UNIVERSITAT POLITÈCNICA DE CATALUNYA

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AUTOMATITZACIÓ AVANÇADA I ROBÒTICA

PhD Thesis

MODELING, SIMULATION AND CONTROL OF A DOUBLY-FED INDUCTION MACHINE CONTROLLED BY A BACK-TO-BACK CONVERTER

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Agraïments

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Abstract

This Thesis studies a complex multidomain system, including the control objectives specification, modeling, control design, simulation, experimental setup assembling and experimental validation stages. The system under study is an energy storage system whose main components are a flywheel, a doubly-fed induction machine and a back-to-back electronic power converter. Along with the study of this specific system, a review is presented of the major techniques employed, namely port Hamiltonian system theory and interconnection and damping assignment-passivity based control, and some original theoretical improvements of the basic control technique are also obtained. The Thesis contains also some ancillary illustrative examples not published previously or published in limited form.

This Thesis studies the port interconnection and control of electromechanical systems. The port Hamiltonian formalism is presented in general, and particularized for generalized electromechanical systems, including variable structure systems (VSS).

Interconnection and damping assignment–passivity based control (IDA-PBC) is a well known technique for port Hamiltonian systems (PCHS). In this Thesis we point out the kind of problems that can appear in the closed-loop structure obtained by IDA-PBC methods for relative degree one outputs, when nominal values are used in a system with uncertain parameters. In particular, we show that, in general, the positive semidefiniteness of the dissipation matrix breaks down, at least, in a neighborhood of the desired regulation point, preventing thus the use of LaSalle's theorem. Nevertheless, we present an example where the closed-loop system regulates to a fixed point, albeit different from the desired one. To correct this, we introduce an integral control, which can be cast into the Hamiltonian framework. Numerical simulations for our example show that the closed-loop system regulates to the desired point, although a rich dynamical behavior is obtained when the feedback parameters are varied.

This Thesis also presents two new approaches which improve the range of applicability of the IDA-PBC technique.

First, we show that the standard two-stage procedure used in IDA-PBC consisting of splitting the control action into the sum of energy-shaping and damping injection terms is not without loss of generality, and effectively reduces the set of systems that can be stabilized with IDA-PBC. To overcome this problem we suggest to carry out simultaneously both stages and refer to this variation of the method as SIDA-PBC. To illustrate the application of SIDA-PBC we consider two an academic example.

Secondly, we present an improvement of the IDA-PBC technique. The IDA-PBC method requires the knowledge of the full energy (or Hamiltonian) function. This is a problem because, in general, the equilibrium point which is to be regulated depends on uncertain parameters. We show how select the target port-Hamiltonian structure so that this dependence is reduced. This new approach allows to improve the robustness for higher relative degree outputs, and, for illustration purposes, it is applied to a simple academic nonlinear system and a DC motor.

The Flywheel Energy Storage System consists of a doubly-fed induction machine (DFIM)— controlled through the rotor voltage by a power electronics subsystem (a back-to-back AC/AC converter (B2B))— and coupled to flywheel. The control objective is to optimally regulate the power flow between the DFIM and a local load connected to the grid, and this is achieved by commuting between different steady–state regimes. A police management based on the optimal speed for the DFIM is proposed.

In this Thesis we propose a new control scheme for the DFIM that offers significant advantages, and is considerably simpler, than the classical vector control method. In contrast with the latter, where the DFIM is represented in a stator flux–oriented frame, we propose here a model with orientation of the stator voltage. This allows for an easy decomposition of the active and reactive powers on the stator side and their regulation—acting on the rotor voltage—via stator current control. This design was obtained applying the new robust procedure for the IDA-PBC technique presented here, for the electrical subsystem. An outer loop control for the mechanical speed is introduced.

Other controllers are also designed along the dissertation. The classical vector control is studied. We also apply the classic IDA-PBC 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. Finally, we also prove that with SIDA-PBC we can shape the total energy of the full (electrical and mechanical) dynamics of a doubly-fed induction generator used in power flow regulation tasks, while with two stage IDA-PBC only the electrical energy can be shaped. These different controllers (vector control, IDA-PBC, SIDA-PBC and robust IDA-PBC) are simulated and compared. The IDA-PBC robust controller is also experimentally tested and shown to work satisfactorily.

A controller able to achieve bidirectional power flow for the B2B converter is presented. Standard techniques cannot be used since it is shown, numerically and also analytically by means of a simpler example, that no single output yields a stable zero dynamics for power flowing both ways. The controller is computed using standard IDA-PBC techniques for a suitable generalized state space averaging truncation of the system, which transforms the control objectives, namely constant output voltage dc-bus and unity input power factor, into a regulation problem. Simulation and experimental results for the full system confirm the correctness of the simplifications introduced to obtain the controller.

The proposed and tested controllers for the DFIM and the B2B are used to implement the power management policy. These results show a good performance of the flywheel energy storage system and also validate the IDA-PBC technique, with the proposed improvements.

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Introduction

Motivation

Electrical power is widely used as a transport and consumption energy. Many industrial applications are fed by electrical power and the tendency is to increase the consumption. Electrical power quality and reliability is critical to every plant's operation. Besides that, in today's energy-saving conscious world, the efficiency in processing the electrical energy is of vital importance. See

`http://ec.europa.eu/dgs/energy_transport/publication/energy_policy_en.htm`

for a glimpse of the importance of the technological issues related to energy efficiency for the design of policies at the European level.

Some applications require a high power peak (as is the case, for instance, of particle accelerators, but also of some more mundane facilities, such as industrial furnaces). In those cases, a local system able to give an instantaneous high power must be used in order to avoid the disruption, or even the collapse, of the entire power grid. While the load is not connected, or is working in a reduced regime, the local system can store the energy, for instance, in electrical batteries (or supercapacitors) or in a flywheel; when the power peak occurs, the batteries can be discharged, or the flywheel braked, and the energy so liberated may be forced to flow into the load, while at the same time trying to kept a high power factor so that the outside power network is not disturbed too much.

In this Thesis we study one of these local energy management systems, namely a flywheel energy storage system. It is an energy-switching system which allows to manage the energy between the local electrical load, the grid and the flywheel. The system is basically made of a doubly-fed induction machine (DFIM) coupled to a flywheel and a back-to-back converter (B2B).

Modeling a system is a very complex task which can be too easily taken for granted. It involves selecting the relevant physics and an associated state description, and this must be done taking into account what the resulting model will be used for. For instance, a very detailed model may be useful for simulation but useless for control design, for which a simplified description is needed so that the available techniques can be applied. This is only an extreme exemple, and a benign one at that, but in many cases, modeling decisions may be hidden in the final model, which may then be used in a different context without having them in mind, eventually leading to wrong conclusions.

The engineering community is mostly familiar with models described by differential equations, difference equations or, in a linear context, by different kinds of transforms. This modeling framework has been extremely successful in the past, and surely will continue to be used in the future for a wide set of applications. However, it has serious limitations when confronted with complex systems. On one side, this traditional approach provides models which do not reflect explicitly the underlying physical structure; it is difficult, by looking at a system of a dozen differential equations, to tell whether they correspond to a bunch of loosely connected subsystems or to a tight system with a rich dynamics, or whether there is just a nonlinear subsystem interacting with all the rest o rather a pervasive nonlinearity spread all over the system. If several subsystems are connected by means of input and output signals, it can be quite tricky to see whether some of the original states will become dependent, and what the effective dimension of the resulting state space will be. Furthermore, and specially when composing a system out of subsystems coming from different domains (mechanical, electrical, thermal, hydraulic, ...), it is difficult, if not impossible, to keep some degree of uniformity or structure in the process. When huge systems, made of many subsystems, heterogeneous or not, are considered, the structure that the individual pieces may possess does not scale well and is lost or difficult to track in the final model.

From another point of view, traditional control theory has essentially dealt with the idea of signals going in and out of several subsystems, or blocks. This is appropriate for the modeling framework described in the above paragraph, but leads to increasingly awkward controllers when bigger systems are considered, specially in the presence of nonlinearities. This is an intrinsic drawback of the signal paradigm, since nonlinearities tend to spread any band-limited signal all over the spectrum, and a lot of controller effort is necessary to compensate for this. This can be dramatically illustrated by several examples of prototype humanoid robots, with huge battery packs which are needed to store the power necessary to quench the big amounts of energy generated by the impacts of the robot legs on the ground when walking.

Parallel to this prevalent modeling and control paradigm, a different approach, based directly on the concepts of power and energy instead of signal, has been used by part of the engineering community. This framework, known as *bond graph* theory and developed from the pioneering work of H.M. Paynter [67], has found in the past its main applications in the modeling of interdomain systems, and has seen a revival along with the expansion of the mechatronic approach. We will not cover bond graph theory in this Thesis, but let us just remark that it provides a framework which is intrinsically domain independent. One of its main virtues is that it can yield models which are *acausal*, *i.e.* the definition of whether a signal is an input or an output of a subsystem is not coded into the model from the beginning, and only when the different pieces are assembled is causality assigned, and the computation algorithm for simulation, that is the set of differential equations, is then obtained. This makes the models essentially reusable, which is something to take into account when dealing with complex systems, or when trying to get a first approximation of a composed model, some parts of which may be refined at a later stage. The reader interested in bond graph theory can consult [19][20][48] and references therein.

As many as the virtues of bond graph theory may be, it has always been somehow short on the control side, and its extensions to distributed systems, that is models described by partial differential equations, have been *ad hoc* and quite messy. This situation changed at the beginning of the 90's, with the formulation by B. Maschke and A. van der Schaft [56] of port Hamiltonian system (PHS) theory, or port controlled Hamiltonian systems (PCHS), as it was originally termed.

PHS theory has resulted from the combination of ideas and techniques coming from the theory of Hamiltonian dynamical systems and the theory of networks. Historically, these two groups of ideas have evolved separately. The Hamiltonian viewpoint has its roots in analytical mechanics, and springs from the principle of minimum action and the Euler-Lagrange equations, to finally formulate the Hamiltonian equations of motion. Network theory concepts have their origin in the electrical engineering community, and constitute a cornerstone of mathematical system theory. While a considerable portion of the analysis of physical systems has been developed using the Lagrangian and Hamiltonian frameworks, concepts from network theory, of which bond graph theory participates, dominate the modeling and simulation of complex physical systems.

PHS theory covers in the same framework both the standard Hamiltonian systems of analytical mechanics and the network-like models which appear in many areas of electrical and electromechanical engineering, in mechatronics and in the mechanics of complex systems, among others. In a sense, it provides the mathematical backbone to bond graph theory,[42] and puts it in a deeper conceptual footing which allows nontrivial generalizations, such as those necessary for the description of partial differential equations models.

The fundamental underlying idea is to associate to the energy interconnection network a geometric structure, called Dirac structure [24][27], which encompasses the symplectic forms and Poisson brackets of analytical mechanics and the fundamental laws of network theory, for instance Kirchoff laws [58], in such a way that a more powerful theory is obtained, able to treat in the Hamiltonian framework the constrained systems which can appear when interconnecting several subsystems.

PHS theory not only allows to formulate, like bond graph theory, models from several domains of physics and engineering in an unified framework, but also offers tools for the analysis, the simulation and, of special interest for technological applications, the control of physical systems [51][65][66]. Moreover, the theory has been extended to deal with systems with dissipation and with systems described by partial differential equations with boundary energy flow, using infinite dimensional Dirac structures, or Dirac-Stokes structures [52][88], which capture the system conservation laws. As an added bonus, this geometrization suggests a discretization method using finite elements based on differential forms [41], which preserve the PHS structure and offer thus sensible advantages for simulation.

One of the properties of the PHS theory is the fact that it allows to clearly separate the constitutive relationships on one side, which normally introduce nonlinear phenomena into the model, and the space-time relationships on the other one, described by the Dirac structure and thus intrinsically linear (this is true for systems with reversible processes, or with irreversible processes but such that dissipation can be described by one-way dissipative elements; the complete inclusion of the thermal domain in the Hamiltonian framework requires a generalization of Dirac structures, namely contact structures, which are nonlinear and are starting to be used to model, simulate and control chemical engineering processes [31]). For instance, Maxwell equations or, to be more precise, Faraday and Ampère laws, are linear and can be described by a certain Dirac-Stokes structure. Nonlinearity in electromagnetism appears when the relationships among the fields E, B, H and D are specified, so that the spatial energy density of the electromagnetic field can be computed, but this is independent of how energy flows from one point to another, which is determined by the Dirac-Stokes structure. One can imagine here that a space discretization preserving the underlying geometrical structure has to offer significant advantages for numerical simulation, especially when several subsystems are interconnected by energy flows.

As mentioned above, PHS theory allows the use of powerful control techniques, based on the computation of a *natural* Lyapunov function for the system, namely its energy or Hamiltonian function, which can be modified in closed loop so that it has a minimum at the desired regulation point; passivity of the Hamiltonian input/output map can be used then to, under suitable conditions, guarantee asymptotic stability. This basic setup, which has a nice physical interpretation [65], can be extended so that not only the closed loop energy function is modified but also the way in which the energy flows and is dissipated in the controlled system, yielding what is called the Interconnection and Damping Assignment-Passivity-based Control (IDA-PBC) technique.[66]

The main goal of this PhD Thesis was to apply these new modeling and control techniques, namely PHS theory and the IDA-PBC method, to the flywheel storage system described at the beginning. The objectives of the thesis included modeling, control design, computer simulation and experimental validation for the different subsystems involved and also for the complete system. Although no major theoretical contribution was envisioned, it has turned out that in the course of the investigations several improvements of the basic IDA-PBC method have been proposed; these improved techniques have been applied to the system under study, greatly improving the performance or the robustness of the closed loop dynamics.

The work undergone in this Thesis has tried to go all the way from the abstract modeling and control theory world to the experimental implementation in a complex setup in the real world, and the results obtained indicate that it has largely been successful. The encouraging results reported in this Thesis indicate that port Hamiltonian based modeling and control is able to improve old solutions and to solve new problems coming from areas of application where energy concepts play a fundamental role.

Most of this Thesis has been done within the GEOPLEX (Geometric Network Modeling and Control of Complex Physical Systems) project, with code IST-2001-34166, of the 5th Framework Programme of the European Commission Community Research:

`http://cordis.europa.eu/fp5/about.htm`.

More details about the project can be found at

`http://www.geoplex.cc`.

Original scientific contributions of this Thesis

The major contributions of this Thesis are listed below. Numbers in parenthesis refer to the accompanying list of publications.

- Power management of a doubly-fed induction machine coupled to a flywheel. (1)(2)(6)
- Contributions on the robustness of passivity-based controllers. (7)(11)
- Contributions on the Interconnection and Damping Assignment–Passivity-based Control technique. (5)
- Passivity-based controllers for a doubly-fed induction machine. (1)(2)
- PI controller, based on IDA-PBC technique, for a doubly-fed induction machine. (8)(10)
- Port Hamiltonian description of the interconnection of a doubly-fed induction machine and a back-to-back converter. (4)(6)
- Passivity-based controller for a full bridge rectifier. (3)(9)
- Experimental validation of some of the proposed controllers. (8)(9)(10)
- Experimental validation of the power flow management of a kinetic storage system.

List of Publications

What follows is the list of publications related to the contents of this Thesis. Papers in preparation have not been included.

Published:

1. C. Batlle, A. Dòria-Cerezo and R. Ortega
   Power Flow Control of a Doubly–Fed Induction Machine Coupled to a Flywheel
   In IEEE Proc. Conference on Control Applications, Taipei, 2004.

2. C. Batlle, A. Dòria-Cerezo and R. Ortega
   Power Flow Control of a Doubly–Fed Induction Machine Coupled to a Flywheel
   European Journal of Control, 11(3), 209-221, 2005.

3. C. Batlle, A. Dòria-Cerezo and E. Fossas
   IDA-PBC controller for a bidirectional power flow full-bridge rectifier
   In IEEE Proc. Conference on Decision and Control, Sevilla, 2005.

4. C. Batlle and A. Dòria-Cerezo
   Energy-based modelling and simulation of the interconnection of a back-to-back converter and a doubly-fed induction machine
   In Proc. American Control Conference, Minneapolis, 2006.

5. C. Batlle, A. Dòria-Cerezo, G. Espinosa and R. Ortega
   Simultaneous Interconnection and Damping Assignment Passivity-Based Control: Two Practical Examples
   In Proc. 3rd IFAC Workshop on Lagrangian and Hamiltonian Methods for Nonlinear Control, Nagoya, 2006.

6. C. Batlle, A. Dòria-Cerezo, E. Fossas and R. Ortega
   Energy-based modelling and control of a multi-domain energy storage and management system
   In Proc. 5th Mathmod Conference, Vienna, 2006.

Submitted:

7. C. Batlle, A. Dòria-Cerezo and E. Fossas
   Robust Hamiltonian passive control for higher relative degree outputs
   Submitted to IEEE Conference on Decision and Control, 2006.

8. C. Batlle, A. Dòria-Cerezo and R. Ortega
   A Robustly Stable PI Controller For The Doubly-Fed Induction Machine
   Submitted to Conference of the IEEE Industrial Electronics Society (IECON), 2006.

9. C. Batlle, A. Dòria-Cerezo and E. Fossas
   Bidirectional power flow control of a power converter using passive techniques
   Submitted to IEEE Trans. on Power Electronics, 2006.

10. C. Batlle, A. Dòria-Cerezo and R. Ortega
    A Robust Adaptive Stable PI Controller For The Doubly-Fed Induction Machine
    Submitted to IEEE Trans. on Industrial Electronics, 2006.

Other:

11. C. Batlle, A. Dòria-Cerezo and E. Fossas
    Improving the robustness of Hamiltonian passive control
    IOC-DT-P 2006-12 preprint, available at `http://hdl.handle.net/2117/318`

12. C. Batlle and A. Dòria-Cerezo
    Modeling and control of electromechanical systems
    Lecture Notes for the II EURON/GEOPLEX Summer School on Modeling and Control of Complex Dynamical Systems, Bertinoro, FC, Italy, July 18-22 2005, available at `http://www-lar.deis.unibo.it/euron-geoplex-sumsch/files/lectures_2/lectures-batlle.pdf`