpler than the classical vector control. Simulations validate the control law.

For the B2B converter a controller able to achieve bidirectional power flow in a full-bridge boost-like rectifier has been presented. The controller has been designed using IDA-PBC techniques for a suitable PHS-GSSA truncated model of the system. The control scheme achieves good regulation of the dc bus and high power factor from the ac side.

Finally, simulations with the designed controller validate the power flow management between the flywheel energy storage system and a varying local load. The system not only provides the active power required by the load, but at the same time compensates the reactive power, so that the power grid sees the load+machine system as a pure resistive load, even for varying inductive local loads.

The main contributions of this Chapter are:

- An IDA-PBC based controller for the DFIM, validated by simulations.
- A SIDA-PBC based controller for the DFIM, validated by simulations.
- A robust IDA-PBC based controller for the DFIM, validated by simulations.
- An IDA-PBC GSSA controller for the full bridge rectifier, validated by simulations.
- Simulations of the flywheel energy storage system.

Chapter 5 presents experimental results of the controllers proposed in Chapter 4. The experimental tests validate both the DFIM and B2B controllers, as well as the energy management scheme.

The DFIM controller tested in this Chapter is described in subsection 4.1.4. The experimental test validates the proposed controller, which does not need flux estimator, controls directly the stator currents as outputs and uses the synchronous reference.

The B2B is tested with the IDA-PBC controller designed in subsection 4.2.3. Several problems have appeared related to the non-continuous features of the real system and the neglecting of higher harmonics in the voltage bus. These results validate both the IDA-PBC method and the GSSA decomposition of variables, *i.e.* the control goals for the harmonic components taken into account are achieved.

Finally, in Section 5.3 the experimental setup is presented and the power management of Section 1.4 is tested. The obtained results validate the power flow strategy.

The main contributions of this chapter are:

- Experimental validation of the IDA-PBC robust controller proposed for the DFIM.
- Experimental validation of the IDA-PBC GSSA truncated controller for the full bridge rectifier.
- Experimental validation of the power flow management of the flywheel energy storage system.

6.2 Future research

Although the work presented in this Ph.D. thesis has achieved some interesting results for the modeling, simulation and control of electromechanical systems, many problems remain open and will be the subject of future investigations.

In the control theory, this dissertation presents several original improvements of the basic IDA-PBC technique, both for the general theory and also regarding its application to specific systems of great technological relevance. Nevertheless, how to improve the robustness of the controllers obtained with the basic technique or its variants is still an open question. In this respect, the formulation of integral controllers for general outputs in the port-Hamiltonian framework is a very promising area of study which certainly deserves further investigation.

As a rather specific subject, but quite interesting from the mathematical point of view, one can consider the study of the zero dynamics of the full-bridge rectifier, which involves nontrivial (class A, 2nd type Abel) differential equations. In this Thesis only the zero dynamics of the DC-DC boost converter, which exhibits the same behavior than the one observed by numerical simulation for the full-bridge rectifier, has been studied analytically.

Further improvements of the controller of the full bridge rectifier, namely consideration of higher harmonics of the DC voltage and inductor current, are also under study, in order to improve the tracking of the ac voltage waveform.

The flywheel energy storage system management is another area which can be studied more thoroughly form the mathematical point of view. In particular, investigations addressing the global stability of the switch between modes are being pursued.

Finally, the application of the techniques and solutions developed in this Thesis to other kinds of electrical machinery, such as synchronous machines or variable reluctance machines, is an objective worth pursuing from both the theoretical and technological points of view, and which will be undertaken in the immediate future.