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# Introduction to AC Motor Control

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## 1.1 AC Motor Features

The principles of operation of (AC) motors may be found in many books, including Hindmarsh (1985), Vas (1990), Leonard (2001) and Chiasson (2005). In this section, some basic facts are recalled, focusing on the features that contribute to the success of AC motors in motion control and to the continuing growth of their applications. "AC motors" refers to electric machines that convert AC electric energy into mechanical energy. There is a wide variety of such machines that differ by their operating principles, physical characteristics, and power level. Considering their operating principles, AC motors are classified in two main categories: induction and synchronous.

Induction motors exist in two main types, squirrel cage and wound rotor. In wound rotor machines, both the stator and the rotor windings are made of individually insulated coils. The rotor coils are made accessible on the stator side through slip rings. In squirrel-cage machines, the rotor windings are replaced by longitudinal bars placed in slots beneath the rotor's outer surface. The rotor bars are connected by circular conductors placed at the extremities. Operationally, a squirrel-cage motor is similar to a wound rotor motor with short-circuited windings.

For both types of motors, the stator windings generate a rotating magnetic field when supplied with polyphase AC. The speed of rotation of the field is given by the stator current frequency divided by the number of magnetic pole pairs created by the windings. By Faraday's and Lenz's laws, currents are induced in the rotor windings whenever the rotor speed differs from the speed of the magnetic field produced by the stator. This speed difference, called slip speed, must be kept small to guarantee high-energy conversion efficiency. Under this constraint, a change of rotational speed requires an adjustment of the stator electrical frequency.

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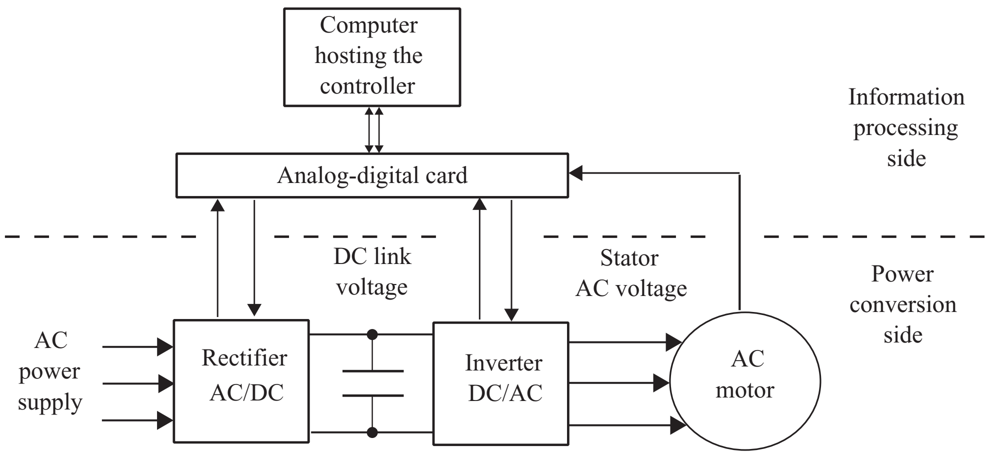


**Figure 1.1** AC motor control architecture

Synchronous motors also exist in two versions, namely, permanent-magnet and wound rotor. Unlike induction motors, there are no induced rotor currents in synchronous motors in steady state, because the rotor rotates at the same speed as the rotating magnetic field. A motor torque is developed due to the interaction between the stator rotating field and a rotor field generated either by permanent magnets or by an injected rotor current.

For both induction and synchronous motors, variable speed operation is possible if the stator supply frequency is made variable. Until the development of modern power electronics, there was no simple and effective way to vary the frequency of the motors' supply voltages. Nowadays, reliable high-speed switching power converters are available that serve as actuators in AC motor control. Specifically, an AC motor is supplied with power through an association of two power converters, a rectifier and an inverter (Figure 1.1). The former, also called AC/DC converter, converts the AC power provided by the grid into DC power. Control of the rectifier is not always implemented, but is useful to regulate the DC voltage, or to enable regeneration of power to the grid. The inverter, also referred to as DC/AC converter, transforms the DC voltage into an AC voltage with a specified frequency. The result is achieved by chopping the DC voltage at a high rate, typically using a pulse-width modulation (PWM) technique. In this respect, it is worth emphasizing the considerable progress made in computer technology, which has resulted in fast multiprocessor computers and high-performance analog-digital interfaces. This progress has made possible the real-time implementation of sophisticated methods to control the power converters associated with AC machines.

DC motors require schemes similar to Figure 1.1, but with lower bandwidth requirements and fewer channels. However, ACs are produced in conductors through mechanical commutation, rather than electrical commutation. The commutators of DC motors are complex and vulnerable. As a result, AC motors offer a higher power/mass ratio, relatively low cost, and simple maintenance. AC motors exist with a variety of characteristics and in a large range of sizes, from a few watts to many thousands of kilowatts. For these reasons, AC drive systems have already replaced DC drives in several industrial fields and this widespread proliferation is expected to continue. Nowadays, AC drives are used in almost all industrial applications, such as the following:

1. **Transport:** vehicle traction, marine propulsion
2. Milling in cement, steel, paper, and others industries
3. Pumping/compressing in oil and gas industry
4. Cranes and industrial vehicles
5. **Domestic machines:** lifts, washing machines, and others.

## 1.2 Control Issues

### *1.2.1 State-Feedback Speed Control*

The prime objective in AC motor control is to make the rotor turn at a desired speed despite load variations. If the desired speed is constant, one talks of speed regulation, while tracking problems correspond to time-varying speeds. The desired speed, also called the speed reference signal, is often unknown a priori, making the control issue more difficult. Indeed, the achievement of a desired rotor speed profile necessitates a sufficient motor torque to overcome the load torque, but also to provide the required accelerations of the rotor during transient periods.

In AC induction motors, the generation of a given torque necessitates a sufficient level of rotor magnetization, that is, a sufficiently high flux magnitude in the rotor. Flux control is thus not independent from the problem of speed control and both are acted upon through the inverter control signals. These signals are binary signals commanding on and off conduction modes. The electromechanical nature of the motor entails nonlinearities associated with products of fluxes with currents and fluxes with speed. Furthermore, the three-phase nature of the motor means that the overall model is nonlinear, of high dimension, as well as controlled through binary signals. A common practice consists in reducing the model dimension by resorting to Park's transformation, which projects the three-phase variables (generally referred to as *abc*) on a two-phase rotating coordinate frame (generally referred to as *dq*) (see, e.g., Blaschke 1972; Leonard 2001). The binary nature of the inverter signals is generally coped with by averaging the signals over the PWM period and letting the control design be based on the corresponding averaged two-coordinate model (see, e.g., Sira-Ramirez and Silva-Ortigoza 2006). Model nonlinearity is handled using modern nonlinear control design techniques, including state- and output-feedback linearization, Lyapunov control, sliding-mode (SM) control, passivity-based control (Ortega *et al.* 1998; Isidori 1999; Sastry 1999; Vidyasagar 2002; Khalil 2003).

The basic ideas described so far lead to the control strategy depicted in Figure 1.2.

### *1.2.2 Adaptive Output-Feedback Speed Control*

The basic state-feedback control strategy of Figure 1.2 assumes that all controlled system parameters are known. However, some system parameters are generally not known a priori, and may even be varying in normal operating conditions. In particular, the stator and the rotor resistances are sensitive to the magnitude of the currents, and thus undergo wide variations in the presence of speed reference and load torque changes. The rotor-load set inertia and rotor friction coefficient may also vary (e.g., in transportation applications). To maintain the control

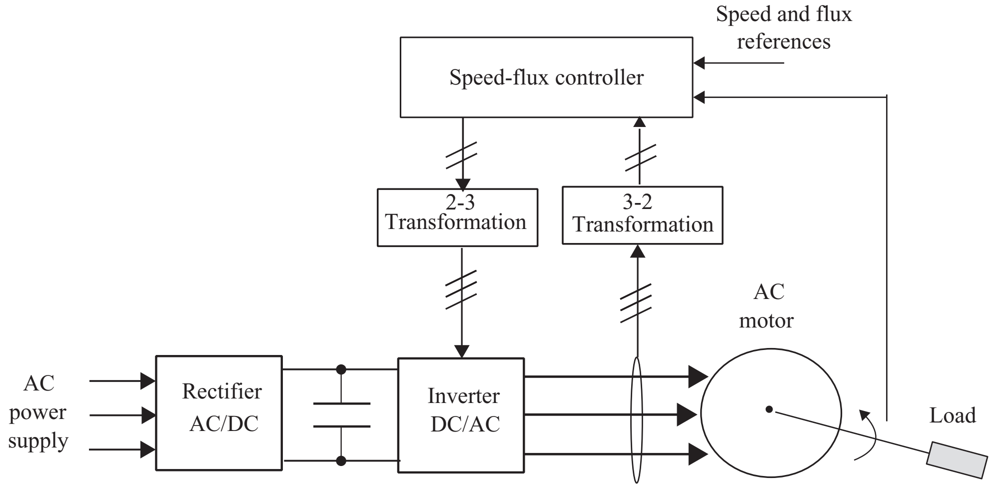


**Figure 1.2** AC motor basic control strategy: state-feedback speed control

performance at the desired level despite changing operating conditions, the speed controller may need to be reinforced with a parameter adaptation capability (Krstic, Kanellakopoulos, and Kokotovic 1995; Astolfi, Karagiannis, and Ortega 2007).

Another limitation of the control strategy of Figure 1.2 is that all state variables are assumed to be accessible through measurements. However, reliable and cheap sensors are only available for stator currents and voltages. Flux sensors are generally not available on machines because of their high implementation cost and maintenance complexity. Mechanical sensors (for speed and, more rarely, torque measurements) are common, but also entail reliability issues and extra maintenance costs due to physical contact with rotor. Therefore, state observers are attractive to obtain online estimates of the states based only on electric measurements (Besançon 2007). Sensorless controllers involving online state estimation using observers are commonly referred to as output-feedback controllers. Modern control strategies, illustrated in Figure 1.3, combine both features: parameter adaptation and sensorless output-feedback.

### *1.2.3 Fault Detection and Isolation, Fault-Tolerant Control*

Like any complex system, AC motors are facing faults in otherwise normal operating conditions. Faults may originate from the failure of certain system components, for example, sensors, inverter, rectifier, power supply, or even stator/rotor windings. Sensor failure may result in a loss of observability, while inverter, rectifier, or supply failure may cause a loss of controllability. Regardless, the controller designed on the basis of a faultless model may see its performance deteriorate drastically, sometimes causing unsafe operation of the whole system. To prevent unsafe running and continuously guaranteeing an acceptable level of performances, a fault-tolerant control (FTC) system is needed. The development of FTC systems has been an active research topic, especially over the past 15 years, and a review of relevant concepts and methods can be found in Blanke *et al.* (2000), Steinberg (2005), and Zhang and Jiang (2008), and Noura *et al.* (2009). Distinction is usually made between passive and active FTC

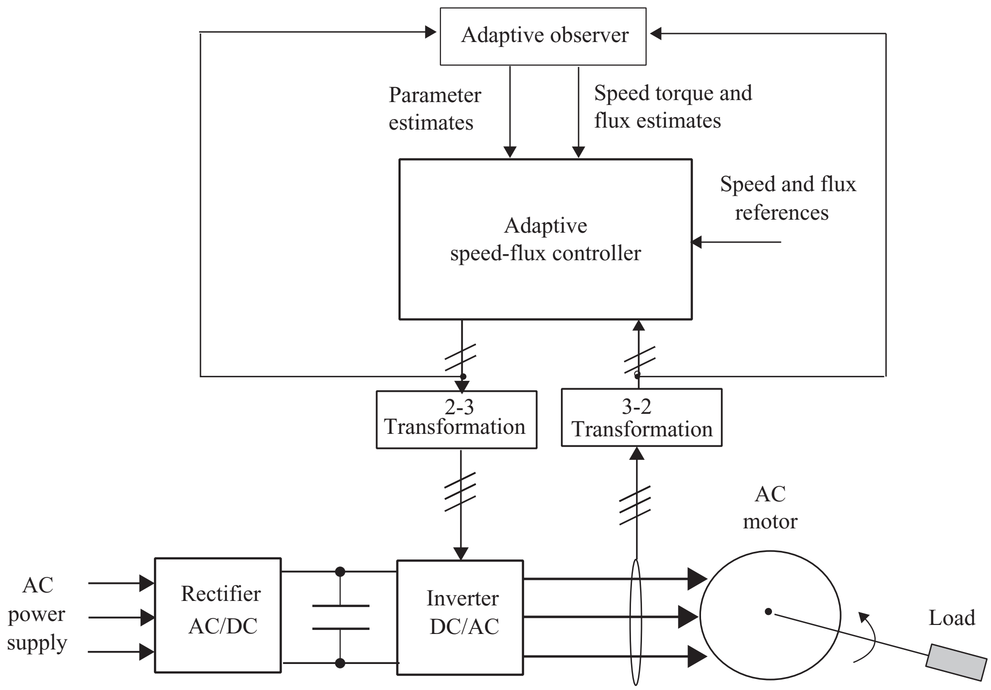


**Figure 1.3** AC motor modern control strategy: adaptive output-feedback speed control

approaches. In the first case, component failures are considered as disturbances and a single control law is designed so that it is robust against the predefined set of disturbances. The active FTC approaches are those that dynamically react to fault occurrence by performing control reconfiguration. This is mainly done in two ways:

1. Selecting online (within a set of predesigned laws) the control law that best fits the detected fault type.
2. Redesigning online the control law to adapt it to the detected faulty situation.

Active FTC approaches require a fault detection and isolation (FDI) module. The role of the latter is twofold:

1. Making a binary decision, either that something has gone wrong or that everything is fine.
2. Determining the location as well as the nature of the fault.

FDI techniques are broadly classified as information-based, model-based (MB), and artificial-intelligence-based. An overview of MB techniques is provided by the survey papers Willsky (1976), Isermann (1984, 2005), Hwang *et al.* (2010). In this respect, observer-based FDI is particularly suitable to build up FTC in presence of mechanical sensors failure. This is illustrated in Figure 1.4.

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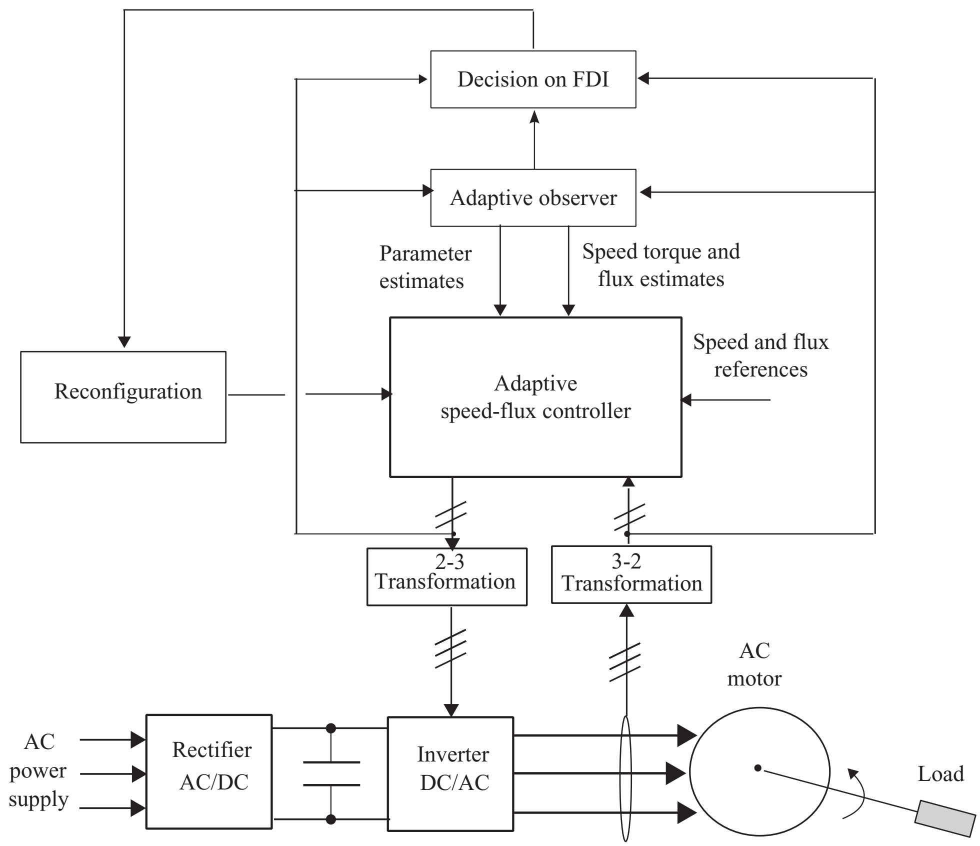


**Figure 1.4** AC motor fault tolerant control strategy: failure mechanical sensors accommodation

### *1.2.4 Speed Control with Optimized Flux*

It is common to set the flux reference to a constant value that generally equals the machine's nominal flux. However, energetic efficiency is only maximal when the motor operating conditions, essentially determined by the load torque, remain close to the nominal conditions. In practice, the torque may be subject to wide-range variations. Then, in presence of small loads (compared to nominal load), maintaining the nominal flux entails a waste of energy and a lower than optimal energetic efficiency. However, if the motor flux is given a small value, the achievable motor torque may not be sufficient to counteract large load torques. In general, speed-control strategies involving constant flux references do not guarantee optimal machine performance in the sense of maximal energetic efficiency and maximal torque. To remove the above shortcomings, it is necessary to let the flux reference be dependent on both the speed reference and the load torque. Thus, the flux reference must be state-dependent (Figure 1.5). Flux weakening is also used for both synchronous and induction machines to maximize the torque at high speeds in the presence of voltage constraints.

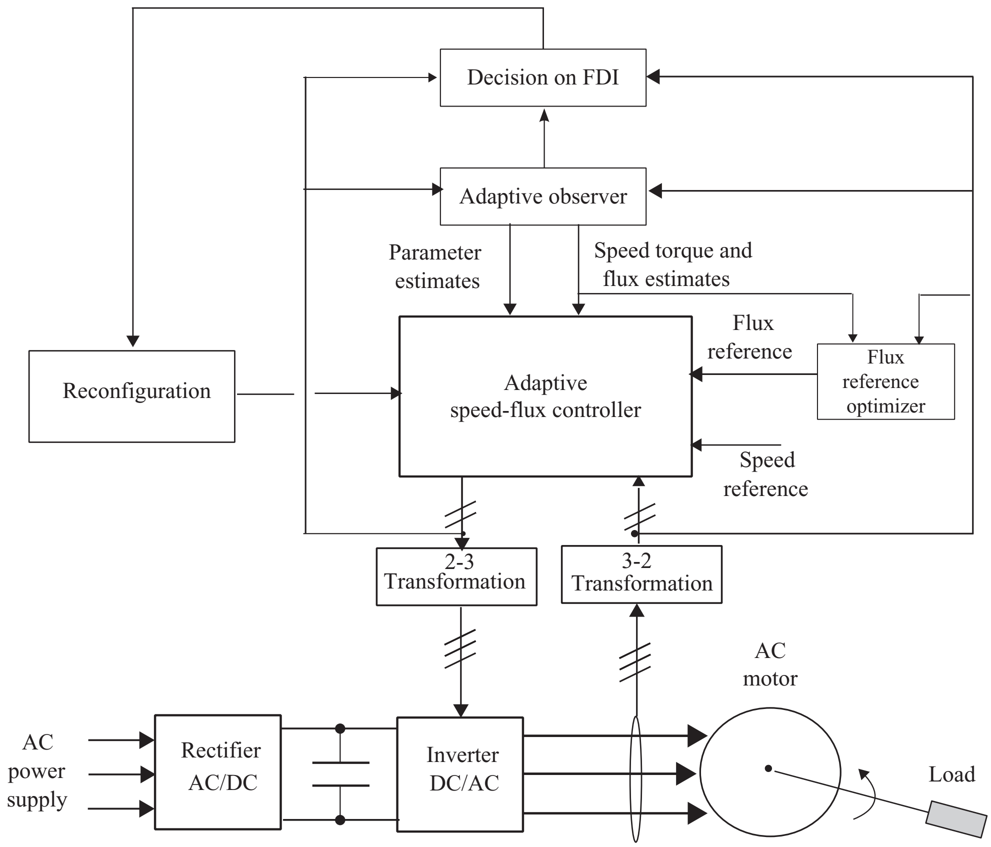


**Figure 1.5** AC motor control strategy combining ftc and flux optimization

### 1.2.5 *Power Factor Correction*

The role of the rectifier in Figures 1.2, 1.3, 1.4, and 1.5 is to convert the supply AC power into DC power and transmit this power through a constant DC link voltage. Regulation of this voltage is desirable for the AC motor to operate effectively. Moreover, the rectifier-inverter-motor set strongly interacts with the AC power supply net as the power flow is bidirectional: the direction depends on the speed profile and on load variations. Then, undesirable current harmonics are likely to be generated in the AC line, due to the strongly nonlinear nature of the association “rectifier-inverter-motor.” This harmonic pollution has several damaging effects on the quality of power distribution along the AC line, for example, electromagnetic compatibility issues, voltage distortion, larger power losses, and so on. In this respect, existing standards (e.g., IEEE519-1992 and IEC 61000-3-2/IEC 6100-3-4) indicate specific current harmonic limits, expressed in terms of power factor. Of course, the harmonics and power factor correction (PFC) can be improved using additional equipment and/or over-dimensioning the converter. However, this solution is costly and may not be sufficient.

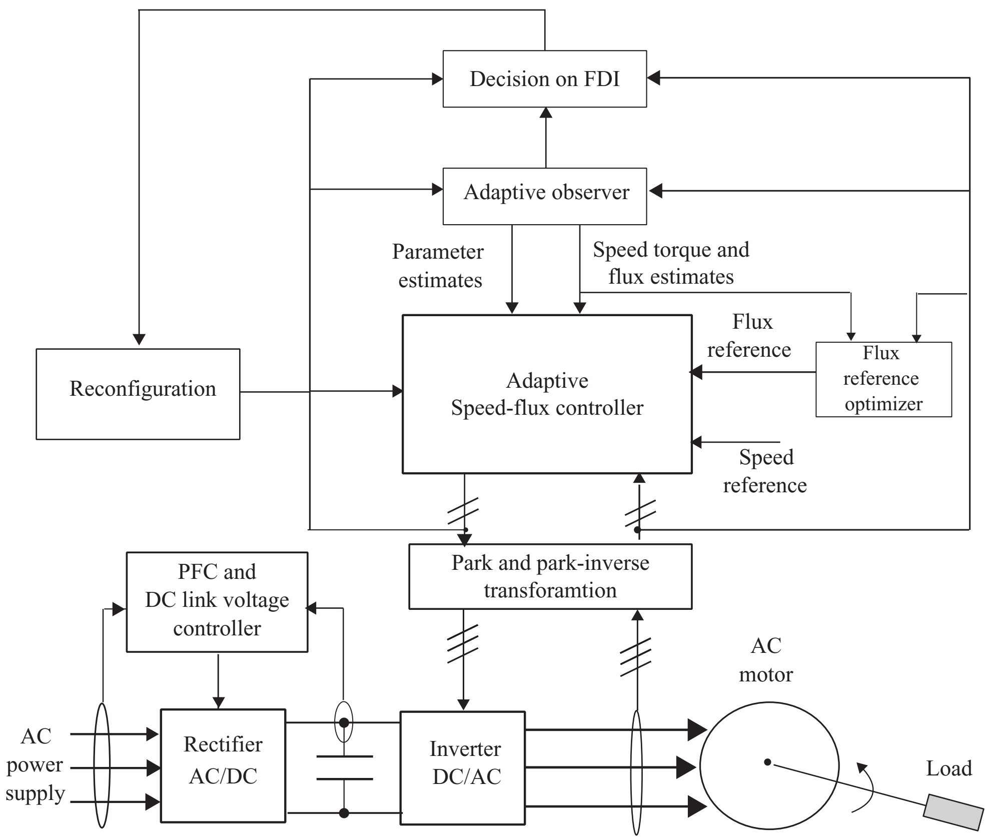


**Figure 1.6** AC motor global control strategy combining ftc, flux optimization and PFC

In light of the above remarks, it becomes clear that a high-performance control strategy deals with the control problem for the whole "rectifier-inverter-motor" set, seeking simultaneous achievement of all relevant control objectives, namely, tight speed regulation for wide set-point variation range, FDI, flux optimization despite large load changes, and PFC. Figure 1.6 describes a global control strategy accounting for all requirements.

## 1.3 Book Overview

The main control problems relevant to AC motors have been briefly described in the previous section. The present book is not intended to be an encyclopedic survey of all existing solutions for all types of AC machines. It rather aims at showing how modern control methods involving sophisticated design and analysis techniques are beneficial to AC motors. The focus is on the most significant types of AC motors and a representative sample of application fields. The book gives an illustrative presentation of the motors and control methods, referring to specialized monographs for the required technical background in machine theory. In addition to the present introduction, the book includes 22 other chapters organized in five parts, briefly overviewed in the following subsections.

### *1.3.1 Control Models for AC Motors*

The first part of the book is about modeling of AC motors and their relevant power converters. It consists of Chapters 2 and 3, respectively, which are devoted to induction motors and synchronous motors. The physical principles of these machines and associated power converters are recalled. The corresponding three-phase models are established, and it is shown how simpler two-phase models can be obtained using specific coordinate transformations. Identification methods are presented for estimating the model parameters using experimental data. The established models will prove to be useful for control design in later chapters.

### *1.3.2 Observer Design Techniques for AC Motors*

The second part of the book includes four chapters on observer design for AC motors. Chapter 4 is about the design and analysis of sensorless state observers for induction motors. Estimation issues and observability properties in induction motors are reviewed. The case of lack of speed measurement and unknown electrical parameters is considered. Then, a unifying observer approach is presented that includes sensorless observer design and its convergence analysis. The performance of the approach is evaluated, both by simulations and experiments.

Chapter 5 deals with state observers for active disturbance rejection in induction motor control. Generalized proportional integral (GPI) observers are proposed, in combination with linear output feedback controllers, for the direct field-oriented control and the classical field-oriented two-stage output feedback controller design. An observer-based active disturbance rejection scheme cancels the lumped effects of exogenous, time-varying, load torque disturbances, and of the endogenous state-dependent nonlinearities. The high-gain GPI observers estimate online the output phase variables and the lumped disturbance inputs affecting the underlying linear dynamics. Experimental results are presented for angular velocity and angular position trajectory tracking tasks, when the induction motor is subject to chaotic load torque profiles generated by an armature current programmed DC motor.

In Chapters 4 and 5, the nonlinear state observers are developed for induction motors assuming a continuous-time implementation. However, in modern control applications, continuous-time systems are only observed through sampled output signal measurements. Then, a classical solution consists of constructing a discrete-time approximation of the (continuous-time) observer. This solution is somewhat burdensome computationally, and does not necessarily preserve the convergence properties of the original continuous-time observer. Chapter 6 presents a different solution based on the hybrid continuous-discrete estimation principle. Hybrid observers are designed for induction motors taking into account communication constraints. They are formally shown to maintain satisfactory estimation accuracy when applied to the (continuous-time) system model, and the theoretical result is confirmed using experimental data.

Chapter 7 is on observer design for permanent-magnet synchronous motors (PMSM). A special emphasis is placed on the loss of observability arising at zero-speed without mechanical sensors. This issue is dealt with by using an observer design method based on a high-order SM. The obtained observer turns out to be robust against disturbances and avoids the chattering phenomenon inherent to standard first order SMs. Stability and finite time convergence of the observer are analyzed and commented upon. Experimental results are carried out to highlight the technological interest of the proposed method. The constraints and issues of real-time computation are discussed.

### *1.3.3 Control Design Techniques for Induction Motors*

The third part of the book includes seven chapters dealing with control design techniques for induction motors. Chapter 8 is about the use of high-gain observers in the control of induction motors with and without rotor position sensors, emphasizing closed-loop analysis of field-orientation schemes, and including the impact of orientation errors. The framework for studying field orientation in the presence of model uncertainty is used to design and analyze a nonlinear output feedback controller that requires only measurements of the rotor position and stator currents. The controller is designed to be robust to uncertainties in the rotor and stator resistances as well as to a bounded, time-varying load torque. A high-gain observer is used to estimate the rotor speed and acceleration from its position measurement. The same framework is extended to a case where only stator current measurements are available. In this case, a high-gain observer is used to estimate the speed from the field-oriented currents and voltages.

Chapter 9 is on adaptive output-feedback control of induction motors. It addresses the problem of adaptively controlling induction motors in order to achieve rotor speed and flux magnitude tracking, all without resorting to mechanical sensors. Uncertainties in the load torque and the rotor and stator resistances are accounted for. Adaptive output-feedback controllers are developed and formally shown to solve the control problem. The controller involves online estimation of the unknown parameters. The specific observability and identifiability conditions that allow for the exponential tracking and identification of the uncertain parameters are emphasized in terms of persistent excitation conditions. The key idea of the control and estimation design relies in adopting a two-time scale strategy by performing a sufficiently slow adaptation for the stator resistance estimate.

Chapter 10 is on nonlinear control of induction motors for speed regulation with maximal energetic efficiency. It is noticed that optimization cannot be properly coped with if the magnetic circuit nonlinearity is not accounted for. The controller includes an optimal flux reference generator (optimal in the sense of minimal stator current consumption) and a nonlinear regulator obtained using the backstepping design technique. It is shown that the controller regulates well the motor speed and the rotor flux in presence of wide-range variations of the machine speed reference and the load torque.

Chapter 11 presents an experimental evaluation of two robust control design techniques for induction motors, including a nonlinear backstepping technique with integral terms that improve robustness against parametric uncertainties, and a high-order SM technique designed for its intrinsic robustness quality. The two controllers are experimentally compared using an industrial benchmark setup.

Chapter 12 is on multiphase induction motor control. The motor is represented by a new complex dynamic model where the harmonic injection is considered and represented using the power-oriented graphs graphical technique. Different field-oriented control strategies are designed in the multiphase and compared by investigating the trade-off between the different solutions that differ in required control degrees of freedom.

Chapter 13 is on the control of a wound rotor, or doubly-fed induction machine (DFIM) and associated AC/DC rectifier and DC/AC inverter. A multiloop nonlinear controller is developed using the backstepping design technique. It includes three regulators of rotor speed, DC link voltage, and PFC, respectively. The controller is formally shown to meet its objectives, that is, accurate motor speed-reference tracking, tight regulation of the DC Link voltage, and PFC.

Chapter 14 is on FDI in induction motors. Both MB and data-driven (DD) methods are developed. The MB approach involves SM observers based on residual evaluation and thresholding. DD methods, also referred to as "motor current signature analysis" (MCSA), are designed using processing techniques based on FFT, Hilbert transforms, and more advanced time/frequency combined analysis techniques.

### *1.3.4 Control Design Techniques for Synchronous Motors*

The fourth part of the book includes six chapters on synchronous motor control. In Chapter 15, PMSMs are considered and the control problem is solved using a passivity-based output-feedback control. The structure of the main block of the controller comes from the application of the technique of interconnection and damping assignment passivity-based control. It involves different observers that estimate the mechanical coordinates (speed and load torque) and stator fluxes (which, in turn, are used to obtain information related to the mechanical position). Both simulation and experimental results are included.

Chapter 16 is on adaptive output-feedback control of PMSMs. Assuming that only stator currents and voltages are available for feedback, a novel sixth order nonlinear adaptive control algorithm is designed, which does not rely on nonrobust open-loop integration of motor dynamics and guarantees, under persistency of excitation, local exponential rotor speed tracking. Satisfactory performance is obtained even in the presence of inaccurate motor parameters, time-varying load torques, current sensing errors, and discrete-time controller implementation.

Chapter 17 is on robust fault detection and control of PMSMs. It proposes first a robust speed observer making use of currents measurements only. Next, a control law fed by speed observations is presented, and closed-loop stability of the overall system is proved robustly with respect to parameter variations of the dynamic model of the motor (inertia, friction, and load) with known bound. Finally, a residual-based detection approach is discussed for sensor faults affecting current measurements.

Chapter 18 is on digitization of variable structure control for PMSMs. SM controllers are designed to control the motor position and velocity and currents. The aim is to suppress mechanical resonance and reach high performances of PMSM servo systems, such as fast response, strong robustness, and high precision. In addition, an SM-based mechanical resonance suppressing method is proposed. An observer is applied to estimate the load speed and the shaft torsion angle. Finally, a high-order SM control is designed to guarantee the stability of the system. The digitization of the designed SM controllers is discussed for the purpose of practical implementation. The discretization behaviors of PMSM servo systems are analyzed, which helps obtain approximate boundary conditions for the sampling period.

Chapter 19 is on the control of interior permanent-magnet (IPM) synchronous motors. The control trajectories in terms of the current and voltage limit boundaries for optimum drive response is discussed. Techniques of sensorless control are proposed via direct torque control (DTC) in the stator *dq* flux estimation and in the rotor frame via stator flux and rotor position observers. Both open- and closed-loop operations are described. Techniques of sensorless control combining signal injection and observer methods at very low speed and covering a wide speed range are also included.

Chapter 20 is about nonlinear state-feedback controllers for three-phase wound-rotor synchronous motors. Considering the "converter-motor" set, the method makes it possible to provide motor speed regulation, in addition to other important control objectives such as PFC with respect to the grid supply and DC Link voltage regulation. To achieve these objectives, an adaptive control strategy is developed, based on a nonlinear model of the whole "converter-motor" set. The adaptation feature is motivated by the uncertain nature of some motor characteristics, for example, mechanical parameters. The closed-loop system stability and performance properties are formally analyzed using averaging theory.

### *1.3.5 Industrial Applications of AC Motors Control*

The last part of the book consists of three chapters devoted to applications of AC motors in some industrial fields.

Chapter 21 is on AC motor control applications in vehicle traction. It describes the requirements of vehicle traction applications that AC drive systems must meet. The chapter reviews recent trends of vehicle traction drive architectures in the marketplace and in the available literature. It discusses suitable motor types, control requirements, energy storage and management issues between drive and regenerative braking modes of operation, and battery sizing. The battery management system with temperature compensation for charging and discharging current limits and for monitoring the state of charge (SOC) are discussed. The converter systems between batteries and the motor drive are designed for efficient management of bidirectional power flow. Examples of vehicle traction systems that use induction and IPM machines are included, as well as other types of machines in commercially available traction applications.

Chapter 22 is on induction motor control applications in high-speed train (HST) electric drives. It illustrates how state observers can be useful in fault diagnostic for modern high-speed electric traction applications. State observers are used for online estimation of motor speed and load torque. The analysis of speed and load torque signals makes it possible to assess the state of speed sensor and torque transmission systems in electric traction vehicle. When some malfunctioning is detected, for example, in the case of speed sensor faults, the motor control system can be switched to speed sensorless mode. The proposed diagnostic system is applied to a HST propelled by an induction squirrel-cage motor. Simulation and experimental results for a high-speed traction drive are presented.

Chapter 23 is on AC motor control applications in high-power industrial drives. The applications discussed include steel mills, cement and ore mills, ship drives, pumps and compressors for petrochemicals and electric power industry, paper mills, and so on. The brief features of the industrial AC drives developed by the leading manufacturers worldwide are presented together with new developments and trends for the future.

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