

Preface

Electricity as a vector of future energy

For the general public, the second half of the twentieth century is considered, in terms of technology, as the age of electronics and electronic applications. From transistors to integrated circuits, microelectronics and nowadays nanoelectronics have given rise to inventions and devices that have completely changed our means of communication and information: television, cellular phone, personal computers, CDs, DVDs, communication satellites and the Internet have become so overwhelming that our society is often referred to as the society of information and communication. The survey carried out by the trustworthy association of electricians, electronics engineers and radio electricians (IEEE), in the November 2004 issue of the journal *Spectrum*, is therefore not surprising at all. Out of the 40 specialists surveyed in terms of research priority and major technological evolutions over the next decade, 38 mainly mentioned Internet, telecommunications, nanoelectronics, nano and biotechnologies among others. Only one of them considered energy products as a priority for our future. This is striking if we consider the current revolutions taking place in the energy field: scarcity and rocketing cost of raw materials, market liberalization, high expectancies for engineers to accomplish miracles—transformation of the laws of physics to constraint currents to follow the laws of the market, and Kirchhoff's laws not considered as obsolete anymore—and some European regions on the industrial decline due to a lack of foresight in the energy field.

Whatever the perspectives may be in terms of communication society, the twenty first century will be characterized by deep changes in our energy production and consumption. Be it due to the scarcity of some raw materials or environmental issues, we are about to enter a new era in which all potentially useful sources of energy will be needed and the consumption of available energy will have to be as rational as possible.

In this context, electricity will become a major vector in terms of energy production be it from natural resources such as wind, tides, swell, river flow, sun or from sources of nuclear origin with nuclear fusion as a long-run objective.

Electricity will also become a major vector in terms of rational use of produced energy. Cogeneration, wind mills, hydropower plants, hybrid vehicles and high-speed rail transport as a competitor of air transport, are among the many elements that already embody this evolution. Electrical engineering has evolved increasingly in the last 30 years, thus making these applications possible. Although they were not very apparent, research works in the electrical engineering field were numerous and innovative in those years. Material evolutions, progress in terms of computer-aided design, the development of power electronics and control and setting techniques now enable the design of new electromechanical conversion systems, innovative both in terms of performance and fields of application.

The induction machine is a striking example of this evolution. Dozens of years ago, this network-powered machine still seemed a cost-effective and robust machine, yet only capable of driving at a quasi constant speed load that did not require frequent starts and stops to gain an acceptable energy yield. Nowadays, powered with a voltage inverter with pulse-wave modulated control, it has become the reference machine for variable speed drive going from kW to MW. By coupling up its inverter with a vector control, this machine even offers dynamics and high torque accuracy, which is well suited to applications requiring high-speed traction. Equipped with a wound rotor, network connected, thanks to its stator and powered with a rotor converter, it has also become a generator well suited to the production of electrical energy by windmills since it enables the turbine to adapt its speed based on that of the wind.

If one tries, however, to reach its theoretical limits in terms of accuracy and setting, the induction machine remains hard to control. Indeed, one cannot generally measure all the quantities that are specific to its state and the estimation (observation) of the non-measurable quantities is toughened by the evolution of its parameters due to temperature and saturation. All issues are therefore far from being solved.

Vector Control is a Standard

The “vector control” of alternating current machines, heritage of Blaschke works in the early seventies, has become a settled standard. This method has largely been used and deepened by researchers. When technologies became mature enough (micro-processors for real-time calculations, power electronics for cost-effective inverters), it gave rise to wide industrial ranges in the early nineties. The possibility to give the induction machine dynamic performance similar to direct-current motors (the reference in that field) then appeared. It enabled benefit from two major advantages: an economical one—the induction machine being the least expensive actuator—and a technical one—from its absence of a mechanical commutator. The continuous decrease in the cost of permanent magnets may question this hierarchy in the future, putting induction machines at the front of the stage again. This machine is the ideal one, yet it is considered as too expensive for wide-scale applications.

The vector control is a “standard” as it is widely used: for instance, every TGV (High Speed Train) passenger benefits from it. However, the adjective “standard” does not imply that this method prioritizes a unique solution. The “vector control” sets the basis for “basic” mathematical methods and models. It leads to various control architectures as it offers a decoupling between the “d axis” (the “flux axis”, rotor flux in its classical version) and the “q axis” (the “torque axis”). People used to induction machine control using the Park transform know that very well. More generally, the vector control of the rotor flux of the induction machine is an intelligent transposition of the good properties of the synchronous machine, which itself was a transposition of the excellent properties of the direct current motor.

Although many books can be found both in French and English on induction machines control, the book written by Benoît Robyns, Bruno François, Philippe Degobert and Jean Paul Hautier differs from the others thanks to its originality, as shown in the following paragraphs.

Control, estimation, observation and robustness are many issues that need to be taken into account simultaneously

The following paradox must be emphasized: the vector control owes its good properties to the emphasis put on a particular variable, the rotor flux, that gives way to a “simple model” but usually this flux is a non-measurable internal variable. Simplicity is a relative concept that will be linked to a more detailed concept, that of “direct model”, that needs to be “reversed”. The guiding principle of this book is the following: how can the initial issue of control be linked with the corollary and even more important issue of “estimation and observation” of the rotor flux? The hinted difficulty behind all that has to do with “robustness”. How can the control be “robust” despite many difficulties in determining the rotor flux? These concepts will be further explained in this book.

The first context has to do with control or “direct model to reverse model”

Some of this book’s authors have been pioneers in the designing of controls directly deduced from modeling. They have highlighted the fact that physical models can lead to control laws if a structured method is applied. “Direct modeling” can be deduced from physical laws. From direct modeling, naturally, a certain type of “inverse modeling” will emerge, that is to say, control laws and implantable algorithms. This method, based on physical arguments and especially on energy, is excellent. It benefited from a rich past. Control engineers use it with their own and more abstract tools in, for example, the “input–output linearization with state reversion” or the “passive control”, that give similar control architectures yet require a quite consistent mathematical background. The authors also made a fundamental and strategic choice. This choice consisted in adopting a graphic representation, as opposed to the approach adopted by many system

theoreticians that used very abstract representations only, that is to say only equations far from the physical reality. The authors have developed their own graphic representation, called the C.O.G. “Causal Ordering Graph”, which is very useful from a methodological point of view. This graphic representation naturally forces a control designer to structure his/her system correctly. It is legitimate to think that other graphic representations are equally acceptable. The “good old transfer functions” allow for a similar approach, if and only if the designer constrains himself/herself to structure them correctly to highlight the physical properties that give way to “direct models”. This condition is not always met, far from it. Many functional diagrams published in the scientific literature are indistinct and therefore hardly usable in control design. This requires a “certain expertise”, which some people in the scientific community already have. Electrical engineers who worked on controls were used to “adjusting” their equations to “decouple the d and q axes”, for instance. The method given by the authors enables to justify, structure and systematizes these researches on decoupling. The “input–output standardization” of the automation enables to apply this property as well, but under a more abstract mathematical form that requires either powerful mathematical tools (for instance, the “Lie algebra”) or a “very good intuitive sense”. The pedagogical virtues of the C.O.G. are real and enable students to become familiar with fundamental concepts such as “causality”, with its “rigid relations” (pictures by algebraic equations) and its “causal relations” (described with integro-differential equations). “Rigid relations” can be “inverted in open loop” but causal relations can only occur in “closed loop”. Justifications for this can be given either using “physics vocabulary” (and energy concept) or “mathematical vocabulary” (properties of differential equations) or “automatic vocabulary” (properties of closed-loop systems). These different approaches (graphical, physical and mathematical) go together very well and offer a variety of approaches that can be used depending on the expectancies of the reader.

Direct and reverse models of the induction machine, considering vector control

The authors of this book have applied their method to the classical modeling of the induction machine in dynamic state in the various references used in “control”: the “natural” three-phased reference—the one used in windings and from which Faraday’s law in physics was derived—and the two-phased references either fixed or rotating (Park transform). The term “control” will need to be further clarified, as it covers activities other than the control itself. What is obtained is not “a” model but “a class” of models since two fundamental and strategic choices remain to be made: choosing the frame of reference and the state variables. The author’s methodology systematically tackles these two issues and associates graphic representations (thanks to C.O.G.) with differential equation representations and state model representations, as is commonly done in automatic control engineering.

This book does not pretend, however, to cover all use cases of these models. An encyclopedia, tedious reading, would be needed to do so. This book has to do only

with the vector control depending on rotor flux. The authors therefore clearly place themselves in a “control context”. The model obtained has to be a “direct model easily reversible”. This brings the authors to the concept of “maximum structure control”, highly competitive yet extremely requiring. This “maximum structure control” leads to control algorithms that associate open-loop “compensations” (either additive or multiplicative) and closed-loop regulations. All state variables need to be known at all times. Hence the fundamental need for real-time computation of non-measurable variables. Naturally, this process leads to the concepts of controllers, estimators and observers, which will be explained further.

When using controller controls, the knowledge of non-measurable variables becomes unnecessary (by avoiding compensation terms and regulating measurable variables only). However, these controller controls have to offer great interest frequency gains and are sometimes complex to calculate to ensure robustness and disturbance rejection. For this, see the deduced controllers of the H_∞ theory, usually very high, requiring tough simplifications on one hand and the reaction for an increased simplicity on the other hand, which led to “fuzzy controllers” which can easily be determined only in theory. Here appears once again the compromise that engineers are familiar with: “enough for, not too much for fear of”—correctors complex enough to give sufficient performance, not too complex to be effectively implementable. The engineer, with his art, has been highly praised since his/her intuitions enabled him/her to solve compromises satisfactorily, in his/her own context. This came from a long interiorized experience that made him/her an expert who often forgot where his/her knowledge came from. This context does not necessarily correspond to the context of another designer, hence the difficulty to transmit experience.

Two generations of vector control to be harmonized: Estimators and observers

It deals with the induction machine control using classical vector control, which requires knowledge of the non-measurable (in the general case) rotor fluxes which are necessary to determine the frame (precisely the rotor flux frame) with much simpler equations. They enable decoupled control which we need. In addition to that, the model is a nonlinear one—the torque is given by products and the orientation angle by a division. There must not be a unique way to solve this issue, contrary to what would be the case with a linear system. The modeling itself of a well-known machine requires hypotheses: hypotheses with or without a priori on the flux orientation? These “details” (?) clearly emphasize the concrete experience the authors have with these issues. The classical structures are hardly robust and some advanced and very competitive techniques—the Kalman filter expanded to the parameters to reach robustness—are highly appealing yet remain very requiring to be implemented. The authors themselves remain in a context where the implementation will have to be reached with simple means. This requires a “good modeling”, not in the physical sense (it is known) but considering the control to design and implement. From that point of view, this modeling technique

would suit many users looking for a compromise between simplicity and performance. The goal must be anticipated. For this, many studies made by the whole community and authors in particular and a sorting between sterile developments and developments that led to an efficient strategy were actually needed. Young engineers and researchers therefore have a high interest in benefiting from the experiences of their elders. They do not have time to lose on countless and dead-end paths.

Considering this point of view, some paragraphs are essential: the paragraph dealing with the “explicit technique for frame orientation”, as called by the authors—this paragraph uses classical formulas of vector control—but the paragraph on “implicit technique for frame orientation” is less usual and will play a fundamental role in the future. Once again, the authors belong to the first generation of vector control, to which belonged the people who discovered the “ideal orientation”, that is to say the rotor flux reference frame, which is a wonderful idea even though robustness issues derive from it.

The authors have to consider the second generation of vector controls, that uses “without a priori” models on the orientation of the reference frame in order to be less sensitive to approximations on the modeling, and that alludes to the general theory on estimators and observers.

The estimator is an open-loop process simulation. Needless to say, this simple and very natural method is hardly “robust” since not all equations and parameters of the machine are known. Yet it is a classical method. The observer consists in a closed-loop algorithm and the algorithms of the Luenberger (deterministic concept) and Kalman (statistic concept) filters have become classic today. They are subject to numerous studies in laboratories and are used in some industrial applications. These observers are more competitive yet more complex to design and heavier to implement. The theoretical performances are ideal ones if robustness is ensured, but this condition is far from evident.

This is due to a move in the context: from “control issues” themselves, the interest is now on “observation issues”. The correct control strategies have been identified but such controls require non-measurable variables, since we have seen that the correct control equations highlight the rotor flux, which is a non-measurable variable. Physics allows to determine this variable through real-time calculation thanks to a wide range of equations. However, with the standard approach, these equations depend on two parameters: rotor resistance and rotor inductance. Both quantities are prone to variation, because of temperature or saturation. Stator resistance can be problematic with different perspectives. How can we make the system insensitive to variations?

We are not dealing with standard linear models. Some tricks have to be found to determine, for example, a reduced-order rotor-flux observer (this type of flux observer is easier to settle). The observer, who can also be a full-order observer, needs the implementation of a “gain matrix”, which will bring about determination and robustness problems. The designer must have high-level skills which are clearly difficult to pass on.

The implementation of a Kalman filter extended to the four parameters of the model (that is to say a linearized nonlinear eighth order), with variable coefficient gains, is not a purely academic exercise, even though satisfying results can be found in scientific works and are used in sophisticated industrial applications.

Correct models, control and observation, robustness and implementation

A careful reader will very likely notice a few persistent allusions to some issues. It is all about choosing a “correct model” depending on a very strict criterion, which is not an easy task. The “correct model” will allow to solve this problem, which is not posed in explicit terms and not properly formalized. Most of the time, a clear statement of the problem is reached only when a solution has been found. The correct model should answer four questions simultaneously, intellectually apart but interrelated in practice: control, observation, implementation and robustness. The control should be “competitive” in terms of dynamics. Observation will have to make up for the instrumentation failures (since the sensors are missing). Implementation should be “simple” and the whole should be “robust”. This is quite promising.

When considering control issues, the robustness concept has become highly pregnant. Linguistically speaking, a system is robust if it carries on working properly with changing conditions. It obviously brings about many questions. What does “working properly” mean? What do “changing conditions” correspond to? Practice has it. If a device is still working after several approximately ten practical sessions with imaginative students and its proportion of damage, then it is surely robust. Is it possible to sell a speed variator and wait for the users (customers that have paid for your product) to show their (dis)contentment? Of course, robustness can be observed thanks to reliable theoretical tools (structured singular value, μ -analysis). They are more commonly used to test the dynamic behavior of a system when parameters vary within physically acceptable limits. They are quite complex and do not always lead to the synthesis of robust controls. Empirical methods, often established from simulations, can also be used. The designer develops a control that is supposedly robust, and then, he carries out a parameter variation and checks the robustness of the device through simulation. This kind of an empirical practice is fairly common.

One good thing is the simplicity of this method, but it requires the combination of different elements: a reliable simulation process, and representative digital tests. Mr. Benoît Robyns and his collaborators brought to light a genuine and effective approach that uses the parametric sensitivity theory, another tool that does not enjoy sufficient consideration in our community.

One essential tool: the parametric sensitivity

The sensitivity theory should be taught as one of the fundamental science tools for engineers, just as variation calculation and optimization (optimization often occurs through variation calculation). It seldom happens and a curriculum reform should

be carried out in that sense. Many engineers and researchers unconsciously carry on sensitivity studies. They simply change a parameter in the process to check whether it is still working. Theoretical tools have been developed and a fundamental book has also been published on the matter (Franck, 1978). Besides, the sensitivity method does not require very sophisticated mathematical tools. Rigor and application are the only prerequisites that will allow for the computation of the function derivatives of several variables and compound functions. The authors' credit relies on the application of this method to the analysis, criticism and optimization of the useful variable estimators in order to optimize their robustness.

Sensitivity is a simple and powerful tool, since it can quickly provide the characteristics of an algorithm answering this fundamental question: is it sensitive to parameter variations?

The use of such a tool goes a long way toward showing the originality of the authors. They decided to compare different controllers (some of them being particularly simple). They also compare simple estimators (that are obtained in without a priori and with a priori approaches), and notice that some of them have complementary characteristics. There is no ideal solution but some are better than others in specific operating situations.

As it is restricted to "specific operating situations", the best option might be to adapt the control and observation to these situations (low or high speed, small or big load torque). A constant optimization process needs to be carried out choosing the best control and observation. It appears to be an "adaptive control", but this method is not well accepted in the field of motor control where transients can be very long and very short at the same time. Identification and controller choice cannot be performed simultaneously (considerable delays), while applying the controls. In such a context, those "(pseudo) adaptive controls" are actual "non-linear controls". An algorithm can easily compute the best estimation and best control with the help of measurable variables without any delay. The question now is to know how to bring together these laws of estimation and nonlinear controls.

Fuzzy supervisor. Desensitization. Optimization

Fuzzy logic principles, established by Zadeh, were meant to provide tools to control improperly modeled systems that you still have a good knowledge of. Their reaction to stimulation is approximately known. From such basics, control rules have been defined, and expressions like "fuzzification" or "defuzzification", appeared in the scientific literature. Obviously, this method was in complete opposition to two traditions: the tradition of systems physics specialists who were looking for a precise modeling of their devices, and the tradition of automatic systems specialists who were developing very sophisticated and competitive mathematical tools. The fuzzy control hardly ever used precise physical models or powerful mathematical methods, which is both its interest (with an increasing tool complexity, it is easy to understand that a community had a rough reaction in favor of a comeback to simplicity) and its limit (why not use a model that we know is working?). Thus, in the nineties, many conflicts concerning industrial system

control blew up. Some noticeable works using the fuzzy approach have been published, although most of the works done concerning electric actuators were really disappointing. Too many articles only dealt with elementary axis controls, trying to deal with the predictable variation of the mechanical parameters. The “actual control” (torque determination) results from frame orientation and current loops that are designed with traditional controls. These “fuzzy controls” were only meant to compete with PID that regulated the speed, and comparisons were established improperly with badly conceived PID. Fuzzy logic can offer much more.

That is exactly what the authors of this book established. For one thing, the authors had an issue to settle: synthesize a vector control including both the actual control and the rotor-flux estimation trying to “desensitize”, with a final view to reinforce the whole system. Moreover, they have developed a genuine approach on how to use fuzzy logic. If the authors use the sensitivity functions, their aim is to desensitize the control and make it as less sensitive as possible to parameter variations. “As less sensitive as possible” means that we are dealing with an optimization problem. This problem is quite difficult, and the authors managed to find a very genuine solution. Sensitivity studies have established that two expressions of flux estimation (explicit and implicit) are complementary. Both of them have good use restrictions (“good use” referring to the desensitization to parameters variations), but how can we take advantage of each of them? The key is to use a fuzzy supervisor that will find the happy medium between the two expressions depending on the operating point. In practice, this supervisor is settled as a simple predetermined and established nonlinear function. One may wonder what a happy medium is. How can we optimize this complex system that mixes control and estimation?

Again, fuzzy logic will be roped in. It is artfully used as a heuristic optimization method that is meant to solve this problem.

In conclusion

Readers will not only enjoy a new study on vector control but they will also be introduced to useful concepts and tools that are often disregarded: the control through model inversion; the necessary variable estimation; the entanglement of the control and the estimation of nonlinear systems; the sensitivity theory; robustness and desensitization and finally, the good use of fuzzy logic as an optimization method for nonlinear systems.

Jean-Paul Louis, Professor at the E.N.S (French higher education school)
of Cachan

Francis Labrique, Professor at the Université Catholique of Louvain

Vector Control of Induction Machines

Desensitisation and Optimisation Through Fuzzy Logic

Robyns, B.; Francois, B.; Degobert, P.; Hautier, J.P.

2012, XXVI, 222 p., Hardcover

ISBN: 978-0-85729-900-0