Introduction

For the countless operations of its machine tools, its robots and its "special machines", modern industrial production has a tremendous need for elements called "motors": these machines must impose on tools in motion (generally in rotation) a torque, a speed or a position, all determined by a high level decisional element. Execution rapidity and precision are necessary for a high productivity of quality. Electric motors have thus taken a predominant position in the "drive control". Consequently, they are found in modern industrial production – but also in many "general public" applications, even if in this book we will mainly discuss the professional applications. Indeed, they have a predominant position because of their maneuverability and their (relative but effective) ease of use. Hydraulic motors (for example) have much better performances in terms of "torque-mass ratio", but they are much trickier to control.

Historically, direct current motors were the first to be used because – in some aspects – they were ideal: excellent performances in terms of speed and of implementation ease, on the converter level (a thyristor rectifier or a transistorized chopper are sufficient), as well as on the controls level. Indeed, the "electromagnetic torque" is proportional to the "armature current". Therefore, a simple "current loop" imposes the torque, and then a "speed loop" is sufficient to produce a electronic "speed variator" (see on these topics Chapter 1 of [LOU 04b] written by J.-P. Hautier). The serious disadvantage of DC motors is the "mechanical collector" – the exact element which allows this ease of implementation. However, this mechanical "converter" could have fragilities (wear) and risks of accident in wet or dusty atmospheres. Moreover, the armature current circulates at the rotor. Therefore, cooling is not easy, which limits the motor performance, because the current and thus the mass torque cannot be very high.

Introduction written by Jean-Paul LOUIS.

The development of power electronics – involving the extension of the use of the inverters – has made it possible to supply the alternating current machines as easily as the direct current machines. There is however an additional constraint: we must know the rotor position, and therefore it is necessary to install a mechanical sensor (or to fulfill this function by other means), in order to carry out the "electronic collector" operation using a "self-control system".

This book belongs to a monograph series devoted to AC motors, and specifically discusses synchronous motor control, which has a prominent position among these motors. For a long time, the most widespread synchronous machine was the alternator, i.e. a generator. However, the operation is mainly in motor mode – even if during transients, it transfers to a generator mode. As long as we only had fixed frequency alternative sources, the synchronous motor could only turn at fixed speed. The development of power electronics completely changed this situation. Thanks to thyristor bridges (operating in "line commutated inverters") self-controlled synchronous motors first appeared: they were especially used in high powers, for rolling trains, for example, or for traction (the first high-speed French trains). The component development (transistors, GTO) for the "forced switching" inverters facilitated the variable frequency supply of alternating current motors and led to their development in a wide range of applications. Lastly, the massive arrival of microprocessors led to powerful controls, thanks to sophisticated and complex algorithms, which were executed very quickly in real time.

The first alternating current machine used as a motor was the synchronous motor, mainly with a permanent magnet excitation. The use of a position sensor (or of an equivalent function) made the self-control machine possible and, thus, made it operate (almost) like a DC motor: the torque is indeed proportional to a current (known as the "q axis", as we will see in Chapter 3). With respect to direct current motors, the synchronous motor has technical advantages. Initially, the "armature current" circulates at the stator. Therefore, cooling is easy. We can then have currents – thus torque-mass ratios – much higher than for DC motors. Also, there are no more fragility or safety problems because of the mechanical collectors, replaced by "electronic collectors" (without wear or sparks). The robustness becomes excellent. We understand that the components' manufacturers (the motors themselves, inverters, and controllers) developed very efficiently with competitive product ranges.

These synchronous machines, thus used, have received various names: "synchronous self-control motor" or "electronic switching synchronous motor". The industrial name is often "brushless DC motor", or "DC motor without collector"[1].

1. This term is often allocated to synchronous motors with trapezoidal field distribution, supplied with square wave currents, which will be discussed several times in this book.

The predominance of the synchronous motors with permanent magnet excitation is obvious, as most of the chapters of this book will testify. The reduction in manufacturing costs of high-efficiency permanent magnets is certainly at the origin of the scope expansion of these machines.

Competition has come from the other conventional AC motor, the induction motor. Thanks to its simple and robust rotor, this motor has the great advantage of being naturally more economical than the synchronous motor. This argument is industrially very strong. But the induction motor is more difficult to use for drive control. Much work has been undertaken in order to supply and control the induction motor with performances close to those of the synchronous motor (thanks to "vector control"). Books will be devoted to this motor in the framework of this monograph series. Let us only remark that the price decrease of the permanent magnets, obtained thanks to the efforts of the iron and steel industry, puts the economic advantage of the induction motor in perspective with respect to the increasingly used synchronous motor.

This book is part of a series published by ISTE-Wiley and Hermes-Lavoisier. Two books have already been published. They are devoted to modeling motors for their control [LOU 04a and LOU 04b]. Another volume has been devoted to the identification and the observation of electric machines [FOR 10]. One of the volumes presented the general methods relative to the control of electric machines [HUS 09], and another has presented the technological problems [LOR 03]. Electric motors control is associated with the static converter's control (here, inverters), and in the past, works concerning electric machines control have especially taken an interest in the converter's control (often very complex). Nowadays, with the development and progress of the technical realizations, there is a relative decoupling between these two activities, in particular when the inverter is at forced switching and controlled in pulse-width modulation (PWM.): another monograph specifically discusses these questions [MON 11], being centered on modulations and on current controls.

The program of this book is thus targeted at the presentation of the control laws of the "conventional" synchronous motors. Another monograph (forthcoming) will present control laws suitable for more "non-conventional" motors, which are often specific alternatives of synchronous motors. Conventional synchronous motors are defined by their respect of specific hypotheses making, in particular, the immediate use of the "Park transformation" (or *d-q* frame) possible. Those hypotheses are recalled in Chapter 1 of this book, by Jean-Paul Louis, Damien Flieller, Ngac Ky Nguyen and Guy Sturtzer. We can summarize them in a few words: linearity (without saturation), first harmonic (sinusoidal field distribution) and symmetry (or "circularity"). But very often, the motors installed in industry do not completely check all these hypotheses (for example non-sinusoidal or trapezoidal field distribution). Moreover, we present expansions, showing that there is an "extended" meaning to this "conventional" adjective. This first chapter summarily exposes the basic models, necessary for the design of the synchronous motor controls:

– models in the "natural" three-phase reference frame (or "*a-b-c*");

– models in the two-phase Concordia reference frame (or "$\alpha - \beta$");

– models in the rotor reference frame, or Park reference frame (or "*d-q*");

– with extensions to some non-sinusoidal field distribution machines.

The crucial stage of the motor control (whatever its type), is torque control. Therefore, two chapters (Chapter 2 and 3), by Damien Flieller, Jean-Paul Louis, Guy Sturtzer and Ngac Ky Nguyen, are devoted to this fundamental question. The first problem to be solved is the establishment of "direct models" defining "inverse models" that are in fact the control laws. We then obtain algorithms that are "vector controls", whose core is "self-control" (necessity to synchronize the currents with the back electromotive force (back-EMF), therefore *in fine*, with the position). This vocabulary was popularized by the induction machines control, but perfectly applies to the synchronous motor. There, the controls suitable for electrical drives is in agreement with the general methods of control science, such as the "input-output linearization with state feedback" that power electrical engineers naturally practice when they realize controls with "decoupling between the *d* and *q* axes".

The vector controls show that to impose the torque, we must impose – and thus regulate – the currents. There are two large families of current regulations:

– there is the controls family regulating the three-phase currents in the natural *a-b-c* reference frame; these currents are those effectively measured;

– and there are controls regulating the currents in the Park "*d-q*" reference frame. These currents must be reconstructed by real time calculations.

The first solution is *a priori* technically simpler and was the first to be implanted. It has the advantage of working with real currents and thus of leading to immediate current (security) monitoring, but it is more difficult to obtain good results, because of the presence of static errors during the tracking of sinusoidal references – except specific strategies (one of them will be presented).

The second solution is naturally more efficient, because the current references in the *d-q* frame are "continuous". But, as it required more real time calculations, it was popularized only when dedicated components appeared on the market.

These two approaches each have their advantages and disadvantages. Chapter 2 (for controls in the *a-b-c* reference frame) and Chapter 3 (for controls in the *d-q* reference frame) present and discuss them. For reasons of simplicity, the controls are presented in the case where inverters are piloted in PWM. [MON 11] gives other alternatives of current control (for example, “hysteretic controls”).

The second problem encountered by specialists is relative to the determination of the optimal form of the motors’ feed currents. Indeed, very often the motors manufacturers seek to obtain the best torque/mass ratio. This often leads them to machines without a sinusoidal field distribution. Then, the optimal currents (exactly supplying the required torque by minimizing the Joule losses) are no longer sinusoidal. Chapter 2 gives us very powerful analytical tools in the case of the natural *a-b-c* reference frame for the particular case of the non-salient pole machines (with cogging torque). Chapter 3 shows the possibility of a geometrical approach combined with the Park transformation, in order to define efficient solutions, in particular for salient pole machines (also with cogging torque).

The electric motor’s control has several borders: we have just skimmed over one of them, the converter’s control. There are other borders: the “position” and the “drive control”. In this last domain, Chapter 4, by Jean-Paul Louis, Damien Flieller, Ngac Ky Nguyen and Guy Sturtzer, mainly exposes examples of “electronic speed variators” with a synchronous motor. The “speed variator” is a control unit that is very common in industry. It must generally be “transparent” for the user. The aforementioned control unit imposes a speed reference coming from a higher hierarchical level. The motor must then have a speed response with extremely fast dynamics. The problem of torque control is the first stage, presented in Chapters 2 and 3 and illustrated by several solutions. The problem of the speed control is the second stage, largely depending on the mechanical load.

The mechanical load can be simple, purely inertial for example, with a constant load torque. This is the case generally considered in many studies, and it will be the case discussed here. But the reader must know that users often encounter much more complex cases. Let us quote two quite representative cases: variable inertia mechanical load (as in robotics or with unwinder-rewinder); load with elastic links, dry and viscous frictions difficult to identify or oscillating modes (as with rolling trains). We thus leave the domains specific to the electric motor’s control seen by power electrical specialists, because they estimate to have completed their task when they have carried out a good torque control. The “drive control” in complex cases comes to the general automatics applied to complex mechanical systems. A monograph has tackled these questions [HUS 09].

However, some drive control problems are coupled with specific properties of the electric motor. Chapter 4 is centered on these questions and written by Jean-Paul Louis, Damien Flieller, Ngac Ky Nguyen and Guy Sturtzer. The authors discuss in this chapter examples of axis control applied to the most conventional mechanical system, because it is regarded as a generic example: constant inertia, viscous friction and load torque piecewise constant. They show that the strategy of torque control (such as it was presented in Chapters 2 and 3) has an influence on the performances of the speed control and that, consequently, the same control cannot have the same performances according to whether we associate it with a torque control in the *a-b-c* reference frame or with a torque control in the *d-q* domain.

We will also see that the conventional controls of the synchronous motors applied to this generic example have a great advantage. Indeed, with the traditional mechanical sensors, *all the state variables are measurable*, and therefore there are very efficient controls, in speed as well as in position. Thus, we will examine (by assuming that the machine is well controlled in torque, from the methods seen previously) several regulations and feedbacks approaches (*P*, *IP* controllers and introduction to the load observers). Some robustness aspects are examined.

Torque controls (and thus current controls) presented in Chapters 2 and 3 are modeled by conventional continuous equations: algebraic equations, differential equations, transfer functions. The controls described by these models are immediately transposable when similar components are used. But for a long time, implementations have been carried out with numerical technologies: microprocessors, specialized signal processors, FPGA. Another book has developed these aspects [LOR 03]. Digital technology introduces new problems. Chapter 5, by Flavia Khatounian and Eric Monmasson, discusses questions associated with the implementation and the digitization of current and speed controls of synchronous motors. This chapter considers points not discussed in the previous chapters: numerical regulations of current and PI-type speed, fast sampling frequency for current loops, and slower frequencies for speed and position regulations, with the recognition of the various constraints due to the technical realization.

Indeed, the concrete implementation imposes specific studies. It is necessary to model the interfaces and the sensors, in particular the position encoder. Then, element by element, we must study the phenomena to be taken into account in the framework of a numerical implementation: selection of the sampling frequency, delays due to the time taken by the various calculations and due to the PWM, quantization effects on the measures, problems due to the resolution of the incremental position encoder and to speed determination by numerical differentiation, control discretization, PWM cut, implementation of the reverse transformation of the reference voltage of the *d* and *q* axes with the question introduced by the difference between the angle used for the Park transformation and its real value. The chapter gives an original summary of these various problems, a summary not often presented explicitly in specialized books and papers. It gives in particular a very complete "time diagram" and precisely lists the various "critical periods" to be examined.

Torque controls (presented in Chapters 2, 3 and 5) and speed controls (Chapter 4) have been limited in practice to "vector control" controls associated with piloting the inverter in pulse width modulation. This approach can now be regarded as conventional and is very often used industrially. These approaches have the advantage of decoupling the static converter's (inverter's) control of the machines themselves. This decoupling is simple, which is a great advantage in the industrial domain. We cannot however guarantee that the overall outcome is optimal[2]. However, other approaches have appeared in the last few years, regarding the "predictive control" and the "direct torque control" (or "DTC") concepts. They are "smart" controls seeking to optimize the motor-inverter association to obtain new properties.

Chapter 6, by Jean-Marie Rétif, first of all presents the torque "direct control" method. This method has especially been developed for the asynchronous machine. It is quite useful in high power when the machine is supplied by a relatively low frequency inverter. It is presented here in its version for the synchronous motor. By principle, the DTC uses heuristics based on known tendencies on flux and electromagnetic torque variation. The heuristics determine the inverter configuration, supplying the best voltage fluctuation to be supplied: the control thus associates the inverter modeling with the motor modeling. The control itself is *in fine* carried out by hysteresis controllers, therefore very fast ones. As a result, this method is likely to give the shortest possible torque response times. One of the constraints is that the arithmetic unit (generally a microprocessor) is constantly calculating to introduce a switching control, only when a threshold is crossed. This method is thus very constraining for the processor. In addition, it introduces variable switching frequencies, which can be undesirable.

This is why alternatives are introduced, for example fixed frequency DTC. It is preferable to generate a control based on an analytical model, rather than from heuristics built on evolution tendencies. Moreover, the current development of the control theories applied to the electric motors strives for a "hybrid approach", for which the control is no longer the required voltage, but the inverter configuration. We then reach a control family increasingly used nowadays: the "predictive controls". Chapter 6 thus shows an application to the synchronous motor of a "direct predictive control". The conventional two levels voltage inverter has only eight distinct configurations and we can easily determine, by a model which is linearized

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2. We once again have the classic problem opposing "local optimizations" and "global optimization": the machine control can be optimized in itself and the converter control can also be optimized in itself (two local optimizations). This does not guarantee that the *set* machine-converter is optimally controlled (global optimization). This problem is nowadays well known by the electrical vehicle specialists, seeking to drastically minimize all the losses of the whole electric system destined for this embedded device.

on a short horizon, the best configuration at a given moment. The author gives examples of very efficient strategies.

The predictive control does not lead to a single control, but to a *control family* with various properties and application fields. As it is very promising, another application chapter of this approach is presented. Chapter 7 gives an example of predictive controls tolerant to the inverter faults, by Caroline Doc, Vincent Lanfranchi and Nicolas Patin. This example shows that modern controls bring solutions to significant problems (control under fault conditions), which could hardly be dealt with by conventional approaches, such as the vector control conceived in the *d-q* axes, naturally presupposing that the machine and converter are normal. Therefore, the new controls strategies bring new *services*.

This is also the case for the two final chapters of this book. The conventional synchronous motor controls require a position sensor to carry out the self-control, even for a torque or a speed control. However, there are some cases where we wish to make controls "without sensor", i.e. without mechanical position sensor. Various reasons explain this fact: economic, size or reliability reasons, or to be able to continue working in "degraded operation", when the sensor signal disappears (failure, accident). These themes have been discussed for a long time, but are still open to discussion. Many solutions have been proposed and this is why this very important question is studied in two chapters of this book.

Maurice Fadel, in the Chapter 8, takes a look at the characterization of the control without mechanical sensor of the synchronous motors. Indeed, the position is no longer a measured variable, but a magnitude rebuilt by a real time calculation – in particular with an extended Kalman filter with respect to model reference control. This magnitude then has a certain dynamics influencing various motor controls, as well as the various observations, particularly of the load torque usually integrated in the control. This last question was summarily presented in Chapter 4 of this book. It was discussed thoroughly in Chapters 7 (by Maurice Fadel and Bernard de Fornel) and 8 (by Stephan Caux and Maurice Fadel) of another monograph [FOR 10].

Chapter 8 examines the different dynamics: of the position observation, of the load torque observation, of the speed control, compared with the inverter decoupling frequency. The point of view is non-linear and is concerned with the global stability of the set observer-control, which makes up the electronic speed and/or position variator.

Chapter 9, by Farid Meibody-Tabar and Babak Nahid-Mobarakeh, takes a more specific look at deterministic observation methods of the synchronous motors position. These methods often use an estimate of the electromotive force (emf), because it has important advantages (it requires the knowledge of only a small number of electric variables). The disadvantage of these methods lies in the convergence domain limit. There are thus important stability problems. This is why the point of view adopted in this chapter is basically non-linear, to bring guarantees to the global stability of a control with a position estimate. The main method is due to Matsui. This method is very interesting, but unfortunately has a limited convergence domain. In this chapter it is, however, shown that there are solutions to extend the control convergence domain. The authors thus study a methods family to estimate and observe the position and speed without a mechanical sensor. They also examine the control properties using this observation: stability, dynamics and robustness with respect to the parametric errors.

This book thus proposes a broad overview of the conventional (or almost conventional) synchronous motor control, from traditional methods (regulations with inverter controlled in PWM) to very promising advanced methods, such as direct controls and predictive methods. We give extensions of modeling and of methods, by stressing the very important question of the controls without mechanical sensors.

Other questions remain, but they do not directly concern the problems of torque, speed or position control of a synchronous motor supplied by a voltage inverter controlled in PWM. These questions relate to other supply modes, or to other nonconventional types of motors: we then talk about “special machines”. They are often – more or less – synchronous. It is logical, after the conventional synchronous motor control, to consider them. These questions must be the subject of a future monograph.

This work is dedicated to the memory of René Husson (Nancy) and Manual da Silva Garrido (Lisbon), who contributed to the quality of EGEM treatises ([HUS 09] and [LOU 04a], Chapter 1).

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