Didactic testbed for B-learning of advanced power control methods in an AC motor.

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***Abstract*—This manuscript shows the design of a testbed for a remote laboratory that controls a three-phase AC motor. Different power control techniques and modulations are used and implemented in conventional and multilevel converters. Some of them are physically implemented, and others simulated through Hardware- In-the-Loop because of the high cost of its procurement or construction.**

The methodology proposed studies different power control techniques and modulations to control the mechanical power of an electric motor. Each technique used is analyzed deeply according to its applications, advantages, and drawbacks.

This didactic tool intends to create significative learning as *STEM education*, using the didactic testbed proposed and applied to control systems and power electronics. For that reason, this paper creates a remote lab as a Blended-learning configuration, which instructs advanced power control concepts inside the faculty of basic sciences and engineering of the Universidad de Los Llanos. Different courses will be benefited from this tool as electric machines, industrial electronics, dynamic systems, motion control, and others.

***Index Terms*—AC motor, B-learning, industrial electronics, motion control, power control, remote laboratory.**

I. Introduction

USe didactic material streamlines any learning process, regardless of the knowledge area.

A didactic device is an element or resource created to promote a better student understanding of a specific topic. Consequently, a simplified definition shows the didactic devices as a tool that facilitates the task of generating learning [1-6]. Currently, professors use a wide variety of teaching materials to teach and expose concepts and theories. This achievement is an assembly between knowledge acquired in the classroom and practice.

However, when thinking about teaching materials for teaching power control, some of these tools can be dangerous if not handled properly [3-5]. Mishandling of these tools could cause from minor injuries to serious bodily harm; therefore, its uses should be under presence of trained personnel.

Didactic devices can range from simple devices that demonstrate their basics behaviors to whole test benches with more complex characteristics [4-7]. Use these applications can accelerate the cognitive development of people. For example, some studies have evidenced the effectiveness of useful tools as recreational activities on the internet or even digital terrestrial television (DTT) for a learning purpose [8].

The complexity of the didactic devices often depends on student size, social circumstances, and media available. In this specific case, as it is an asynchronous machine power control, the material is aimed at students with basic understandings of electronics who wish to consolidate their studies in the power management area [9].

The use of variable speed drives has enhanced the industry, providing flexibility to modify mechanical power used in a motor. Also, these control permits reducing costs and space. This device works as an AC-AC converter with a DC intermediate stage. This converter rectifies and obtains a dc bus from the three-phase input voltage, then invert and convert in ac, the dc voltage through discrete switches.

There are multiple alternatives to obtain a motor power control, but its efficiency, protection, and useful life of the equipment vary according to inverter modulation [10]. As common modulations, we can find PWM, PSPWM, LSPWM, SPWM, SVPWM, SVM, among others [11-15]. The modulation selection could determine by comparing through its Total Harmonic Distortion (THD) in the response they produce. This disturbances phenomenon is a consequence of the harmonic signals. High THD causes heating in the machine generating a loss of efficiency and life reduction of the device [16,17].

II. Framework

This section includes the pre-established educational goals of the didactic testbed, thus as all theoretical foundations use and its analysis applied. Initially, this section shows clearly the main aims of this educational resource. After, three topologies are selected for the testbed with their respective power control techniques and modulations.

A. B-learning objectives

This testbed has different objectives, that depend on the student level and progress. Three levels are differentiated:

- **Low Level** - To know which modulations, topologies, and controllers are commonly used for power motor control.
- **Medium Level** - To analyze the technical advantages and drawbacks of the topologies studies and power converters used in industrial environments.

- **High Level** - To design an analysis methodology which can be extrapolated to any converter topology that permits evaluates and contrast its behavior and energy performance with other converters.

Methodology proposed to be used with this remote lab covers all these objectives. First of all, e-students will approach the theory of each modulation, topology, and control. After, the e-student learns through safe experimentation (*B-Learning*) all these concepts. Different manual guides are designed to lead in an incremental knowledge of the power control on electric motors. Then, the student compares the different concepts used inside each topology permitting generating indicators for performance comparison. Finally, each student creates its methodology to evaluate different kinds of controls, including other topologies to the show in the remote lab.

B. Proposed inverters topologies

Three inverter topologies are proposed for the remote laboratory. Each topology has fundamentals required by electrics, mechanical, and electronics engineers. Especially, engineers that required advanced training to develop their labor in industrial environments.
This topology gives the know-how of power controls, taking theory and putting it into practice. Topology selected are the conventional three-phase inverter, a capacitor h-bridge multilevel inverter (MLI), and modular multilevel converter (MMC).

On the other side, all three-phase systems as simplified using the *Clarke* and *Park* transformation. Both transformations are well-known and defined inside the literature. The *Clarke* transformation for abc voltage is defined in (1). *Clarke* transforms a three-phase system (abc), with 120 degrees offset between phases in a bi-phase system inside a rotational frame. The new system has a 90 degree offset between α and β. This phase simplification permits an easier indirect control of the abc system. Additionally, the Park transformation is used to determine the direct d and quadrature q vectors (2), which is a stationary frame associated with the angular velocity of the electric motor. So, with the quadrature current I_q and direct current I_d is possible to manipulate the torque in the motor.

$$\begin{bmatrix} V_\alpha(t) \\ V_\beta(t) \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} V_d(t) \\ V_q(t) \end{bmatrix} = \begin{bmatrix} cos(\omega t) & sin(\omega t) \\ -sin(\omega t) & cos(\omega t) \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{2}$$

1) Conventional three-phase inverters: Conventional three-phase inverters are commonly used in almost all industrial processes. See Figure No.1. Power control of this inverter is easy and simple. Normally a hard-switching technique permits the turn-on and turn-off of the switching devices (Mosfet, IGBT, and others). We can find different modulations to implement hard-switching as PWM and SPWM. However, these modulations can generate drawbacks as undesirable harmonics, also Eddy parasite currents inside the stator.

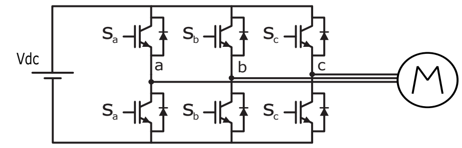

Fig. 1. Conventional three-phase inverter

When this inverter is used as a Variable Frequency Drive (VFD), the main aim is the I_q current that controls the torque. The I_q current is directly proportional to its torque. For this reason, two control methods used are the Maximum Torque Per Ampere (MTPA), and the Direct Torque Control (DTC).

2) Multilevel Inverter (MLI): This MLI generates a voltage signal purer without undesirable harmonics. To do this, the MLI reproduces the sinusoidal wave with little voltage steps. H-bridges as commonly used in different levels, main and auxiliaries, to generate all changes of voltages. A voltage asymmetry to use in this inverter is 1:3:9. That means the voltage of the first auxiliary level (yellow) is the third part of the main voltage, and the auxiliary 2 (in green) is the ninth part of the main. With this relation, we can guarantee 27 levels between positive and negative peak voltage.

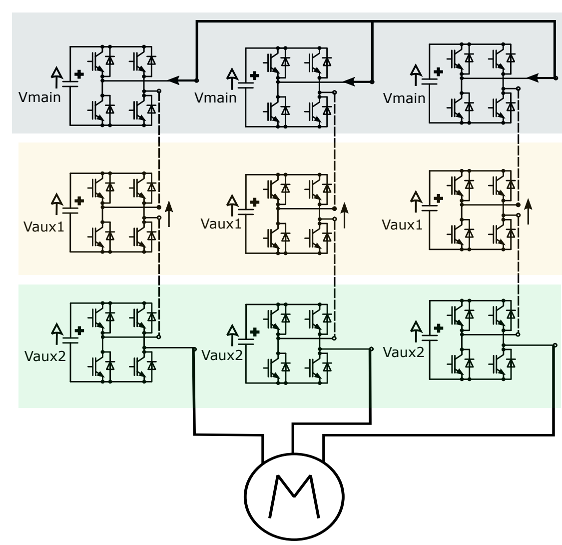

Fig. 2. Topology selected for Multilevel Inverter (MLI).

The power motor control for this topology is the same as used in the conventional triphase inverter. MLI varies the voltage THD and its energy efficiency compared with the topology before mentioned.

3) Modular Multilevel Converter (MMC): Modular multilevel converters, also called M2C, is the newest and promising technology with multiples uses. Some of its uses are being developed at this time, taking advantage of its bidirectional power flow. This uses comes from battery power banks of some MW as Tesla Powerbank, going by motor control until energy transmission to high distances with losses reduced using *High Voltage DC* (HVDC). This remote laboratory would be incomplete without this type of technology.

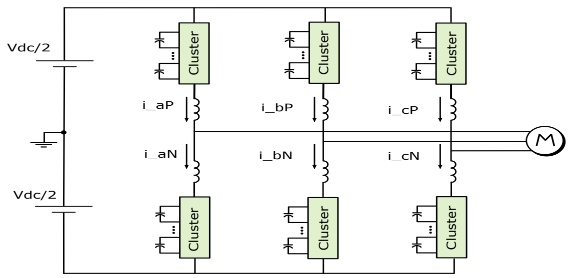

Fig. 3. Modular Multilevel Converter - MMC.

As shown in Figure 3, this topology is composed of 6 clusters, two by each leg. Each cluster is a sum of voltages, that comes from half-bridges or full-bridges, similar to MLI. MMC permits boost the dc voltage, when works as a rectifier, infinitely. Thus, the HVDC has been possible giving some advantages as reduces losses, prevents parasite currents, and eliminates the skin effect over copper conductors.
On the contrary, when the M2C works as an inverter it can modulate voltage and current simultaneously, through its circulating currents. This means that voltage and current are controllable, permitting better control of the electric machine.

C. Modulation techniques

As modulation techniques to use inside the inverter are selected the PWM and the *Space Vector Modulations* (SVM), both with its variants. These modulations are previously explained inside the power control lectures.

1) Pulse Width Modulation (PWM): The PWM technique refers to the grouping of procedures to alter the duty cycle D of the pulses of a switched signal. Conventionally this signal is created comparing three triangle signals T_s with phases shifted of $2\pi/3$ with a M_s modulate the sinusoidal signal. When $T_s > M_s$ each output changes to high logical state. On the contrary, the PWM is used in multiple power applications and energy converters as control of thermoelectric elements, among others. Usually, this technique can work in noisy environments.
Two PWM variants can be annexed to the learning aims due to their high application in power electronics, the Phase Shifted-PWM (PSPWM) and the Level Shifted-PWM (LSPWM). Both PWM variants can be used in multilevel converters to generate discrete sinusoidal waves with lower THD.

2) Space Vector Modulation (SVM): This technique allows analysis that the induction motor in a decoupled way, similarly to the direct current motor with separate excitation. That means it admits an independent control of the flow and the torque. Thus, the non-linear induction motor model is simplifying to a model with two orthogonal axes. So, the flow control is directly proportional to the direct shaft current I_d, and torque control is associated with the quadrature axis I_q. This system uses by referencing the alternating three-phases system of stator currents to a non-stationary orthogonal coordinate system that rotates synchronously with the rotating magnetic field. In this new system, the I_d and I_q currents are rotating vectors, hence its name: vector control. Exist two possible ways to perform this type of control (direct and indirect). They differ according to how it acquires the stator flux vector.

III. Methodology of remote laboratory proposed

The remote laboratory is shown in Figure No. 4. All combinations between topologies and modulations are possibles. Each student uses a GUI interface through their personal computer to access the remote laboratory. Sessions establish between students' computers and real-time web servers are recorded in a database (DB).

The conventional and MLI are the uniques topologies implemented in PHiL. MMC topology is implemented in SiL, due to the high cost of implementation. Additionally, the SiL mode generates a rapid implementation of new topologies before being under construction.

When a student finds occupated all PHiL resources, the server addressed it to a SiL mode. All sensors and instrumentation required by hardware are worked on-site. A remote technician will monitor the HiL operation meanwhile the student does his remote practice.

A. Hardware of AC power control of conventional inverter

1) Design of power stage: AC-DC converter has a three-phase rectification stage whose construction consists of three legs, composed of two diodes in series and a high-capacitance and high-voltage filter to eliminate the ripple of the rectified signal. Its operation intends to supply a direct current to the inverter circuit to later, together with the switches' commutation, resume the alternating behavior and power the AC motor.
The 6A10 diodes and 3300uF@450v capacitors are selects due to their high current and voltage operation. As the capacitor selected is oversized and bulky to support 400V, this capacitor can substitute by a capacitors' bank, working with the same voltage. The inverter stage complies with the classic topology of a three-phase full-bridge Voltage Source Inverter (VSI) inverter. Each of its three legs consists of two MOSFET switching devices in series, each provided with a diode in reverse connection to conduct the reactive current back to the external DC source.

2) Design of control stage: Concerning powering the drivers and optocouplers, the circuit design uses the single-phase power outlet of the facility. A step-down transformer is used that takes the 115V supplied by the electrical installation and reduces it to 15V and 6V. This process allows working with voltages supported by conventional elements, reducing the complexity of the circuit.
The signal enters a rectification stage to convert AC energy

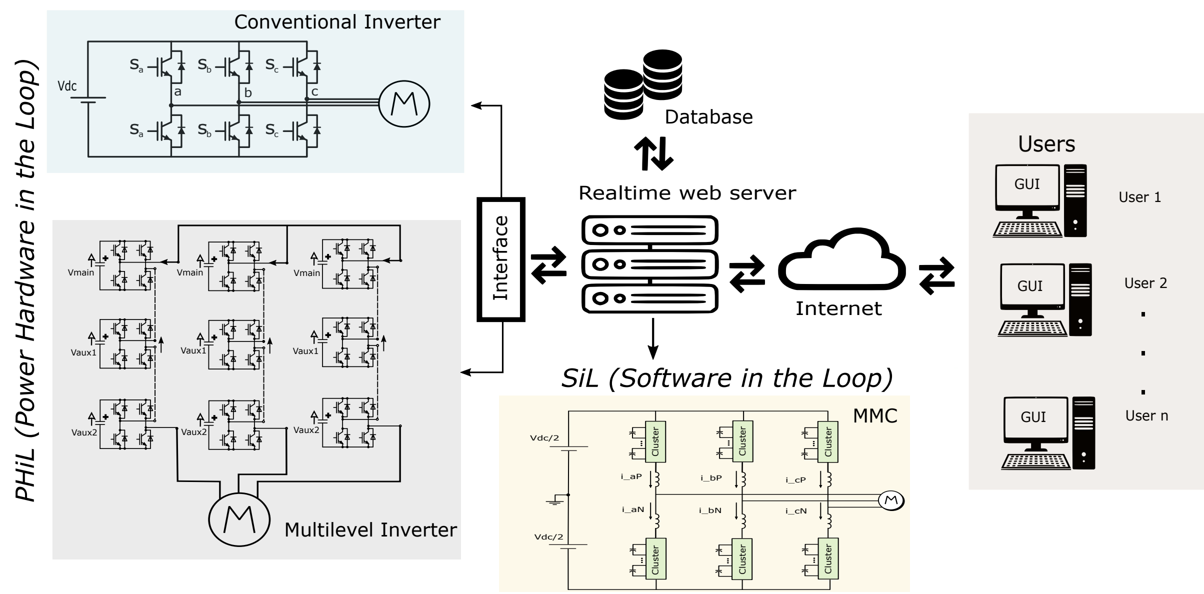

Fig. 4. Proposed didatic testbed to study advanced power control methods in three inverters topologies: conventional triphasic inverter, MLI and MMC.

into DC energy. The rectifier diode 1N4007 produces an alternating DC half-wave signal that feeds the capacitor that acts as a filter. In this case, it recommends a high capacitance value to effect better filtering of the DC signal. Regulators 7818, 7815, and 7805 are used as voltage regulator devices to produce the DC sources bus. These elements capture the voltage peaks that may occur and set the output limit at 18V, 15V, and 5V, respectively.
The voltage demand in V_{GS} between 12 to 20 V and the appearance of floating grounds product of the commutation of the switching devices, make necessary intermediate elements as optocouplers. The devices choose to solve the above drawbacks and conditions are IR 2110.

3) Circuits and Auxiliary elements: As the inverter operation implies peaks of current and voltage, it is necessary to prevent element damages that guarantee optimal functionality through protection methods. Mainly, these problems stay in the Control Processor Unit (CPU) and the power elements. The CPU manages at a high level the inverter and also generates all control signals. On the other side, the power elements control the VSI active power [10].
Different optocouplers circuits offer sufficient guarantees to be satisfied regarding the protection of the programmable card. This is because this element produces that the circuits, in which it acts as an intermediary, are wired isolated. However, as it is a power switching element drive, the current and voltage that it must withstand are considerable.

4) Power control of Electric Motor: To implement a control method for the different topologies is proposed the MTPA of an AC synchronous motor. In this case, we use a permanent magnet synchronous due to its existence in the laboratory. Figure No. 5 shows how the I_a and I_b are sensed and transformated using $Clarke$ and $Park$ transformations. With $I_d = 0$, I_q can be used as a reference for motor torque.

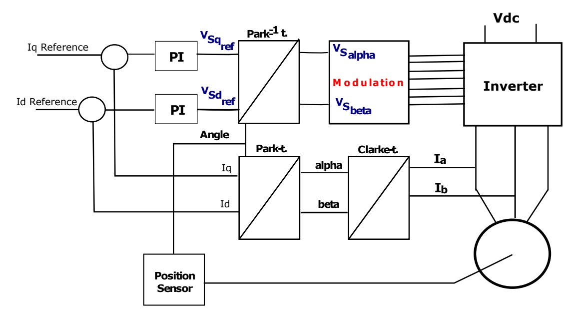

Fig. 5. MTPA implemented by an AC motor (PMSM)

IV. Results

In this section are reported some results, which are obtained from SiL and HiL. For SiL, different circuits are implemented in Matlab Webserver as a part of the learning process. As hardware was build two prototypes that are in continuous improvement.

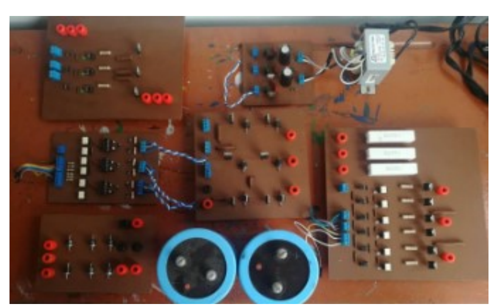

Fig. 6. PCBs of Conventional inverter for supply a 1/4 hp motor

Figure 6 is shown a first approximation to the conventional inverter, which was built using Mosfet. This inverter controls a

1/4 hp electric motor. On the other side, Figure No. 7 was built an MLI to controls a 20 kW PMSM. Manipulate this power control can be dangerous for inexpertise hands, for this motive is relevant to use the proposed remote lab. Some results of this

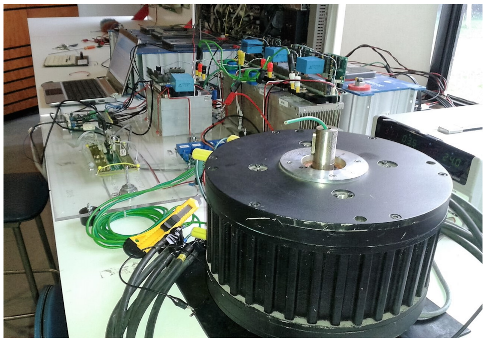

Fig. 7. Multilevel inverter for a PMSM

simulation are shown in Figure No. 8, and Figure No. 9. Figure 8 shows different voltage levels without any PWM inside. This nearest vector selection is a basic concept for understanding MLI. Posteriorly, Figure No. 9 demonstrates how SVPWM works.

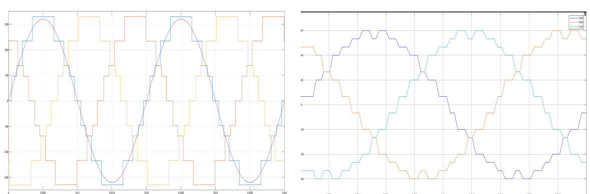

Fig. 8. Nearest vector as SVM in MLI and Variation parameters on simulation (20 V/div)

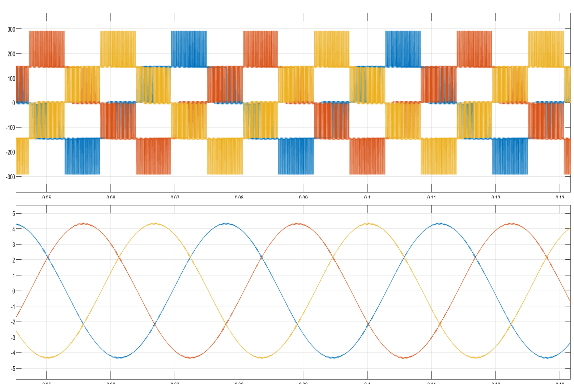

Fig. 9. Voltage and current simulated for a SVPWM

Some PHiL results are shown in the next figures. Initially, a hard switching of the conventional inverter is performed as PHiL. From this process, Figure No. 10 and Figure No. 11 were obtained. It is important to remember that any modulation is taking into account. Only two states are used, on and off. From this process, the student must conceptualize how it is a waste the energy. A register of all energy losses (switching and conduction) is recorded on the DB. This exercise demonstrates how important is modulation over the switching inverters.

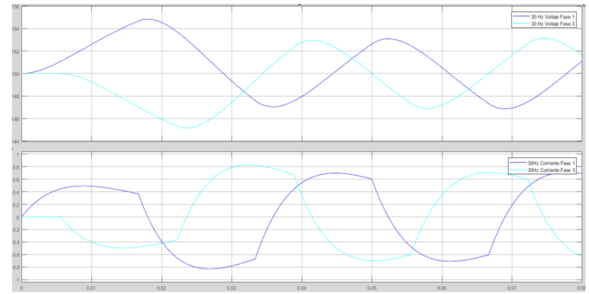

Fig. 10. Results of voltage and current of 2 phases of conventional inverter @ 30 Hz

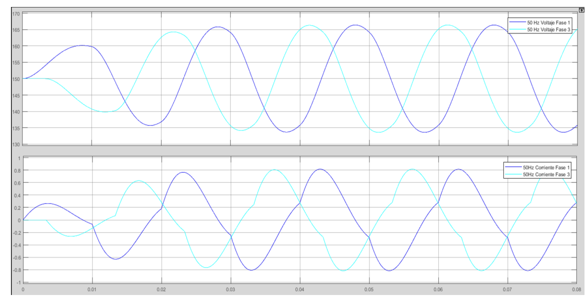

Fig. 11. Results of voltage and current of 2 phases of conventional inverter @ 50 Hz

After, an MLI is performed through PHiL as shown in Figure No. 12. On this graph, it is possible to understand how the THD voltage can generate some problems inside the inverters.

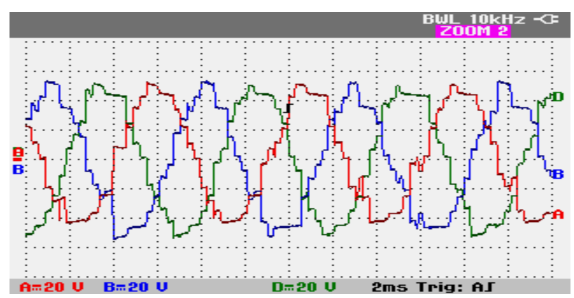

Fig. 12. NLC voltages presents in the MLI

Then different figures show how the MTPA works to control the power of the electric motor. Field-oriented control is shown in Figure No. 13, where is possible to observe how the frequency and voltage increase when the PMSM accelerates.

Figure No. 14 reports a fast start of the PMSM, which is carried to its nominal voltage without any mechanical load. To break the PMSM inertia the electric motor requires a 0 Hz value, i.e. DC current. Then frequency and voltage must increase its value to give more electric power to the motor.

Posteriorly, normal behavior for a PMSM is reported in Figure No. 15. A back-EMF is generated by the rotor inertia when is disconnected the power supply of the electric motor. That means that the electric motor starts to generate energy using its permanent magnets.

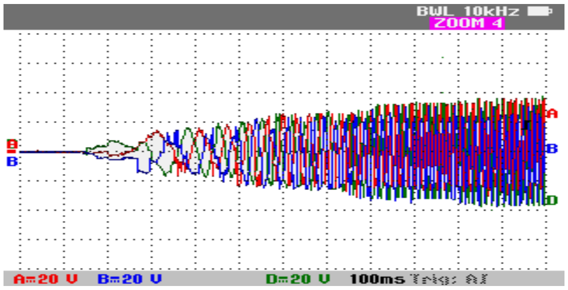

Fig. 13. Change of voltage and frequency generated by FOC

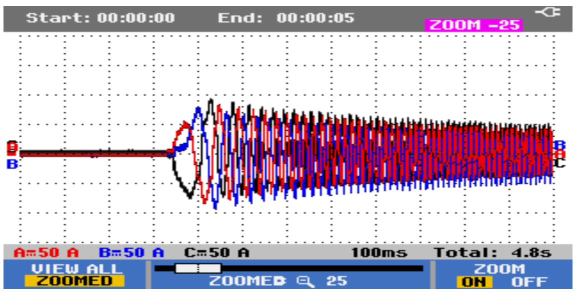

Fig. 14. Fast start of PMSM using FOC with MTPA technique

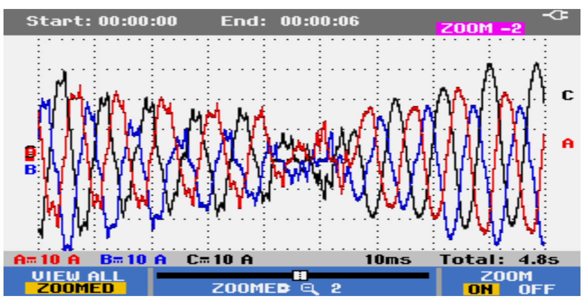

Fig. 15. Change of traction to generation of PMSM

V. Conclusions

This B-learning methodology can generate a faster comprehension of theoretical concepts related to power control on motors. This educational tool must be every day improved, pursuing all aims proposed by the area.

Also, this remote laboratory prevents two aspects: (1) any personal damage to the students, permitting that focus on its learning process; and (2) problems of access to power control knowledge, for engineering students, in contingencies of social isolation, such as Covid-19.

This remote laboratory is still under development, especially the subject of the web page and computer access control by students. So, any improvement to the learning methodology or technology control topics could be implemented.

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