Electrical Actuators

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Identification and Observation

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Introduction

Electric actuators, at least the most traditional ones (direct-current machine and alternating-current machines working under Park's assumptions), have been the subject of a very large number of scientific studies and industrial realizations, and we can consider that they are currently well understood. The control structures use the machine's decoupling properties in both axes (direct axis for the flux and quadrature axis for the torque), and the performance and robustness of the regulators are well adapted to the system specifications.

The implementation of overlapped regulations makes it possible to control the dynamics of the main variables, magnetic flux and rotation speed (via the torque), and to create "active safety features" (instant limitations of power amplitudes for example). These controls are even more efficient as long as the designer has precise models with known parameters. In fact, controllers most often use the innermost properties of actuators. The "direct model" is derived from the physical equations of the machine. From this model a reverse model is then obtained enabling direct access to the control architecture and allowing the selection of the control algorithms, the regulators or the controller best adapted to the original specifications. Knowledge of the physical laws and parameter values is therefore a requirement.

In addition, these controls involve variables whose direct measurements cannot always be achieved such as the magnetic flux and the electromagnetic torque of the induction machine; even if flux and torque sensors exist, they are very expensive and not often used. That is also the case with the rotation speed since controls without mechanical sensors are increasingly widespread. High performance controls require a very good knowledge of these variables.

Introduction written by Bernard DE FORNEL and Jean-Paul LOUIS.

This work is based on the expertise of the authors which have a threefold experience of research, teaching and industrial applications. This book is intended to provide the reader with a reference work on parameter identification, both “off-line” (in the background) and “on-line” (in real time, during the control operation) and of estimation or observation of the variables of alternating-current electric machines that cannot be directly measured.

The reader will observe that all chapters in this book devote an important part to modeling. From the one which identifies the speed of a machine without mechanical sensor to the one that enables the estimation of the parameters of a saturated induction machine, the variety of models is large. The goal of this book is to provide the user with the methods necessary to acquire the expertise that will enable him to choose the most appropriate model, and not necessarily the ideal model (since the perfect model that solves all problems does not exist).

In this book, many different approaches are explained in order to find the best compromise between two opposite constraints:

– the physical validity of models often quite complex to account for the large number of phenomena;

– the mathematical model that must be handled by real time computers and therefore must be simple enough. In fact, the calculation period is linked to the fastest time constants of the physical system. Some are very short and the electric machine control is very demanding in terms of execution time of the algorithms.

The measured variables, either online or offline, can also be submitted to a physical filtering or a numerical process treatment.

The chapters of the first part of the book (1, 2 and 3) are dedicated to measurement and parameter identification of the synchronous and induction machines. The authors have tried to give an overview of different aspects: steady state measurements of physical parameters, including some non-linearities (saturation, for example), and dynamic parameter estimation in order to gain a better understanding of the machine’s physics, as well as enabling the creation of the dynamic models necessary to develop the controllers. We had to find compromises between the “white box” and “black box” approaches. In order to do this, we had to use:

– off line measurement or identification of physical parameters required by the simulation models and necessary for controller implementation;

– the real-time identification of parameters for adaptive control that takes into account the parameter variations linked to conditions of operation, magnetic state, temperature, etc. This online identification uses filtering techniques, mainly the Kalman Bucy technique.

The chapter “Identification of Induction Motor in Sinusoidal Mode” by E. Laroche and J.-P. Louis is an extension of the classical methods for measuring induction machine parameters. These usually rely on an equivalent circuit where leakage fluxes are first divided between the rotor and the stator, then, for convenience, referred traditionally to the rotor. The steady-state model gives access to several parameters, which can be rightly used for transient state analysis or for control, such as for vector control. An equivalent circuit can be exact, but its parameters may not be measurable physically, or without unacceptable errors. Moreover, the well-known no-load and short circuit tests are not sufficient to obtain the required precision. In the end, the magnetic saturation must be taken into account by the high performance controllers, and introduced into the models. Optimized parameter identification methods are thus developed: which models should we use? Can we identify them? What measurements should we make? Modern methods go beyond the simple optimization method to estimate the best parameter values: there is a need to “optimize the optimization”.

In the chapter “Modeling and Parameters Determination of the Saturated Synchronous Machine” by E. Matagne and E. de Jaeger, the authors present a Park model but without considering the usual linearity hypothesis. This enables the authors to not only present the classical tests which make it possible to determine the numerical values of accessible parameters, but also to introduce the “cross saturation” phenomenon caused by the intrinsic non-linearity of magnetic materials. This is an appropriate model to harmonize the traditional and modern points of view. In particular, the “magnetic quadrature” condition requires the use of the “magnetic co-energy” concept (at the expense of the magnetic energy which is a state function of essential physical signification). In this chapter, the authors show that measurements must be performed with great precaution, and that the experimenter must know and understand the physical properties of the models (for which he is looking to identify the parameters) well: non-linearity effects, iron losses, etc. A good knowledge of the order of magnitude of the parameters is useful if not mandatory to carry out fine measurements and carefully make the necessary approximations. Clearly, the authors have sought to pass on their own experience in the domain.

In the chapter “Real-Time Estimation of the Induction Machine Parameters”, Luc Loron considers “on-line” or “real-time” processing for the determination of variable parameters (temperature dependent winding resistance, inductance, which depend with the magnetic state of the cores) and non-measurable variables (flow and velocity for controllers without mechanical sensors). In the preceding chapters, the models were close to the machine physics and the parameter identification tools were quite cumbersome necessitating an “off-line” process of the recorded data. On the other hand, on-line processing imposes real-time algorithms, which have short calculation times and robustness. They cannot destabilize the system, and they must provide trustworthy data at every moment. The reader will find in this chapter not only reliable information on the least square method, on the extended Kalman filter theory and the Luenberger observer theory, but also advice on their implantation and concerning the relevance of models (reparametrization), the validity of algorithms, the problem of monitoring (still very open to discussion), the influence of the sampling period, the analog filtering of measurements, the adaptation of algorithms when parameters or variables are no longer identifiable, etc. Again, the concrete experience of an expert is put at the disposition of future practitioners.

The second part of the book (Chapters 4, 5, 6, 7 and 8) focuses on several specific studies involving the control of these electric machines:

– study and implementation of reduced order observers and methods to determine the robustness of observers for the induction machine;

– estimation and observation approaches of the load torque and the rotor angular position of the synchronous machine.

The chapter "Linear Estimators and Observers for the Induction Machine (IM)" by Maria Pietrzak-David, Bernard de Fornel and Alain Bouscayrol concerns the estimation and observation of non-measurable variables. In an induction the magnetic flow, an essential value for the control of this machine, is not accessible through direct measurements. In fact, flux sensors in the air-gap greatly increase the cost of the machine; they constitute intrinsically fragile elements, and they often produce very noisy signals. They are only used for prototypes. A large part of this chapter is dedicated to the estimation or observation of the flux state. The estimation of the rotation speed and of the load torque is also studied. In this chapter, the modeling is critical since the "natural model" (referred to as the real windings) given by the physics of the system must be rewritten to meet the objectives. The numerous works carried out by the community of specialists have shown that the choice of four electric state variables (stator and rotor fluxes or currents) on the one hand, and the choice of the reference frame (link to the stator, rotor or to the rotating flux) on the other hand, play a very important role in the control structures of the speed controller (vector control or direct couple control). These particular choices for the state variables and the reference frame also influence the performances of the estimators and the observers. The authors present the estimation and observation of the flux of the induction machine with the help of automatic and signal processing tools: the complete order deterministic observer (synthesized with the help of pole locations) and the linear stochastic observer (Kalman-Bucy filters synthesized using optimization methods). These observers are then associated with structures dedicated to speed observation. Various non-linear observation methods (adaptable, of variable structure) are also presented. The authors of this chapter present several solutions based on their expertise and illustrated by examples. Researchers and engineers, facing these questions, now have access to a variety of solutions, which should help them not to waste their time with solutions badly adapted to their problem.

The chapter "Decomposition of a Determinist Flux Observer for the Induction Machine: Cartesian and Reduced Order Structures", by Alain Bouscayrol, Maria Pietrzak-David and Bernard de Fornel focuses on very specific problems and solutions. The goal of this chapter is the study and creation of reduced order observers leading to smaller models and algorithms than those given by general theories (based on extended models). The authors also consider extended observers, but with a very interesting, even if but not very traditional, original solution of "Cartesian structures". In this solution, the extended observer is broken down into (coupled) sub-observers, each one corresponding to the variables relating to an axis. We must clarify that this breakdown corresponds to an approximation justified by the time scale difference between speed of rotation and electric variables. In this way, the fourth order observer is replaced by the combination of two reduced order coupled observers for a simpler synthesis. It is well adapted for certain specific problems:

– robust estimation of the stator flux for "DTC" commands (Direct Torque Control);

– robust estimation of the rotor flux for traditional vector controls.

The authors use a Cartesian observer for stator and rotor flux to highlight the inability of observing the zero speed flux and provide a complete synthesis of this observer. The discretization of the Cartesian observer is simpler than the one resulting from an extended observer. The authors present several variations of reduced order observers and a number of synthesis examples. Since numerous studies on these subjects have been already published on this topic, the readers will appreciate suggestions for well adapted solutions given by experienced authors.

The chapter "Observer Gain Determination Based on Parameter Sensitivity Analysis" by Benoît Robyns proposes original tools for the resolution of a traditional but tricky problem. The rotor flux observer, for the vector control, is a real-time simulation algorithm of electric equations (either extended or reduced order) with matrix of undetermined gains. These gains are normally chosen by pole location techniques. However, since they depend on speed, they should be continuously recalculated at each sampling, which greatly increases calculation time. In practice, we often define speed ranges where chosen gains are constant. But this is in contradiction to the selection of "good poles" and to the robustness of this observer in terms of the various parameters. In order to resolve this contradiction, the author uses a very powerful, and not sufficiently known, tool called parametric sensitivity which provides access to observer errors made in the determination of the flux. With the sensitivity study, the observer's gains are chosen to greatly reduce its parametric sensitivity, and maintain a satisfying dynamic. In this chapter, the author clarifies his models, algorithms and choice criteria. His theoretical results are supplemented by representative, precise and well explained examples. He shows the advantage of an extended observer, optimized through a sensitivity study, compared to a reduced order observer. The latter seems more sensitive to rotor resistance error, the most critical parameter in the vector control.

In the "Observation of the Load Torque of an Electrical Machine" chapter, the authors, Maurice Fadel and Bernard de Fornel, develop different load torque observation structures based on the mechanical quantities that can be measured. For electro-mechanical actuators, the requirements on speed and position control have a strong impact on the drive control loops. The electromagnetic torque must be perfectly mastered to obtain the most satisfying speed or position evolutions.

In addition, the mechanical loads often show ill-defined characteristics at low speed or in the vicinity of zero or quasi-zero speeds. The variable speed drive's control in these specific operation zones can turn out to be problematic and the traditional control laws are often inadequate. The proposed study develops a detailed model aimed to improve the global behavior of the actuator.

The major contribution involves the load torque observer which, due to its structure and operation, can monitor the perturbations inherent to the internal structure of the electrical machine (cogging torque, electromotive force distortion, etc.) resulting from load parameters variations. This quantity, the torque that should be compensated, is then injected in the control law in order to smooth the machine's effective torque. The system thus functions in disturbance rejection.

The solutions presented in this chapter are based on studies conducted at LEEI (Laboratoire d'Electrotechnique et d'Electronique Industrielle in Toulouse and now a team of LAPLACE laboratory) and resulting in experimental prototypes with digital controllers and extensive measurements sytems. The chapter details the problem associated with:

– noise and filtering of speed and/or position measurements;
– an erroneous identification of parameters;
– excessive dynamic response of the controller or of the observer.

Several results, most of them experimental, confirm the relevant character of the approach and the robust performances obtained in presence of load and/or machine parameter variations. One of the main objectives of this work is the search for the necessary compromise between control stability and the observer dynamic based on the disturbance rejection effectiveness and drive parameters variations. These questions result in a specific look at the choice of the observer dynamic in relation to controller settings and to the number of sensors used.

In the last chapter of the book, entitled “Observation of the Rotor Position to Control the Synchronous Machine without Mechanical Sensor”, the authors, Stéphane Caux and Maurice Fadel, review several position estimation approaches to get rid of this measure and thus suppress a mechanical sensor. For some applications, a “low resolution” reconstitution of the position is sufficient, mainly in the case of a synchronous trapezoid electromotive force machine. Two more precise methods are then presented by the authors using either the Kalman filter or an analytical redundancy approach called Matsui’s observer. Kalman’s method is very systematic and corresponds to a calculation intensive algorithm, with the usual problems of Kalman gains definition, initial covariances and statistic properties of noise. Moreover, the Kalman filter is sensitive to position initialization errors. The analytical redundancy algorithm is simpler than the Kalman filter and provides better estimation at low rotation speeds than the latter. Performances of both estimators were compared over different speed ranges and for parameter sensitivity and initialization errors. The studies found in this chapter offer practical suggestions for their implementation (filtering) and adjustment (choice of gains, observers selection, identification of noise sources, initialization and calibration). They show the feasibility of the rotor position estimation and provide fundamental information on the choice between the different approaches.

This second part of this book completes the first one dedicated to the definition of measures, to the key models and to the estimation and state observation tools. It presents the application of these methods and tools to control several actuators based on synchronous and induction machines. In particular, it describes:

– the study and implementation of reduced order observers and methods to determine the observers’ robustness for the induction machine;

– the estimation and observation approaches of the load torque and angular position of the rotor for the synchronous machine.