Welcome to the “Elektron Whisperer” Column

I am riding my motorcycle. The flow of wind causes the back of my ponytail to give me a sensation of having luxuriant hair. Sitting atop an engine with wheels, at the moment that I start moving, I realize that the speed on such a two-wheel vehicle is already three to eight times that at which human beings were ever meant to go walking. My objective in this new column is to tell you stories—some of those I learned in my life, others I experienced myself. I hope you grasp the feelings that I had when learning or living those stories. As such, transformation happens. We “the people” have been transforming our society for the past 200+ years at a pace that exceeds by hundreds the rate at which our world has been transformed throughout all of previous history. We expect that our children and grandchildren will be better empowered, all things considered in their lives, maybe as a driver or a rider, truly experiencing magnitudes more than what you and I had so far. The wind blowing on the back of my hair on my motorcycle tells me all of this.

I have been living and learning (tools, techniques, hints, and tricks)—this is what we call the age of wisdom. In fact, it is similar to learning to take care of the maintenance of a motorcycle. Electrical engineer as a vocation! I am a person, a man who happens to have been working as an electrical engineer, by choices that I made, given my past course of actions and decisions, believing in the horizon ahead. Still, I am yet improving my teaching skills, conducting research in my professional area, and mostly trying to make our society more interesting and meaningful. I realized that I can contribute to making our students become not only professionals but better people, and possibly with very advanced engineering skills. The hope is that humankind will keep our planet sustainable and socially fair, with better equity and inclusiveness, each one of us deserving life, happiness, daily food, shelter, and education, all of us providing our families with affordable energy, opportunities, and more. In this respect, electrical engineering, electronics, and technology are key matters for our future.

“The Elektron Whisperer” (TEW) is my effort to motivate you to follow your path of creativity, in doing and making. Our tech stories made us what we are today and will continue to nurture what we leave for future generations. The pace of stories is a stride faster than walking, slower than riding a bike—my motorcycle is electric powered, so I will have a conversation with you about induction motor drives in this launching of TEW.
—Marcelo Godoy Simões

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INDUCTION MACHINES operating as motors or generators are very important for our modern society. Industry, rural, and household applications utilize induction motors for at least 85% of the applications of rotating apparatus. They dominate the market of electrical motors and consume more than 60% of total industrial electricity in industrialized countries.

Introduction to Induction Machines and Their Motor Drives

The main reasons for such motors to be so adopted are their very low-cost design, their strength and reliability, and their inexpensive maintenance. There are no permanent magnets—consequently, the manufacturability is constrained only by the availability of iron and copper devices for punching the magnetic steel sheets and of electromechanical technicians capable of understanding how to do the winding and assembling. In this 21st century, there are further relationships among energy savings, sustainability, and global economics. Therefore, the use of induction machines became of primordial importance in regard to sustainability and widespread manufacturability.

From the early invention of induction machines toward the 1970s, there have been concerns about starting up those motors when they have a direct connection to the utility grid. Another constraint has been the required reactive power needed to maintain the magnetization. The currents circulating in the machine are responsible for the active power (mechanical shaft power exchange) and magnetic flux for the machine to operate. The magnetization is related to the amount of reactive power, where current through the copper wiring will not produce active power, instead increasing the apparent power and overall losses. Until the 1970s and 1980s, induction machines were mostly considered to operate only at a constant speed with a fluctuation around the synchronous speed (slip frequency), and they were regarded mostly for constant-speed applications. They would be connected to the ac supply, and then some transient and inrush current would develop, eventually settling down to a constant electrical frequency of operation, rotating at a shaft speed (revolutions/min) that would depend on the number of poles, with a slight variation around the synchronous speed that would depend on the mechanical torque (slip frequency increases for increasing torque). It was acceptable that induction motors could have variable frequency—as long as it would not change rapidly; sluggish methods were then employed.

With the invention of thyristors, specifically silicon-controlled rectifiers (SCRs) by General Electric (the birth of power electronics), they became the power devices capable of high voltage and current control. Cycloconverters developed a lot in the 1960s, and natural commutation was employed for controlling the average voltage of an ac source applied to a load by delaying the trigger for turning on the SCRs. There were developments in the 1960s and 1970s with complicated forced commutation (McMurray topologies) of SCRs with capacitors to impose commutation conditions for thyristors. Those were the early induction motor drives and circuits for soft-starting control. From the 1960s until the 1980s, it was very common to have controllable torque on the rotor winding of slip ring machines with rotor connection.

Thyristors on natural commutation heavily depend on a lot of constraints of circuit parameters and topology. In addition, there are effects regarding the voltages and currents on the machine, with the existence of harmonics and losses, causing shaft pulsations. A variable voltage operation for induction machines is typically neither fast nor reliable, and without a careful design, the machine may easily collapse for the lack of magnetization. McMurray was the first researcher to realize that the volt/hertz approach would have to be employed for induction machines. It is possible to have a simplified magnetic modeling of an induction machine where the air-gap flux will be calculated from the stator flux with subtraction of the stator leakage drop (across the stator leakage inductance); the rotor flux is a little further inner in the model, and it is calculated by also subtracting the drop on the leakage rotor inductance. In such magnetic modeling, considered as subtracting the rotor leakage voltage drop from the air-gap voltage. By doing so, the stator resistance can be neglected as well as the stator leakage, the air-gap voltage could be approximated by the impressed voltage, and flux is proportional to such an integration of voltage subtracted from all leakages and losses. Then, a simple dimension analysis gives a unit of volts-seconds for the flux.

It is simple to assume that volts/hertz means a constant area of voltage in time. If such an area (or integration) is constant, then there will be constant flux for the induction machine: keeping the capabilities of torque on the shaft with variable power. McMurray proposed a forced-commutation SCR-based circuit where the voltage would be programmed proportionally to the frequency variation (V/f or volts/hertz), and by slowing down or ramping up the frequency, it was possible to have the first generation of variable-frequency induction motor drives. Scalar control was born.

Natural commutation-based circuits have analog controllers for detecting zero-crossing of the ac supply and delaying the firing angle of SCRs; the turn-off inevitably happens only when the current through the thyristor becomes naturally zero. It is
possible to force a parallel path with a capacitor to deviate the current to have a forced commutation. Those circuits depend heavily on circuit parameters and conditions. Many calculations were made for the design and operation of those circuits; note that this was still the age of the slide rule and the early electronic calculators. Toward the end of the 1980s and throughout the 1990s, there were tremendous developments in the power electronics-based control of induction motors, with better scalar and advanced vector control approaches, the development of direct torque schemes, further applications of digital signal processors (DSPs), application-specific integrated circuits (ASICs), and then field-programmable gate arrays. There was a lot of R&D in advanced techniques in adaptive control, state observers, flux observers, the online estimation of parameters, sensorless control, neural network-based control, and high-frequency signal injection for parameter and robustness improvements. It is important for you to understand the foundations, particularly the d-q instantaneous theory transient modeling of induction machines and control methodologies to allow the implementation of scalar and vector control approaches.

### Early Developments of Induction Motor Drives

The flourishing beginning of power electronics during the decade of 1960s can be marked by an article published by Prof. B.K. Bose titled “Electronic Speed Control of Motors,” *Journal of Industrial Electronics (India)*, pp. 172–182, September 1962, that was essentially a dc drive using thyratrons. General Electric was heavily investing in R&D, hiring expertise, and acquiring resources for a then very advanced team of electrical engineers to work on their invented device: the SCR. Many of the GE researchers continued their careers, becoming famous professors in power electronics, such as T. Lipo and B.K. Bose.

The obvious idea was to use those devices in commanding the impressed machine voltage using natural commutation. In such a configuration, there were a lot of harmonics, some above the base frequency, but there were also subharmonics, caused by the overlapping and folding of the Fourier frequency bandwidth. It was very common to have machines with dangerous shaft torque pulsations (which could even cause fatigue and mechanical breakdown) before the age of pulsewidth modulation (PWM) and transistors; those early motor drives had to have lookup tables for preprogrammed pulse
patterns to avoid the torque pulsations and resonances of those harmonics. When controlling voltage, at a constant fundamental frequency, the machine flux is not maintained. Therefore, motors could become weak and fail their electromagnetic stability conditions for energy conversion.

In 1961, William McMurray (who is considered to be the “founding father” and guru of power electronics) invented forced commutation techniques: the McMurray and the McMurray-Bedford inverter, and then the ac-switched commutation in 1980. At that time, most of the achievements were quietly done by industry people, and there is no analytical article or report on how volts/hertz was conceptualized in the 1960s. For all practical purposes, the V/f control of voltage-fed induction machine drives is attributed to McMurray, although it is not clearly mentioned in the literature.

General Electric published several books, application notes, studies, and implementations of cycloconverters and ac voltage control with thyristors. Those notes and books became established in the early 1960s literature and served as technical literature for several generations of future students and researchers; I read, studied, and still keep some of those application notes in hardcopy today.

During that time, thyristors were devices for real operation in high voltage. The bipolar junction transistors were available only for radio applications, audio, and TV applications; they were of very low frequency for switching operations—transistors for ultrahigh frequency were of very low power. There was no modulation for inverters. The sinusoidal PWM (SPWM) technique was invented by A. Schonung and H. Stemmler in 1964, as reported in the Brown Boveri Review, in their article on static frequency changers for reversible variable-speed ac drives, but it took many years before it was applied in regular transistor-based converters. Joachim Holtz wrote a very nice article on PWM for electronic power converters in the Proceedings of the IEEE in 1994; by that time, SPWM was established for three-phase two-level-based transistor bridges as well as single-phase H-bridges.

When McMurray deployed thyristors in the forced commutation of motor drives, he essentially started the revolution of variable-frequency motor drives. The open-loop volts/hertz control technique became popular. A good experimental evaluation would be conducted for machine performance measurements, allowing one to fine-tune a lookup table to maintain the flux nearly constant for variable-speed drive operation, allowing good dynamic control and torque/ampere performance. It was possible to extend the induction motor speed range beyond the synchronous frequency by imposing flux weakening; increasing speed would have a constrained voltage at the machine terminals, and the shaft would be limited to the maximum power rating of the machine specifications. Therefore, the motor drive would transition to a square-wave mode, i.e., the induction machines would be wired with their floating neutral, avoiding the circulation of the third harmonics. The programmable firing patterns of SRs would keep harmonics and subharmonics somewhat under control. The whole drive system was optimized to mitigate the effects of fifth, seventh, 11th, 13th, and 17th harmonics. The triplets (harmonics of order 3k) did not influence the machine performance yet contributed, of course, to the core and converter conduction losses.

Based on the literature of early proceedings from the 1960s to 1970s, the state-of-the-art of induction motor drives became dominated by the voltage-fed square-wave six-step inverter; forced commutation of thyristors was used, and frequency control was implemented with timers and analog control in a voltage-fed inverter. Those early inverters had dc-link voltages controlled by a front-end thyristor bridge rectifier, making such SCR-based front-end rectifiers bidirectional for the regenerative mode of the machine and making it either in regenerative braking or in real generation mode. For very high power applications, on the order of megawatts, there were some applications of current-source converters with SRs on natural commutation.

Throughout the 1970s and early years of the 1980s, there were considerable research results, and the industry started making closed-loop speed control with slip and flux regulation. Those were mostly analog control circuits, with operational amplifiers for signal processing and even analog-based PI or lead/lag compensators. There was a hybrid design of analog with digital gate logic integrated circuits; the lookup tables could be preprogrammed in ROMs, maybe electronically erasable programmable ROMs (EEPROMs). The first generation of 4-b and 8-b microprocessors started to become available. But very few electrical engineers were brave enough at that time to apply them for any industrial real-time control. The upcoming microcomputer-based technology with 8-b and 16-b microprocessors was more expensive than analog circuits. In addition, the culture of writing software in assembly code associated with the complexity of bootstrapping a microprocessor-based digital controller, without an operating system (OS), only from the reset button, was a herculean challenge; very few knew how to do these microprocessor tricks in the power electronics and power system community until the beginning of the 1990s.

Before such a revolutionary time of thyristors, SRs, and natural commutation, there were other theoretical contributions that took many decades to be adopted. Power electronics
technologies then became influenced by the early foundations of three important original contributions.

1) A very important female engineer, Edith Clarke, was fundamental for all of these theoretical advances. In 1926, she published an article titled “Steady-State Stability in Transmission Systems,” describing a mathematical technique to model a power system. She designed a graphical calculator, similar to nomography and abacus techniques, that was adopted by the emerging power system engineer community.

2) Then, Park (in 1929) as well as Kron and Stanley (in 1938) made original contributions to the quadrature two-flux reaction theory of electrical machinery. A breakthrough happened with the introduction of the ideas of indirect vector control (IVC) by Blaschke in 1972; by then, all were theoretical analyses, supported by mathematics and physics. In the 1970s, it was by then an established 20th-century field that became scientific and technological and was called electrical engineering. Note that mostly no transistor-based inverter was ever deployed until the early years of the 1970s; probably, Blaschke had some experiments quietly done at Siemens that were never disclosed to the public.

From the middle of the 1970s to the early years of the 1980s, analog circuits with operational amplifiers were implemented in solving those theoretical equations capable of controlling induction machines; typically, the power electronics modulation was done only with hysteresis band controllers, easily implemented with Schmitt-trigger analog comparators. All of these were achievements made before the “age of PWM.” The analysis of the rotor d-q currents in the rotating reference frame made possible vector control with the synchronous reference frame and stationary reference frame dynamic models of the machine. Currently, such IVC methodology is defined as the Blaschke equations.

In the meantime, there was the introduction of Texas Instruments (TI) DSP boards, allowing fast calculations in real time; the families C20 and C25 were fixed point (based on integers), and C30 was a floating-point DSP processor (based on IEEE numerical floating-point standards). Those DSPs from TI and a few manufacturers (for example, Analog Devices and Motorola) became a contemporary digital control heaven for implementing all sorts of control approaches, new PWM techniques, and real-time control. By 1995, a new age in power electronics, dominated by the intensive use of DSPs, microcontrollers, and fast digital hardware implementation, was brewing and becoming mature.

The first time I observed the implementation of an analog operational amplifier-based vector control implementation for an induction machine was in 1988, by a student, Guillermo Garcia; his Ph.D. advisor was Prof. Edson Watanabe from COPPE UFRJ (Brazil). I met Guillermo during the second “Seminar in Power Electronics” held by the Federal University of Santa Catarina in 1989. (I was still working on my master’s degree.) He told me all about such amazing induction motor modeling and control strategies.

It still took me a few years to develop my own wind energy system (in 1994) with two back-to-back PWM voltage source controllers, made with Powerex insulated-gate bipolar transistors (IGBTs). The gate drivers, adapted from a Siemens handbook (with two TI C30 DSPs), were the SPWM for the d-q controllers and were implemented in a Henning ASIC running a fuzzy logic control written in SIMNON, with a neural network control developed with a DOS-based software called NeuralWare+. Everything was simulated with SIMNON and coded in the C language, compiled, and uploaded to the DSP boards with a serial cable connection, and the whole system was hosted by an IBM PC on DOS, probably version 6 or a little updated from that version, with a graphical user interface written with a Turbo C language for DOS. This was around 1994–1995. At that time, MATLAB was only for scripting M functions, Simulink was not even available yet, the most powerful software for simulation was ACSL, MATRIXx was available for state-of-the-art numerical algorithms for FORTRAN-based computations, there was EASY-5 by Boeing, and circuit simulations in Spice were running in Unix and Sun workstations. During that time, the Internet was mostly a command line via Unix commands. The very first browser, called Mosaic, became available about the same time that Java was released for the first time in 1995.

By the way, I remember purchasing my first book from Amazon at that time. It was done with a request by e-mail, considered to be an electronic order. Amazon was then an obscure bookseller promising to deliver any book wanted, for the lowest cost; deliveries came via the U.S. Post Office and arrived in less than one week from the order made by e-mail. The payment was made by sending them a FAX with the credit card number, and there were no sales because it was the early phase of e-commerce. It has been a long way since 1995 for Amazon, currently a multibillion-dollar international
company. By analogy, we were at the hard-coding, assembling, and debugging age compared to our current age of modern hardware-in-the-loop control, cloud services, renewable energy, smart grids, and an accelerated rate of development speed in our early 21st century. The wind is still blowing on the back of my ponytail; we are way more advanced than 40 years ago.

**Induction Machines Drive Enhancements for Modern Life**

Variable-speed induction motors are important for energy-saving purposes. Most industrial applications have centrifugal-type load applications. The change of torque is proportional to the square of the speed, and consequently, power changes in proportion to the cube of the speed, and then, energy will vary at different speeds. Variable-frequency drives manage energy consumption by changing the speed continuously, so variable-speed control would be desirable for a variety of applications: moving air and fluids; household and commercial heating and ventilation; industrial applications; and maybe lifting water, moving belts, and container systems. The bulk of industrial applications requires energy efficiency, reliable dynamics, and cost-efficiency for diverse shaft rotating mechanisms. Variable-frequency drives may need speed feedback when the precision of speed measurement is fundamental. There are heavy-machine electrical motor drives for construction and transportation. Speed control is important on a shaft. Typically, on one side of the shaft, there is a load or a prime mover that could impress torque. If the device on the shaft imposes constant speed, the motor drive will have to impress a torque control and vice versa. Induction motor drives must be programmed for either torque or speed closed-loop control.

Since the end of the 1990s, a lot has improved in the area of induction motor drives. There has been the implementation of estimation methodologies, for example, to avoid speed sensors or some other variables that could be measured to estimate other signals. This class of motor drives is defined as a sensorless motor drive control. To have sensorless motor drives, the estimation techniques depend on a mathematical model. The model needs most certainly voltage and current feedback, or maybe only current signals, to estimate the speed and/or the torque. The model will have an influence on the accuracy of the machine parameters, and then, the measurement of motor parameters would be important, or some other class of parameter identification will have to be implemented. The flow of the concept is that such a motor drive may depend on speed or torque measurement, which can be estimated with a model that depends on measuring voltage and or current variables, which may require parametric identification of the machine in advance or in real time. The stability of the induction motor drive closed loop will be affected by how the signal flow of the mathematics and physics is implemented. Advanced control (analog and/or digital) is required for mathematical implementation in real time.

The idea of real-time-based control has been discussed since the late 1980s, and the merge of the knowledge of control systems with power electronics became a reality with digital hardware implementation. Adaptive control and model reference control were developed for induction machines in the 1990s. There was a period of studying how motor drives could be enhanced with high-frequency signal injection; the University of Wisconsin at Madison had a strong group in the Wisconsin Electric Machines and Power Electronics Consortium working on all these advances. The idea is based on the concept that an induction machine made of copper, iron, and magnetic fluxes circulating in a real material—which is not perfect and mostly anisotropic—would then have a carrier signal superimposed on the PWM waveforms, which would support frequency tracking signal-to-noise ratio detection, spectral classification, and advanced signal processing algorithms.

In the very few initial years of the 21st century, there were a lot of implementations of advanced motor drive control with higher layers of system management. The idea of industrial automation, advanced motor drives, and sophisticated control algorithms was already a reality around 2003–2005. But our society started to pay attention to how energy is converted and how fossil fuel, pollution, and global warming are the effects of these last 200+ years of advances since the Industrial Revolution. Something else had to be done to have a sustainable and resilient electric energy conversion. The electricity that was unknown in 1850 became a requirement for modern society in the 21st century. An induction machine can convert mechanical power from a wind turbine, from a hydropower turbine energy, from steam power plants, or from any gas turbine. We must have a more well-designed system than what used to be a simple motor drive 20 years ago. This well-designed system can provide power balance control from the mechanical side, toward the drive, going into another inverter connected to a grid, and the whole system needs layers
of control, with advanced signal processing, further communications, and data requirements.

In the past 20 years, we have been experiencing the advent of “green energy policies.” Several countries are working on regulations for the installation of small- and medium-power distributed energy resources, including renewable and alternative energy sources, with storage solutions and bidirectional smart meters. All of these paradigms require power electronics interfaces. We may also have induction machines, induction generators, and other types of rotating or static devices connected to “intelligent power sources” delivering power to “smart grids.” Those intelligent power sources cooperate to meet the energy demand by exploiting renewable energy at their maximum extent, making possible smart grids where enhanced information technology throughout a comprehensive ecosystem will have improved capabilities with a better impact on the environment, improved science and technology, and bettering economics and lifestyles.

We moved from long-ago concerns of constant speed and reactive power consumption or poor voltage regulation on those primitive grids that directly connected induction motors to power electronics-enabled ones. Nowadays, motor drives allow four-quadrant bidirectional operation, with enhanced real-time control, with tremendous possibilities in the development of more integrated power electronics-enabled power systems. We have superb contemporary deployment and have done most of the retrofitting of legacy systems toward modern adjustable speed and torque control of induction machines; by now, we are making possible what we today call smart-grid applications.

To Be Continued.

Thank you for reading “The Electron Whisperer” (TEW) column by Marcelo Godoy Simões. See you next issue!

Biography
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