A Concise History of Induction Motor Drives—Part 2 [History]

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A Concise History of Induction Motor Drives — Part 2

By Marcelo Godoy Simões

INDUCTION MACHINES have a robust construction and relatively low manufacturing cost. Induction machines are more economical when compared with synchronous machines or permanent magnet (PM) machines.

TEW Story of the History of Induction Motor Drives

We are in an age of transformation, from an old paradigm of using our resources and assuming them to be eternal, to an understanding of the finite nature of our resources and the impact we have been making on our world in the past 200 years. We now work toward a sustainable net-zero energy path. We find ourselves amid such a great shift in the way we harness and utilize energy. A transition from fossil fuels to renewable sources is important because decarbonization, digitalization, deregulation, and decentralization (4D) are only possible with a sustainable source of energy. We must have energy, electrification, and education (3E) for a better future; 3E is what makes 4D happen. In our current era of progress, the paradigm of energy conversion is shifting from fossil fuels to renewable sources. We must consider sustainability and the circular economy, so in this second part of the historical narrative of induction motor drives, let us grasp the accessibility of the manufacturability of induction machines. Simple and robust construction primarily employs materials abundant in nature, such as iron, copper, and aluminum, some resins, and basic industrial supplies. With those resources plus an understanding of electromagnetism, energy conversion, electrical circuits, and a bit of hands-on experience, people may acquire the skills necessary to craft an induction machine from scratch until final assembly. It is necessary to have magnetic steel lamination and the help of electromechanical technicians and some trained motor-wiring specialists. Then we can bring about an induction machine, to serve its rotational needs for an electrified sustainable future. By investing in education, we spur further development of the local economy, also creating new labor and craft opportunities. Induction machines are invaluable for our present and future generations, maybe even a treasure for humankind. As educators, we should cherish and nurture science and technology in our electrical engineering schools and communities. These serve to provide both a sustainable solution and a cultural resource. May those induction motors and generators continue to spin their magic and bring us toward a brighter tomorrow (and may the Force be with you). We human beings have been obsessed with managing our time, which probably started with the Industrial Revolution. When people were agrarians, they had all the time in the world and were not concerned with time. They wanted to plant crops, farm animals, and take care of their families, and they were dependent on nature; thus, they were along for the ride no matter the time. When we became industrialized, factory owners needed workers to work together; thus, leisure time became even associated with waste—the waste of time. However, try to lift your eyes and look at the boundless tapestry of the night sky, with such a sense of marvel and mystique from the sheer scale of the cosmos, uncountable galaxies, and incalculable stars. When we lift our eyes and gaze at the night, there is a thrilling excitement and a sobering humility, all at once. Time has become a commodity in everyone's minds, and we have surrendered because the modern life of the past 200 years has made us stop looking at the skies to wonder. Our eyes are always on our level, particularly focused on smartphones and computer screens, which gives the pretense of not wasting time! "The Elektron Whisperer" is intended to encourage wonder, curiosity, and the desire for more knowledge. Anaximander is considered to be the first intellectual of humankind; he made us see that if the way we think is flawed, then there is no means by which how we think would be correct. What we think rarely matters; it is how we think that really matters. Reason without philosophy, without open minds, without scientific thinking is dogma. Therefore, induction motor drives can help us advance our electrification capabilities for a sustainable future. Study it, understand it, teach it. Henry Thoreau said, "The question is not what you look at, but what you see." —Marcelo Godoy Simões

Electromechanical Considerations

For high-power applications, any competitiveness of small PM-based machines becomes less perceptive since for high power machines, they are typically custom made. For medium and small sizes, the variation in price is dramatic, reaching an 80% difference. For most residential and rural and some small commercial sizes, induction machines are less expensive than any other machine. For the same kVA rating, induction machines are larger than synchronous machines because the magnetizing current circulates through the stator. A part of the magnetic iron is for the excitation of the machine. PM machines would be of course more compact. Depending on how the magnets are mounted, there are maximum speed constraints. For such applications as induction generators, where the machines are connected to the grid, maybe with a front-end power electronics interface, they will have fewer constraints on the turbine speed control, they are naturally stable, and they have very low maintenance requirements. Grid-connected induction generators without any power electronics would have constraints on starting up, and their reactive power requirements have to be provided by the grid connection (or from an inverter-based control acting as a static var compensator). Usually, directly connected induction generators will not have a variable shaft speed to optimize any turbine mechanical performance. An exception is doubly fed induction generators (DFIGs). They are directly connected to a grid but with the power electronics on the rotor windings. DFIGs are manufactured for higher power applications above a few hundred kilowatts.

A long time ago, the U.S. National Electrical Manufacturers Association standardized the variations in torque–speed characteristics and frame sizes assuring physical interchangeability among the motors of competing manufacturers. Those standards provided commercial success and the availability of integral horsepower ratings with typical voltages ranging from 110 V to 4,160 V. The only weaknesses of induction machines would be lower efficiency (since the rotor dissipates power) and the need of reactive power in the stator. The latter is not a problem with electronics-based control. Any induction machine is made up of two major components: 1) the stator consisting of steel laminations mounted on a frame in such a manner that slots are formed on the inside diameter of the assembly very similar to a synchronous machine assembly and 2) the rotor consisting of a structure of steel laminations mounted on a shaft with two possible configurations classified as a wound rotor or a cage rotor. The book by the author of this column, titled Modeling and Analysis With Induction Generators, has a chapter on construction details. The induction machine has external magnetic iron in its case, providing a magnetic path for the three-phase stator circuits to interact with the airgap. There are bearings providing the mechanical support for such a shaft clearance (air gap) between the rotor and stator cores. For a wound rotor, a group of brush holders and carbon brushes will be used for the connection to the rotor windings. The winding of a wound rotor could be the three- phase type with the same number of poles as the stator, generally connected in Y with three terminal leads connected to the slip rings by means of carbon brushes. Wound rotors are usually made for very large power machines, where power electronic circuits will control the rotor winding currents. For industrial and commercial applications, typically, squirrel cage rotors are used. Squirrel cage rotor windings consist of solid bars of con- ducting material embedded in the rotor slots and shorted at the two ends by conducting rings. In large machines, the rotor bars are made of copper alloy brazed to the end rings, when rotors are sized up to about 20 inches in diameter. They are usually stacked in a mold made with aluminum casting, enabling a structure combining the rotor bars, end rings, and cooling fan. Induction machines are simple, rugged, and very reasonable in manufacturing costs. Some variations on the rotor design are used to alter the torque speed features, and when machines are used for induction generators, they are optimized for better efficiency, less magnetizing circulating current, and higher-leakage inductance (to boost their output voltage and filter out harmonics), with the cooling capability to keep a low overall temperature of operation even for very low shaft speeds and internal and enclosed environments.

Scalar Control and Field-Oriented Control

It is possible to understand all the theory of induction machines with foundations and principles of electrical engineering, physics, and electro-magnetism. It is possible to use differential equations for the equivalent circuits and state-space formulation for advanced modern control. The use of quadrature d–q axis transformations — from a three-phase to a stationary frame and then from a stationary frame to a rotating reference frame— allows compact formulation in addition to achieving a hypothetical equivalent dc machine on the rotating reference frame. For parameter estimation, model reference control, and induction generator applications, typically, the rotating reference frame does not allow all parameter variation models. Therefore, either the d–q stationary or the traditional abc three-phase formulation can be used for adaptive control methodologies. For rural applications and isolated weak grids, it is still required to have self-excitation techniques of induction generators based on capacitors. It is necessary that people understand modeling and control self-excited induction generators. For modeling and control, differential equations can be written as the state- space model with the feedback signals, e.g., input currents and voltages measured for use in the control loop. While speed is a measurement signal, it is sometimes undesirable because speed sensors are fragile and may fail. Hence, sensorless induction machine drives have been developed. With computer simulation, even complex and advanced control schemes can be totally modeled and simulated before final implementation. When the induction motor drives were initially implemented with thyristors by McMurray, there was a proportional open-loop configuration where machine voltages and currents would be variable in frequency, in order to maintain a pretty constant ratio of impressed voltage by frequency (volts/hertz). The very first transistor-based inverters were similar, and the first generation of transistorized motor drives was defined as scalar control.

The scalar control of induction motors/generators is related to the control of the magnitude of voltage and frequency, so as to achieve suit- able torque and speed with an impressed slip (slip is the angular speed of the machine flux subtracted by the equivalent shaft speed in the machine flux rotating reference frame) under constant flux condi- tions. Scalar control can be easily understood based on the fundamen- tal principles of induction machine steady-state modeling. Scalar control disregards the coupling effect on the machine. The voltage will be set to control the flux and the frequency in order to control the torque. A power electronic converter will be used for a machine, either in series or in parallel with the machine terminals. The series front end is the most typical operation. However, a parallel path system capable of providing reactive power for isolated operation could also be used for an induction genera- tor. In such drives, flux and torque are functions of frequency and voltage, respectively.

Vector control is also called field-oriented control. It has mathematical transformations from the abc three-phase machine model to a rotating reference frame virtual dc model. Modeling of the induction machine will then be used to have the proper alignment of a chosen flux as the orientation. That means the machine flux vector should be aligned either with the d- or the q-axis of the rotating reference frame. Anyone working on this subject should be very careful in how the formulation of the transformations of the abc to the stationary (Clarke transformation) to the reference frame (Park transformation) are made either with power invariant or voltage/current invariant matrix modeling. The vector control orientation has been developed mostly for the rotor flux aligned with the d-axis for indirect vector control (IVC) and with the stator flux aligned with the d-axis for direct vector control (DVC) approaches, but there are other possibilities of transformations, alignments, and choices of the flux or the machine, such as proposed by the universal field orientation (UFO), where any flux could be aligned to any rotating reference frame axis. However, typically, UFO is not implemented in industrial applications, only for academic work.

Scalar control has somewhat lower performance when compared with vector control. In vector control, both the magnitude and the phase alignment of the vector variables are controlled. Scalar control drives may be easier to implement in less expensive electronics. They are popular for pumping and industrial applications and would not require digital signal processor (DSP) control. The importance of scalar control has diminished recently because of the superior performance of the vector controlled drives and the introduction of high-performance inverters and the decreasing cost of advanced micro- controllers in the floating point. High performance inverters offer prices competitive to scalar control- based inverters (volts/hertz inverters). The main constraint to use a scalar control method for induction motor/generators is related to the transient response; if shaft torque and speed are bandwidth limited, and torque varies slowly, tracking speed variations (within hundreds of milliseconds up to the order of almost a second), then scalar control may work appropriately. Hydropower and wind power applications would have slower mechanical dynamics. It seems that scalar con- trol is a good approach for renewable energy type applications, when the cost of implementation might be a decisive factor.

The Last Fifty Years Until Today

Before the 1970s, variable-frequency drives (VFDs) were a concept where volts/hertz was thus proposed. The speed of an induction motor is managed by varying the frequency of a controlled three-phase supply while at the same time maintaining a constant (rated) flux density. The McMurray forced commutation inverter was by the 1960s the approach. In reality, thyristors are not good at forced commutation, and they are a better fit for natural commutation. That is why thyristors are still used for the megawatt converters of the current high-voltage power grid and heavy machinery for mining and construction.

Transistor-based switching started to be used in the first few years of the 1980s, where most of the control schemes for any motor drive would be analog, with operational amplifiers, and maybe with some hard-wired digital logic gates. For such VFDs, at above the rated speed, the applied voltage would be kept constant at the rated value. This operation is referred to as constant power mode. At lower frequencies (lower shaft rpm), the voltage would then be proportional to the frequency. The machine could then be driven in either IVC or DVC until the maximum speed and torque. For a wide-range VFD, starting up from very low frequency, the system may not work well in scalar control. Scalar control must be compensated because the stator resistance has a lot of voltage drop for high power, and some nonlinear boosting should be implemented. Therefore, a wide-range drive could start after few hertz of operation. The VFD will transition to volts/hertz or IVC or DVC, and some variable-voltage power electronics must guarantee such a proportional voltage applied to the induction machine terminals. At the maximum speed, the switching power electronics would stop vari- able voltage by maintaining a constant voltage across the machine terminals but decreasing the flux in order to maintain a safe constant power in the machine. In the 1970s, only machines with open rotor windings would allow flux weakening (with control on the rotor windings). By that time, vector con- trol was just a theory. However, with the revolution of microelectronics, with microprocessors and DSPs, around the middle of the 1980s, the field orientation control of induction machines became possible. Motor drives became more and better feasi- ble and enhanced, moving from the research labs, then to the motor drive manufacturing industry. A wave of advanced control approaches of vector-controlled speed and torque motor drives for industrial applications. During the 1990s to 2010s period, IGBTs and power MOSFETs were fur- ther available as choices for transis- tor implementations for higher volt- age and current ratings. The market of a few hundred watts to some several kilowatts for the medium- voltage application of motor drives exponentially became widespread and worldwide. The old and primitive VFD based on thyristors' forced commutation and the earlier with a bipolar junction transistor would have a lot of audible noise, particularly because the switching frequency was in a low audible frequency, making the windings and magnetic iron stack in the machines vibrate. Bipolar transistors were very slow, and low-frequency open-loop modulation would make torque pulsations on the shaft. There were harmonics and subharmonics when square-wave six-step converters in three-phase systems were implemented, creating dangerous mechanical oscillations that could even break the machine shaft.

The machines during that time had a very quick aging due to the capacitive coupling of the variable high-frequency voltages and currents and the coupling of windings and the external iron case and base carcass, with an overall impact caused by electromagnetic interference. Such crude VFD schemes were not amenable for torque control (typically, those drives were not used as electrical generators), but further mathematical analysis and parametric case studies allowed slip control, that is, a quasi-stationary approximation of the magnetizing flux, so eventually, an average steady-state operation would be achieved. The transient response was not that great. For many years and still today, some industry people and power systems engineers like to curse the bad performance of induction machines based on narratives and tales of the past. However, we may always have uninformed people not aligned with the latest technological implementations. In the past ten to fifteen years, we have had advanced field orientation, signal processing, adaptive control, and modern techniques with hardware-in-the- loop, which can be applied to and implemented in induction machines.

There was a technological revolution in the 1980s with new microprocessors developed for personal computers and associated micro-controllers that were launched with better and faster performance than those of previous generations. Many companies were important in the realm of microprocessors and micro-controllers: Texas Instruments, Motorola, and Analog Devices start- ed to manufacture and sell DSPs. DSPs were better than regular micro- processors because they allowed the multiplication of variables in one computer cycle. Every new edition of a DSP always incorporated more features, with embedded generation of pulse-width-modulation (PWM), easier I/O, and easier serial communication with other devices, with better software tools and better system compilers, typically using C language. Today there are other modern languages used, and quickly, there were discovered new applications of real-time control of induction motors.

During the 1980s, the ideas and methods for induction machine modeling and control were very new to most people. Even the author of this column, who was introduced to the foundations of power electronics around 1984 and knew some control methodologies, had initial difficulties in implementing a VFD for three-phase induction motor con- trol. So this author decided to enroll in a graduate course during his master's program about the general theory of alternating current machines, with a book that was pub- lished by B. Adkins and R.G. Harley in 1957, also a very important work was the publication of the paper "Simulation of Symmetrical Induction Machinery" by P.C. Krause and C H. Thomas in the IEEE Transactions on Power Apparatus and Systems, in 1965. Later Prof. Krause published a book which is now in the 3rd edition. The book was adopted for a graduate course that I took, during the 1980s, which was considered to be advanced. The computer based simulation at that time was still on mainframes or based on compiled languages such as Pascal and C in DOS personal computers or maybe in Unix workstations. Students and researchers would have to implement all the mathematical routines and recipes. The general theory of electrical machines was more conceptual and focused at that time on the approach of having a "primitive machine," i.e., a canonical model that could be handled to represent any type of machine, such as dc motors, asynchronous motors, and synchronous motors and sometimes including damper windings. It was a general introduction to two-axis theory, and most typically, the computer models were implemented to observe how startup transients would develop in the electromechanical system, with harmonics, oscillations, and short-circuit conditions. Such a graduate course would not emphasize vector control, which was not even taught in graduate studies. The first time I learned advanced modern control drives, vector control and scalar control was in the courses taught by Prof. B.K. Bose at the University of Tennessee from 1991 to 1995. In the general theory of electrical machines, the use of the word "general" in the title of the book and associated courses was criticized because concepts were not comprehensive in the sense that every possible type of machine and problem could be dealt with. Typically, PM motors were not included, and neither were variable reluctance types nor stepper motors; no imbalance of machinery was included; and no control approach was employed. Vector control was coming from theoretical foundations, in a few reports and scarce papers; books were mostly adopting space vector approaches, which are very mathematical, fancy, and compact. However, polar complex numbers for electrical machine formulations, with space vector algebraic formulations, were more hindering than motivating.

Vector controlled induction motors can be implemented based on the machine stator flux, air gap flux, or their rotor flux. The d–q trans- formation is made so as to have an alignment of the rotating reference frame with the chosen flux. For example, the d-axis of the rotating reference frame to be with the full vector the flux means any q-axis component would control the torque. Such an orthogonality can be explained by the electromagnetism of machines. Since a q-axis component would have a flux vector projection of zero, any change in the q-axis changes the machine active power only, consequently only changing the machine torque for a constant speed operation. Therefore, a closed loop speed control [with a proportional + integral (PI) initialization, for example] will generate a reference signal that can be used for commanding the torque and consequently the q-axis current component on the machine. A hypothetical virtual d–q machine could be controlled on the rotating reference frame by 1) guaranteeing that the flux is aligned with one axis, 2) guaranteeing that the other axis will control torque, 3) pro- viding any mathematical feedforward or decoupling between the axes, and 4) guaranteeing that the induction machine would have a current controller, specifically, a power electronics inverter where the operation is to impress current.

Most of the time there is a voltage-source three-phase PWM system, with inner current feedback control. To impress currents on the machine terminals, as dictated by the hypothetical rotating reference model, would make such a three- phase induction motor or generator follow the commands given on the hypothetical virtual d–q machine. However, it is possible as well to design current-fed inverters to con- trol an induction motor drive in vector control. Few people understand this scheme. Field-oriented control uses a dynamic model of the IM where voltages, currents, and fluxes are expressed in space vector forms. The IM is described by differential equations, and the model accounts for both steady-state and transient dynamics. Therefore, field-oriented control can achieve excellent performance in transient and steady-state conditions. The simplicity results from the fact that the torque and flux components are decoupled in the adopted reference frame. Two types of field-oriented control are defined based on the position of the rotor flux: indirect and direct. By adding the slip position to the measured rotor position, the flux position in indirect field-oriented control is obtained. The flux position in direct field-oriented control is calculated based on the terminal variables and rotor speed. Since field-oriented control stems from a frame transformation that requires rotor speed, the knowledge of the rotor position needs to be acquired accurately in order to perform such a transformation. The accuracy of the rotor position estimate has a significant impact on the performance of field-oriented control. If such an estimate is not accurate enough, the satisfactory level of decoupling of the torque and flux will not be achieved.

Typically, we can adhere to the vector rotation representation with the d–q rotating reference frame. The books and papers by Bose, Lipo, Novotny, and Simões can be studied for further details. In the quadrature equivalent d–q frame circuit for an induction machine, the stator flux is the integral of voltage across Lm and Lls, the air gap flux is the integral of the voltage across Lm, and the rotor flux coming from the stator side is the integral of the voltage across Lm and Llr. It is possible to imagine that in steady state, those voltages are lagging from one to the next as we move from the external terminals toward the inner equivalent circuit. Consequently, those fluxes would be lagging as well. Historically, direct-vector control was implemented by Hasse with flux pickup coil sensors on the air gap; of course, special machines were constructed for those. Then, IVC was proposed by Blaschke and implemented internally at Siemens. The analytical calculations and feedforward control were based on the rotor flux, i.e., the machine flux toward the right side of the equivalent circuit (typically, the rotor is short-circuited for considering squirrel cage machines). In this case, the system is parameter sensitive on Rr (rotor resistance).

In 1988, there was a paper published by Xu et al., where they implemented DVC based on stator flux. The same voltage integration across Lm and Lls can be computed by measuring the machine voltage terminals and currents, subtracting the voltage drop across the stator resistance and integrating on time; of course, in this methodology, the performance parameter is sensitive to stator resistance, but it is easier to measure the stator resistance than the rotor resistance, and thermal correction has been proposed by B.K. Bose, D. Crecelius, and M.G. Simões. The only practical concern is that a minimum shaft speed and frequency are necessary for the integration to have a good performance, but typically, in any sensorless-based control, there are limitations on the minimum machine speed, temperature effects, or some other parameter sensitivity. The author of this column believes that two strategies are very relevant and should be taught at the bachelor's level of electrical engineering: 1) the IVC based on the rotor flux orientation or 2) the DVC based on the stator flux orientation. UFO was proposed by DeDoncker and Novotny in the same year, 1988, when stator flux orientation was proposed. A general controller could be aligned to any flux, but typically, such a globally based field orientation is not adopted in real life.

Currently, in this second decade of the 21st century, there are very powerful microprocessors, microcontrollers, DSPs, and field-programmable gate array technologies available for any industrial, commercial, or even hobbyist application. The IGBT transistors allow applications on the order of some kilovolts and kiloamps at more than 25 kHz switching frequency, with gate drives and power devices integrated, high compact- ness, and implementation with electromagnetic interference and electromagnetic compatibility at the highest level of safety. Either IVC or DVC will require mathematical transformations; those will involve the following: having either a d–q or a polar space vector formulation of an induction machine or maybe a three-phase (abc) sinusoidal approach establishing a three-to-two- phase (abc) to (ds–qs) projection using a Clarke transformation, where vector control implementations usually assume an ungrounded motor with balanced three-phase currents such that only two motor current phases need to be sensed, and it is necessary to develop the back- ward two-to-three-phase (ds–qs) to (abc) projection, which will then assume a space vector PWM modulator or an inverse Clarke transformation plus one of several possible sinusoidal PWM modulation schemes forward and backward two-to- two-phase, (d–q) to (ds–qs), and (ds–qs) to (d–q) projections using the Park and inverse Park transformations, respectively depending on the chosen flux orientation (stator, air gap, or rotor), the mathematical decoupling torque and field signals to be used in the control strategy plus any necessary sensor measurements for algorithm development.

The IVC is commonly used in industrial applications where a closed-loop speed control will easily operate the drive systems throughout a range from zero speed to maxi- mum speed (with variable torque) and then beyond, where a high speed can be achieved at a constant power and field-weakening mode. For such IVC, the flux angle position ^~eh is fed forward with internal calculations, and the measurement of stator cur- rents (which are also in an inner cur- rent mode control loop for the invert- er) with the measurement of the rotor speed allows the instantaneous calculation of ~e by summing the measured rotor angle corresponding to the rotor speed and the calculated reference value of the slip angle corresponding to the slip frequency ~SL. The idea behind IVC is to use the location of the rotor; such an angular speed will help to calculate the angle ir, and then with the proper calculation of the slip frequency, a feedforward signal would generate ~SL. Both can be integrated and added to generate angle ie, which can then be used for vector rotation and inverse vector rotation. The system can be easily transitioned toward being torque control or speed control, with the management of the PI initializations on the torque loop or speed loop control. For the DVC implementation, there is a decoupling feedforward structure to align the estimated stator flux with the d-axis, which is calculated with the measurement of machine voltages and currents and time domain integration; a DVC works well for speed ranges above 5% of the machine base speed.

We are in an age of energy transformation, from fossil fuel to renewable energy, and sustainability and the circular economy of the whole society must be considered. Therefore, in such a perspective, it is important to understand how the manufacturability of induction machines is accessible to nearly all, anywhere: they have simple and robust construction; the materials utilized are mostly iron and copper, maybe some aluminum and resins; and any industrial base of tools and shop supplies are mostly sufficient as raw resources. For induction machine applications, it is necessary to keep electrical engineering solid as a technological framework. Students with an understanding of electromagnetism, energy conversion, and electrical circuits and with some hands-on skills can learn everything needed to design an induction machine from scratch and order magnetic steel lamination, and with the help of mechanical technicians and someone trained in wiring trans- formers and electrical motors, they can make one induction machine with indigenous grassroots, even spinning further local economic developments with possible new labor and crafts. Therefore, induction machines are certainly a present and a future solution that should be considered as a treasure for humankind, to be kept and nurtured in our electrical engineering schools and communities, as a sustainability solution and a cultural resource.

This two-part article was a narrative about induction motor drives. To learn more, you must study the books and published papers in this vast area; it is very motivating to go in depth in such an exciting learning experience. Thank you for reading “The Elektron Whisperer” column by Marcelo Godoy Simões. See you next issue, with another story about history.

For Further Reading

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Biography

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