Preface

The control of induction motors has attracted much attention from researchers and engineers since 1971. More than 4,000 journal papers have been published on induction motor control and more than 500 specifically on the adaptive control of induction motors: it is still a very active research area since more than 300 journal papers appeared in 2008. The industrial interest in induction motor control is documented by over 80,000 patents on this subject. The availability of low cost powerful digital signal processors and significant advances in power electronics motivated the design of complex induction motor controls. The aim is to achieve the same, or even superior, performance on speed tracking and power efficiency which are obtained by more sophisticated and expensive, but less reliable, electric motors such as direct current or permanent magnet ones. Direct current motors are extensively used in variable speed applications since their flux and torque are independently controlled by the field and the armature current. However, they have disadvantages due to the mechanical commutator and the brushes so that they are limited in high-speed, high-voltage operating conditions. Induction motors are much more difficult to control but have definite advantages since they have no commutator, no brushes, no rotor windings in squirrel cage motors, they have a simple rugged structure, can tolerate heavy overloading, and can produce higher torques with a lower weight, smaller size, and lower rotating mass than direct current motors.

The design of control algorithms for induction motors is, however, very complex for many reasons. It is a multivariable control problem since there are two independent control inputs and two outputs to be controlled: the primary output is the rotor speed to achieve the required dynamic performance, while the secondary output is the rotor flux modulus for power efficiency maximization. It is an intrinsic nonlinear problem since the electromagnetic torque, which controls the rotor speed, is a nonlinear function of stator currents and rotor fluxes, and the operating conditions of interest are away from the equilibrium points so that linear approximation techniques do not apply. It involves parameters such as load torque and rotor resistance which may vary widely during operation; they are critical in the control design and should be identified online to maximize power efficiency. The control design cannot rely on state variable feedback since rotor flux measurements are not easily available. If rotor speed is not measured in order to reduce costs or due to sensor failures and only stator currents and voltages are available from measurements, the control problem is called speed-sensorless. In this case the desired reference signals for rotor speed and flux modulus are to be tracked in spite of parameter perturbations, while both tracking errors are not available for feedback to the controller. The feedforward control which solves the tracking problem in open-loop may be explicitly obtained by computing the induction motor nonlinear inverse dynamics. The stability of the resulting open-loop controlled motor is, however, not always guaranteed since it depends both on the reference trajectories to be tracked and on motor parameters. Even in stable operating conditions the dynamic responses may be unsatisfactory and poorly damped. Hence, feedback from stator currents, and from rotor speed when available, has the goal of enhancing both stability and robustness with respect to parameter perturbations; moreover, it should improve transient behaviors and power efficiency. This book is focused on the nonlinear feedback control design techniques, including adaptive ones, which are required to achieve high speed tracking performance along with high power efficiency in induction motor control.

Besides its technological motivations for electric traction and electric drives, the control of induction motors has an intrinsic interest from the view point of nonlinear control theory, since it involves clearly modeled nonlinear terms such as electromagnetic torque and two critical parameters; the appropriate tools belong to the theory of adaptive output feedback for multi-input, multi-output nonlinear systems. Such a theory started to be developed in 1992 for special classes of single-input, single-output nonlinear systems but it does not encompass the induction motor models. Hence, the control of induction motors constitutes a very interesting case study which evolved into a benchmark nonlinear control problem. In fact, most of the fundamental concepts of nonlinear control theory apply in a nontrivial way. Induction motors are not feedback linearizable by static state feedback but they are feedback linearizable by a dynamic state feedback. It is enough to add one integrator to achieve feedback linearization; this can be done in many different ways even though they all lead to singularities that make it inadvisable to render the closed-loop linear in all operating conditions. Induction motors are input–output feedback linearizable but the input–output feedback linearizing control, which makes the rotor flux angle unobservable, is singular when the rotor flux is zero and it is not power efficient at low rotor flux levels. Induction motors are observable from rotor speed and stator current measurements so that flux observers, including adaptive ones, can be designed. Observer-based output feedback controls can also be designed using Lyapunov techniques. The steady-state dynamics of induction motors are very intriguing: in the case of constant reference signals for rotor speed and rotor flux modulus, they constitute a limit cycle in the state space where the rotating speed of the flux vector is equal to the sum of the desired rotor speed and the so-called slip speed, which depends on the load torque, the rotor resistance, and the flux modulus. In the more general case of bounded reference signals the steady-state dynamics may be very complex. They remain bounded but their stability and attractivity are in general difficult to study. In many cases the attractivity is not global and the stability is not exponential, depending on the reference signals and physical parameters, and instabilities or poor dynamic responses may arise.

Engineers at Siemens and Toshiba developed *ante litteram* in 1971 and 1980, respectively, nonlinear feedback control algorithms which are now called direct field-oriented control and indirect field-oriented control. At that time nonlinear control theory was just at its beginning: researchers were investigating basic controllability (1972) and observability (1977) properties. In fact, the proof that indirect field-oriented control is globally stable was published in 1996. Using today's terminology we can say that direct field-oriented control is an asymptotic state feedback linearizing control which has a singularity when rotor flux is zero, while indirect field-oriented control is a global dynamic output feedback control which has no singularities and allows the motor to start from any initial condition. Field-oriented controls were originally conceived for current-fed motors in which the stator currents can be controlled very rapidly by stator voltages, so that they may be considered control inputs by neglecting the stator currents dynamics; they were then extended to general induction motor models. During the 1980s new important tools in nonlinear state feedback design were developed: feedback linearization and input–output decoupling along with their adaptive generalizations. Good theories proved once again very useful in applications since they led to very innovative control algorithms for induction motors, with superior performance with respect to field-oriented controls. An adaptive feedback linearizing control with online identification of load torque and rotor resistance was developed in 1991. The goals of field-oriented controls and feedback linearizing controls are indeed very similar: they both use nonlinear feedback and nonlinear change of coordinates so that the feedback systems have a simpler structure.

Since both direct field-oriented control and feedback linearizing control make use of rotor flux signals there was a strong motivation to design rotor flux observers. At that time nonlinear observer theory was not fully developed. Nevertheless nonlinear observers for induction motors were designed in 1978: they were called bilinear observers. A complete theory for rotor flux observers, including observers with arbitrary rate of convergence, was successively developed. Adaptive flux observers were also designed which are adaptive with respect to rotor resistance, since rotor flux observers were found to be very sensitive with respect to rotor resistance variations. Identifiability questions naturally arose and were answered using the concepts of persistency of excitation and nonlinear observability. Since 1991 the problem of designing a global output feedback tracking control which does not require rotor flux measurements, is adaptive with respect to load torque and rotor resistance variations, and has no singularities was posed and finally solved in 1999 following the indirect field-oriented approach.

More recently, an important line of research was focused on the design of feedback control algorithms based on stator current measurements only. The absence of rotor speed measurements, which improves the reliability of the motor and reduces its cost, forced the redesign of those control algorithms which make use of rotor speed measurements in many crucial steps. The question itself of speed and rotor flux observability from stator current measurements is rather delicate and leads to the discovery of operating conditions in which observability fails: of course, the concept of nonlinear observability has to be used since the motor model is nonlinear. The study of identifiability of rotor resistance and load torque from stator current measurements leads to the discovery of persistently exciting reference signals for the flux modulus, which is required to be time-varying. Several speed sensorless control algorithms were recently developed which show superior performance with respect to inverse system based controls but are of course inferior to controls which make use of speed sensors.

At the present stage of research on induction motor control a coherent collection of estimation and control algorithms is available, including the most recent speed sensorless controllers. This book collects and discusses, using a unified notation and a modern nonlinear control terminology, the most important steps and issues in the design of estimation and control algorithms for induction motors. Many estimation and control algorithms are reported: their stability is analyzed and their performance is illustrated by simulations and experiments on the same induction motor. An intense and challenging collective research effort (which also involved at various stages the authors of this book) is carefully documented and analyzed, with the aim of providing and clarifying the basic intuition and tools required in the analysis and design of nonlinear adaptive feedback control algorithms. This material should be of specific interest to engineers who are engaged in the design of control algorithms for electric motors and, more generally, to a broader audience interested in nonlinear control design. In fact, induction motor dynamics are surprisingly rich and their control is challenging even to engineers with a strong nonlinear control background. The induction motor is an excellent source of projects, examples, and exercises for courses in nonlinear control design since they can be physically and experimentally tested. The book can be used for graduate courses on the control of induction motors and for independent study.

This book is divided into six chapters and two appendices. Since the stability of controlled induction motors is carefully analyzed throughout the book, the basic definitions and tools from Lyapunov stability theory are recalled in Appendix A. Since in many instances the basic concepts and tools from nonlinear control theory (nonlinear change of coordinates, observability, feedback linearization, input–output decoupling) are used, they are recalled in Appendix B. In Chapter 1, the modeling issues and the basic assumptions are discussed; moreover the structural properties of the models such as observability, parameter identifiability, linearizability, inverse dynamics and steady-state behaviors, including power losses minimization, are analyzed. Chapter 2 is devoted to state feedback control to explore the performance which can be obtained using full state variables measurements, and to examine those controllers which could tolerate the replacements of sensors by asymptotic observers and those which can be made adaptive with respect to uncertain parameters. The estimation of state variables, in particular rotor fluxes and rotor currents, and the identification of physical parameters such as load torque and resistances are discussed in Chapter 3: adaptive rotor flux observers are also presented. In Chapter 4 output feedback controls based on rotor speed, stator current, and stator voltage measurements are presented: some algorithms incorporate flux observers to improve performance, while the most complex algorithm is adaptive with respect to both torque load and rotor resistance. In Chapter 5 speed-sensorless output feedback controls which are based only on stator current measurements are discussed along with their adaptive versions. Chapter 6 contains some concluding remarks. All the control schemes are numerically simulated for the same motor with similar references to illustrate their performance, so that they can be compared: advantages and drawbacks of each scheme are pointed out. Some estimation and control algorithms are validated by experiments. Experimental tests are also presented which validate the motor model and the parameters used. The bibliography collects more than 200 journal papers and books on induction motor control from 1971 to 2009; it is, however, far from being complete and only contains all the material which was actually used during the preparation of this book. Finally, frequent exchanges of ideas and fruitful collaborations with Professor Sergei Peresada on induction motor control are acknowledged with pleasure.

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