Introduction

For the countless operations of its machine tools, its robots and its "special machines", modern industrial production is in dire need of electrical motors that can be used as "actuators": these machines must impose a torque, speed or position on objects in movement (most often in rotation), all of which are determined by a high level decisional element. Execution speed and accuracy are necessary for high-quality productivity. Electrical motors have thus taken a dominant place in the "axis control" that we find everywhere in modern industrial production. We also find such motors in several "consumer product" applications, even if we will consider mainly professional applications in this book. Electrical motors are also present in the motorization of several modes of transport: terrestrial vehicles, free or guided, and ships. The present work specifically covers the "non-conventional" controls of synchronous actuators, and the control of "non-conventional" synchronous motors.

This book is part of a series published by ISTE-Wiley and Hermes-Lavoisier. The first book, devoted to the *Control of Synchronous Motors* [LOU 11], which studies "conventional" synchronous motors, has already been published in English. Let us add that another volume has been devoted to the identification and to the observation of electrical machines [FOR 10]. A further volume has presented general methods regarding the control of electrical machines [HUS 09], and still another has focused on technological problems [LOR 03]. The control of electrical actuators goes with the control of static converters (here, inverters); it has been the topic of a volume [MON 11] that deals with modulations and current controls. Finally, a work has been published on the design of electrical drives [JUF 10] and a book on the diagnostics of electrical machines [TRI 11].

In the previous book, entitled *Control of Synchronous Motors* [LOU 11], we presented the main advantages of electrical actuators, referred to as "synchronous

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Introduction written by Jean-Paul LOUIS.

motors”, in detail. The essential advantage comes from their high performances in terms of mass torque ratio, their maneuverability and their ease of use – these are all relative, but real, factors of their use. Thus particular uses of the synchronous motor that have been created have received various names, such as: the “self-controlled synchronous motor”; often known in industry as the “brushless DC motor”. This first work on synchronous motors dealt specifically with the modeling and control of synchronous actuators *when these are (more or less) conventional synchronous motors*.

Hence it is in this book [LOU 11] that we find the classical models of synchronous machines that either fulfill the hypothesis of the first harmonic: the Magnetomotive Force (MMF) wave is sinusoidal (leading to the usual “Park model”) or do not fulfill it (“extension” of Park models when the MMF wave is non-sinusoidal). On the basis of these models, the first volume presented fundamental concepts such as “self-control” and classical torque control, in the natural referential (*a-b-c*) or the rotor referential ($d - q$). These controls are often referred to as “vector controls” and they are often applied to “axis control” − the speed regulations and/or position regulations of a “mechanical load”: a tool, for instance, or a wheel. We have considered the problems with their implementation by digital components. We consider that these controls are now “classical”. This volume therefore presents the “advanced controls” that are still applied to conventional synchronous motors: *direct torque control* and *predictive controls*. Finally, the self-control − which lies at the centre of most classical controls − normally requires a mechanical position sensor. As, for many reasons, we often do not want to install one, “sensorless” controls, deterministic or statistic, are also presented.

This present book, the second about the control of synchronous or similar motors, has two parts. The first part deals with *non-conventional uses* of the synchronous motor (motors supplied by thyristor bridges, motors in degraded modes, and multiphase motors). The second part deals with the control of actuators that the community of specialists usually refer to as *non-conventional motors* (hybrid motors, linear motors, variable reluctance motors, stepping motors, and piezoelectric motors). These deserve to be associated with synchronous actuators, because their structures most often link them to synchronous machines, with or without excitation. In the title of this work, the adjective “non-conventional” hence has two meanings.

The first part contains five chapters. It starts with two chapters that complement each other on “self-controlled synchronous machines” supplied with thyristor bridges. These assemblies are, historically, the first to have appeared, since the thyristor was the first component in controllable modern power electronics (after the era of vacuum tubes) that appeared industrially. With the development of GTO (gate turn-off thyristor) and of different types of power transistors (Insulated Gate Bipolar

Transistor (IGBT), etc.), this assembly has been restricted to high and very-high powered machines. Furthermore, it remains present in old industrial assemblies that need to be maintained. This device was ingenious and robust. Two thyristor bridges allowed operation in the four quadrants. It allowed genuine self-control, but was complex because the thyristor bridge is − approximately − a pulsed current source, and we need to take the overlap phenomenon in a thyristor bridge into account when it works as a line commutated inverter, which is conceptually more delicate than the rectifier mode. Besides, it was necessary to deal with synchronous machines with dampers and coiled excitation, supplied with a line commutated inverter. There is therefore a very noticeable scientific culture and know-how in this area, which Chapters 1 and 2 present in essential detail.

Chapter 1, by Francis Labrique and François Baudart, is entitled "Self-controlled synchronous motor: principles of function and simplified control model". It presents this device within the framework of approximations often adopted by engineers: thus "transient inductance" is defined and simple electrical diagrams are given for modeling the synchronous machine/thyristor bridge set. However, the currents generated are pseudo pulses (the importance of overlap), so we also need to take into account current harmonics. Thus, analysis, even in steady state, leads to non-trivial, nonlinear models. Chapter 1 analyzes different modes of operation: at the nominal regime and below the nominal regime, operation as a motor and operation as a generator.

For the analysis of transient regimes, a powerful approach consists of performing equivalence between the synchronous machine supplied with the self-controlled thyristor bridge and a direct current (DC) machine with a collector with three segments. The position of the brushes is imposed by the self-control and the rotor position. We can then apply the theory of sliding contact circuits (due to Manuel da Silva Garrido and Ernest Matagne, see also the first chapter of [LOU 04a]) by "averaging" the signals on each switching interval. We then obtain a global dynamic model of the set synchronous machine/thyristor bridge/self-control. It allows us, for instance, to determine the alternating currents in the dampers.

Chapter 2, by Ernest Matagne, is titled "Self-controlled synchronous motor: dynamic model including the behavior of damper windings and commutation overlap". The author studies the same device as in Chapter 1 without keeping the classic engineering approximations. The first issue to deal with is that of the overlap, which plays a sensitive role in the current form and in the torque harmonics. The second concerns the flux dynamics, including those in the dampers. The author finally presents a dynamic model of electrical variables that are coupled with electromechanical variables imposed by control of the thyristor converter. The author thus obtains an accurate torque equation. This approach using equations leads to block diagrams that are adapted to control problems and to the determination of transients. These models, which are powerful and accurate, are completely original and contribute to knowledge on the tools that enable the synthesis of high-powered self-controlled synchronous machines.

Chapter 3, "Synchronous machines in degraded mode", by Damien Flieller, Ngac Ky Nguyen, Hervé Schwab and Guy Sturtzer, also deals with the non-conventional operation of a synchronous actuator. This chapter is about the study of optimization of operations when there are defects in a converter-synchronous machine set. It is an opportunity to remind ourselves of the importance of safety issues in electrical drives: a variator must be able to carry on working, even in the case of a partial breakdown. Several studies have been devoted to these issues, and the present chapter presents an overview of possible failures, the most frequent happening at the level of power transistors (the accidents mostly generate short-circuits and, less frequently, open circuits). Accidents at the level of the windings are far less numerous. These defects normally generate important perturbating torques, which are added to the cogging torque.

In the spirit of the methods to supply "healthy" synchronous machines presented in Chapters 2 and 3 of *Control of Synchronous Motors* [LOU 11], the authors present a general approach of the following problem: how can we optimally supply the "healthy phases" of a machine to compensate for the defects due to accidents? The authors of Chapter 3 in this current book exploit a general optimization method in the case of a *n*-phase machine, with smooth poles and sinusoidal or non-sinusoidal induced *back emfs*, with at least one faulty phase. In this phase, the current can be: 0 (open circuit) or equal to a saturation value, or be a short-circuit current. The general optimization method allows us to calculate the current to be applied in the healthy phases to impose the desired torque while minimizing Joule losses, and fulfilling the constraints on the zero sequence component of the current (free or 0). Despite the multiplicity of possible cases, the authors show the existence of a global formulation marking the intervening back emfs and a scalar coefficient of proportionality, $k_{opt}\left(p\theta\right)$, which varies periodically as a function of position. Coefficient $k_{opt}\left(p\theta\right)$ can be determined theoretically when we know the defect conditions. But these are often difficult to determine in real time. Another good strategy involves identifying $k_{opt}\left(p\theta\right)$ using a learning device, which is allowed by neural networks (the Adaline network). This self-adaptive control allows the currents to reach their optimal values, which are adapted to the defect after a few periods.

The following chapters show an extension to non-conventional synchronous motors. The classic optimization of electrical machines has led to the design and domination of three-phase AC electrical machines. In fact, the three-phase machines optimize the power to mass ratio: they minimize the number of of conductors (and the copper is expensive) and the mass of magnetic circuits (which are made of iron). The three-phase circuits also optimize the number of components in power electronics converters that supply the machines.

New optimization criteria have, however, appeared, particularly in sensitive domains such as air and naval transport, where propulsion equipment failure has catastrophic consequences. It has become necessary to improve *the reliability and safety of operation* by segmenting power. This can be done using a technical solution using machines with a greater number of phases, supplied with static converters with the appropriate number of legs. If a phase (of the machine or converter) is faulty (for reasons of aging or because of accidents with internal or external origins), the phases that remain in working state allow the system to continue working properly. Several types of technical solutions exist for multiphase synchronous motors; we present them in Chapters 4 and 5.

In Chapter 4, "Control of the synchronous double-star machine supplied by PWM inverters" written by Mohamed Fouad Benkhoris, if a three-phase coil is faulty, the system can still work thanks to the other three-phase coil and thus ensure continuity of service. We can see its advantage, for example, in the propulsion of a ship, for instance. The two coils can be "overlapped" or "shifted". These different solutions exist and distinguish these machines from "conventional multiphase machines" where the phases are all regularly shifted. As it is supplied by inverters controlled in PWM (Pulse Width Modulation), this operating mode allows the generation of sinusoidal currents and the limitation of torque ripples. This property, well known for conventional three-phase machines, presents intrinsic difficulties for these non-conventional machines because of magnetic couplings between their two three-phase coils.

The author describes the two approaches to modeling this machine for control design. The first approach consists of acting as if the machine was made of two classical three-phase machines (each being modeled and controlled with the help of classic Park theory − see the first chapters in *Control of Synchronous Motors*, the first book in this series) and taking into account the couplings between these two machines at a higher level. The second approach introduces the coupling from the initial modeling of the six-phase machine and defining an equivalent machine by an extension of the Park approach, and inferring control by "inverting" this model. The mathematical models that allow us to represent these special machines in a user-friendly way are detailed, the essential element being to diagonalize the stator inductance matrix of the double-star machine in order to define a "good" referential frame and "useable" state variables. The controls are inferred from this modeling by an approach that generalizes the "vector control", which is well known in conventional machines, with the "regulation" terms of currents and the "decoupling" terms. Fouad Benkhoris shows that different solutions are possible. He details and validates the main ones: partial diagonalization and total diagonalization.

Chapter 5, by Xavier Kestelyn and Éric Semail, is called “Vector modeling and control of multiphase machines with non-salient poles supplied by an inverter”. The synchronous machines considered have phases that are regularly shifted, like conventional three-phase machines, and show two variants: machines where the phases are independent and single-star machines. The excitation is generated by surface-mounted permanent magnets. The reference example has five phases − but to model the machines, the authors use a vector formalism that can easily be generalized to *n* phases. It is shown that we can determine a referential frame where the inductance matrix is diagonal, which allows us to implement high-performance control.

Thanks to their approach, the authors generalize the well-known properties for the three-phase conventional machine by defining “fictitious machines” that can be equivalent two-phase machines (that take part in the energy conversion) or single-phase machines of “zero sequence” type. In parallel, the theoretical analysis provides useful information: it shows the advantage of star couplings for machines with an odd number of phases, and shows the use of multi-star couplings for machines with an even number of phases. The analysis also answers the questions that arise with the use of higher-order harmonics and shows the necessity of knowing the leakage inductances well. This is very important at the time of design and supply of the machine, and when elaborating control laws to optimize the torque. The authors present different optimal strategies to control the currents of multiphase machines, in different appropriate frames of reference, in order to supply a given torque by taking into account the problem of the distribution of torques between the different fictitious machines. All the methods are validated by experimental results.

The second part of this book contains five chapters that discuss increasingly non-conventional machines; their proximity to synchronous motors is relative, but they are closer in some aspects.

Chapter 6, by Nicolas Patin and Lionel Vido, is entitled “Hybrid excitation synchronous machines”, concerns an immediate extension of the synchronous motor. Even if it remains minor with respect to the conventional synchronous motor with a single magnet excitation, its importance is significant since it extends the performances of the actuator by playing on its excitation. We are in dire need of this in applications linked to transport (terrestrial vehicles and avionics). The problem of the overspeed and flux weakening of synchronous motors is frequently considered, and this chapter presents it as a particular case of the general case considered of the hybrid excitation synchronous machine: a first (fixed) excitation is generated by magnets, and a second (adjustable) excitation is generated by winding coils.

The chapter distinguishes two large families: machines in “series” and machines in “parallel”, according to whether the field lines generated by the windings pass through the magnets or not. The machines in series are high-performance for flux weakening, but more sensitive to demagnetization. There is an advantage of machines in parallel, which can be of short-circuit or non short-circuit type. Short-circuit type machines improve operating safety during an accident involving the legs of the supply bridge, but part of the flux is lost. No short-circuit type machines partially correct the previous inconvenience. The excitation winding coils can be placed at the stator or rotor, and the structures can be with “flux concentration” or “flux-switching”. Whatever structure is adopted, the modeling for control design is a simple extension of conventional modeling of the synchronous machine where the flux embraced by the stator coils is the sum of two fluxes − one generated by the magnets and the other by the windings. The Park representation is well adapted for simplicity and efficiency, even if it (naturally) leads to more complex equations than that which have been given for conventional machines in Chapter 1 of *Control of Synchronous Motors*. The authors infer a simulation functional diagram in the form of block diagrams. The model being obtained, the control law is obtained by its inversion. Since there are more unknown variables (three currents) than equations (one torque), the solution is given by optimization (minimization of losses). The authors give the control diagrams with different regulation loops and the “optimizers”. This approach is also applied to the easier case of flux weakening in the classic single excitation actuator.

Chapter 7, by Ghislain Remy and Pierre-Jean Barre, presents the “Advanced control of the linear synchronous motor”. Initially restricted to induction motors, the linear structure has largely been developed for synchronous motors thanks to permanent magnets and the associated electronics (power and control). We thus have motors with direct linear drive (without reducer or transmission systems − these are costly and introduce defects) at our disposal that are adapted to specific solutions. These include, for example, actuating ultra-fast machine tools (with very high accelerations and speeds) that we want to be extremely rigid and very precise. The authors describe the building structures specific to this class of motors, the “permanent magnet synchronous linear motor”, (PMSLM) that is monolateral with short primary. Then they give models. The first model, in the first harmonic sense (as for conventional rotating motors), is presented and the authors infer a dynamic model formalized by a causal ordering graph (COG). Advanced models allow us to describe phenomena specific to linear motors: the rank 5 and 7 harmonics, the nonlinearities of inductances during the quick current transients, the cogging forces due to the end-effect forces − all these phenomena introduce ripples on the thrust (cogging).

The authors present the conventional controls of the synchronous linear motor: scalar controls (with *V/f* = constant) and vector controls with diverse variants. The authors develop controls by “model inversion” (obtained from COG), which imposes structures with cascade loops. The current loop is inferred from the first harmonic model and dimensioned according to the capabilities of the inverter. To compensate for the cogging forces, the authors present advanced controls such as the use of multiple resonant controllers or feed-forward controls. Finally, rank n derivative controls (or open loop precontrol, in the sensorless case) are presented, which require an analysis and very precise models. The authors show that the generation of the reference value is the major problem for control of the motor when we take into account nonlinear phenomena.

Chapter 8, by Mickael Hilairet, Thierry Lubin and Abdelmounaïm Tounzi, is entitled “Variable reluctance machines: Modeling and control”. Here, we move even further from conventional synchronous motors, since only the reluctance effects (which exist on “salient pole” synchronous machines) intervene. We move further into the category of “non-conventional machines” with constructive variants that are far more numerous than those of conventional machine variants. This is why this chapter focuses on the two families of variable reluctance machines that are the most promising and the most frequently used in industry: reluctant synchronous machines (or synchro reluctance, Synchrel) that have coils *distributed* at the stator; and switched reluctance motors (SRMs), which have coils that are *concentrated* at the stator. There is no excitation at the rotor, which makes these machines very robust, particularly at high speed (when the rotor is often massive). It is this quality that is looked for, because these machines are susceptible to disadvantages (involving torque pulsation and noise for SRMs), also we need to optimize the structure of the machines and their supply.

This chapter first describes the main structures of the Synchrel that must maximize the saliency effect. The authors propose their modeling, which is largely analytical, for control design. The torque is proportional to the product of currents (stator) i_d and i_q, which defines only one equation, so we need to optimize a criterion. Thus, if we optimize the dynamics, we can work at constant i_d. If we maximize the torque for a given current, we need $i_d = i_q$. The authors also present the maximization of the power factor. We often find “vector control” structures that compensate for perturbations terms between the d and q axes. SRMs have a larger field of application than Synchrel machines, their performances being better. SRM operation is situated largely in zones where the machine is saturated. The optimization (of its design and supply) and the modeling must be done within nonlinear frameworks, even if a linear model can be considered for a first synthesis. The nonlinear modelings require the use of coenergy. The implantation makes use of precalculated tables. The SRM only works if it is self-controlled with specific self-control rules. Control strategies − “instantaneous controls” and “average value controls” − are presented whose performances (including in terms of complexity of implantation) are analyzed and compared.

Chapter 9, written by Bruno Robert and Moez Feki, concerns the control of stepping motors. Stepping actuators are particularly well appreciated industrially because we can use them in open loop with a very easy and inexpensive voltage supply. Such a control will not be high-performance so very precise studies must sometimes be done to properly set the limits of use (for a given cost), and in cases where we want to introduce (a little) closed loop. The authors start by defining a generic stepping motor model that is actually a variant of the salient pole two-phase synchronous motor and the torque is described by three terms. The three most common types of stepping motors are:

− the permanent magnet motor (where the dominant torque term is the electromagnetic torque);

− the variable reluctance motor (where the dominant term is the reluctance torque); and

− the hybrid motor, where the cogging torque is taken into account.

The absence of a position sensor (for economical reasons), which is common, means that the control model remains in the “natural referential” (here: α and β, see Chapter 1 of *Control of Synchronous Motors*) and it is *strongly nonlinear*. The authors indicate the approximations that must be carried out on each type of motor.

In the generic case, the authors study which types of control can be executed: the open loop controls with a voltage supply (the most economical) or with a current supply (more costly), and the closed loop controls. For the first case (voltage supply) the modes allowing different operating types − the electrical quarter turn modes and the mixed modes − are presented. The second case (current supply, with a motor that is specially built for) allows microsteps. The authors detail the case of slow movements, the methods for starting, the oscillating responses, microsteps and optimal control (“bang-bang”). The study of quick movements allows us to define the different operating zones of the stepping motors: the stop-start zone and the drive zone. The authors show us how to obtain different speed and acceleration profiles that can be integrated into low-cost processors. Closed-loop controls, which require knowledge of the position, either by a coder or by estimation, are then discussed (see the last two chapters of *Control of Synchronous Motors*). They are therefore more costly and their economical advantage must be justified. The author presents an angle control, that is high-performance but costly. We can also infer frequency control, which is more economical because it can be implanted in open loop. The latter can be completed using a speed control (we therefore need to measure or estimate the speed); the authors provide methods of controller synthesis.

Controlled in open loop, the stepping motor has a strongly nonlinear behavior that restricts its performances at high speeds, where instabilities and “chaotic” phenomena appear. An advanced control method, referred to as “chaos control”, is presented that allows us to widen the operating zone towards higher speeds.

Chapter 10 concerns an actuator that is the furthest from classic synchronous motors. It is not electromagnetic, but electrostatic. Its control calls for analog concepts, such as self-control and vector control. This chapter is entitled “Control of piezoelectric actuators”, and has been written by Frédéric Giraud and Betty Lemaire-Semail. It concerns traveling-wave piezoelectric motors. These motors are an alternative to electromagnetic motors for small dimensions where they can bring a gain of factor 10 for the mass torque ratio. The motors considered are two-phase and are associated with a position sensor. The rotor and stator are in contact, and the mechanical friction phenomena play an important role that considerably complicates the modeling. The dynamic modelings are complex because there is a double energy conversion: electromechanical (indirect piezoelectric effect) and mechano-mechanical (by contact). The authors present the modeling using equivalent electrical diagrams that are restricted to steady states, and hybrid models that associate electrical and mechanical equations − the latter are more precise but too complex. The authors also develop a model that is specifically adapted to control in real time. In the frame of reference of equations of stator supply voltages, a “direct model” makes four domains appear:

− the electrical domain;

− the stator domain;

− the “ideal rotor” domain; and

− the “real rotor” domain.

The energy conversion is situated at the border of the stator domain with the ideal rotor domain, and we can observe an analogy (with duality) with the equations of the synchronous motor when we write its equations in referential α and β (see Chapter 1 of *Control of Synchronous Motors*). This analogy is taken advantage of: the authors infer a model in the referential frame of the travelling wave to obtain equations of $d - q$ type.

This model is formally easier and is well adapted to the determination of a control that will have to have self-control (as for controls of AC machines). It is also useful for defining a torque estimator. The authors then present the large families of control methods of the piezoelectric motor. The first, and most frequent, is based on a behavioral (black box) model, the control variables being able to be the frequency, the amplitude of two-phase voltages and dephasing between these two voltages. The relationships between these variables and the speed are not linear and can present dead zones that need to be dealt with specifically. This situation legitimizes the (less frequent) use of methods based on a knowledge model. This second model family is detailed by the authors, who rely on the "inversion" of direct models. This approach shows the advantage of control on the tangential axis and on the normal axis. It leads the authors to distinguish three strategies according to the variable considered: the normal speed of the ideal rotor, the pulsation of the supply voltages, and the voltage on path *d* in open loop. The authors show us how to create the self-control with the help of a phase locking loop. These controls allow us to avoid stalling phenomena and compensate for effects due to thermal drifts.

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