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Experience-based course on three-phase electrical power conversion

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Abstract—Although electrical machines and power electronics are well studied in the different courses from the first to the third year of university level, they are often studied separately. Many Master's degree students in electrical engineering courses, while having already seen the principle governing electrical machines and power electronics, are unable to deeply describe the operation of a variable-frequency drive of an electric motor. The course presented in this article aims at filling these gaps, by proposing a structure based on experience (70%), with a part of simulation (20%) and some theoretical reminders (10%).

Keywords—Teaching methods, electrical engineer, electrical machine, variable frequency drive, experience-based methods.

I. POSITIONING OF THE ACTIVITY

The PREX (*Pratique Expérimentale* in French) is a course format offered in the second semester of each first year to students of the French National Institute of Aeronautics and Space (ISAE-SUPAERO). Table 1 shows the objectives of the activity.

This course format should promote and improve student learning by relying on several of the six levers highlighted by the study presented by M. Poumay [1]. We will refer later to the third lever presented by the author, namely "Giving meaning to learning by increasing the value of activities in the eyes of the student, particularly by bringing them closer to their future professional experience". In this sense, there are several topics to choose

from and the philosophy behind them is to allow students to approach a subject of study from a practical point of view, whether by simulation, manipulation or both. The topic of this article concerns the study of the power chain for a hybrid or electric propulsion of aircraft.

The development of more electric, or even fully electric, aircraft plays a key role in the fight against global warming. To be able to develop these systems, it is necessary to train engineers with solid skills in the development and use of electric motors.

The choice of the topic of our educational activity is justified by the previous skills of the incoming students who, although they have already seen the principle governing electrical machines and power electronics, are unable to deeply describe the operation of a variable-frequency drive of an electric motor. The reasons for this lack can be found in the previous training system, where the above-mentioned topics are covered in completely separate sessions with a strong theoretical component.

This reflection led us to exploit two other levers, namely "Making the student more active during the course, so as to make his or her learning more profound, more durable and more transferable" and "Increasing the student's sense of mastery or competence".

The course presented in this article aims to foster these dynamics, by proposing a structure based on experience (70%), with a share of simulation (25%) and some theoretical reminders (5%).

During the course, their basic skills around :

TABLE 1: SKILLS TO DEVELOP AND/OR IMPROVE DURING THE PREX.

Learn how to develop an experimental approach in response to objectives	1.a Identify and prioritise relevant physical parameters and quantities
	1.b Criticise an experimental setup
	1.c Predict useful measuring ranges
Develop a critical look concerning measurement technique	2.a Know and criticise the configuration of a measurement chain
	2.b Assess the limits of the sensors used: performance in terms of noise and measurement dynamics
	2.c Identify the limits of measurement accuracy
	2.d Know how to perform an uncertainty calculation
Learn how to use experimental results and extract conclusions in order to communicate them	3.a Ensure post-processing of data
	3.b Carry out an evaluation of the results
	3.c Compare experimental results with (theoretical or numerical) models
	3.d Present results and associated analysis using appropriate support

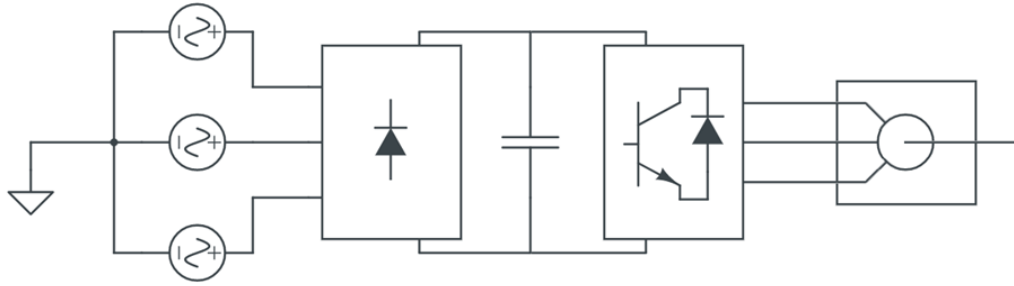


Figure 1: Structure used in the course described.

- Electrical machines,
- Three-phase voltage rectifier (diodes and thyristors),
- Three-phase voltage inverter

are discussed, reinforced, and tested first through simulations and finally through experience.

Each skill is used with the final objective of efficiently powering a three-phase electric machine according to the diagram in figure 1.

The final objective of the course (efficiently powering a three-phase electric machine) is clearly identified and each part of structure is associated to its function, this because, studies [2] have shown the importance of presenting the general problem before proceeding to the study of each part of the complex problem. This allows the student to set up the connection between the different parts in the correct way. It is wise to remember that as a teacher you know the answer while the student is constructing one.

II. USED MATERIALS WITH DETAILS OF COSTS

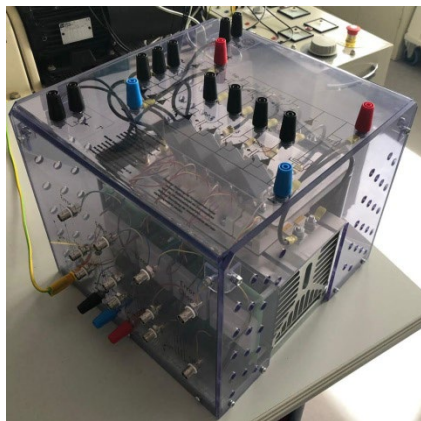


Figure 2: SEMITEACH IGBT system [3].

For all simulations we chose to use PSIM, as it was very well suited to our needs even in its free version.

The rectification (by means of a diode bridge) and the three-phase voltage inverter was studied using a teaching block "SEMITEACH pedagogical three-phase inverter" (figure 1). The rectification, by means of Thyristors Bridge, was studied using a "SEMITEACH educational thyristor rectifier" teaching block (figure 2).

TABLE 2:
USED MATERIALS: COSTS AND OBJECTIVES

Name	Objective	Price
Système SEMITEACH IGBT (fig. 2)	Rectification (with diodes) and three-phase voltage inverter	2000 €
SEMITEACH Thyristor Power Electronics Teaching System (fig. 3)	Rectification and voltage control with thyristors	2000 €
Motor/generator Teaching pack (fig. 4)	Study of an electrical motor/generator	12000 €
Leroy Somer UMV 4301 variable-frequency drive (fig. 4)	Comparison of a commercial system with an home-made system	3500 €
PWM control electronics board	Understanding PWM control	200 €



Figure 3 :SEMITEACH Thyristor Power Electronics Teaching System [4].

The electric motor/generator and all its properties (speed, torque, starting current, etc.) are studied using the Leroy educational energy conversion bench in Figure 4.

Table 1 summarises the educational systems used in the course and the objectives behind each application. A focus

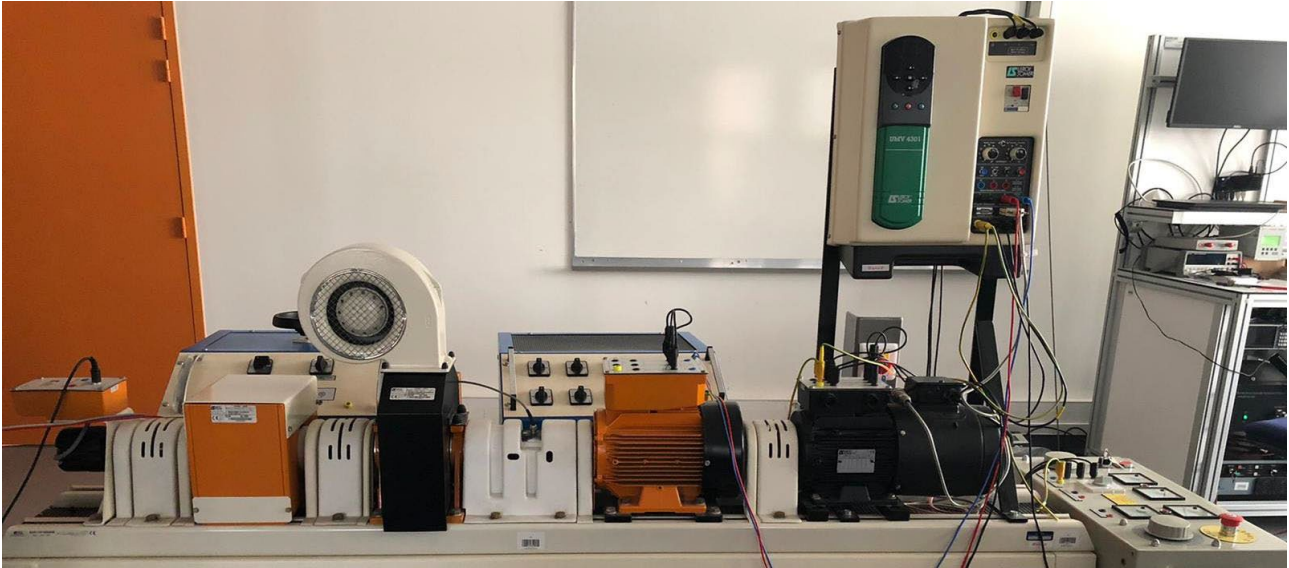


Figure 4 : System used during the course, including: variable three-phase power supply (bottom right), asynchronous motor (bottom center right, black), commercial variable frequency drive (top center right), synchronous generator (bottom center, orange), speed and torque control (bottom center, white), electromagnetic brake (bottom left)

on the price of each system is also presented (Table 2) to allow the reader to get an idea of the implementation costs to build the course.

From an experimental point of view, a number of probes, cables and oscilloscopes have been used to display the voltages and currents of the different electrical set-ups, as well as computers being used to perform simulations. These tools are not counted in the table 2, as they are shared assets not attributable to a single course.

III. EXPERIMENTAL PRACTICE PROCEDURE

The course covers 20 hours, the students were organised in pairs and supervised half of the time (~10 hours) by two teachers. During the remaining 10 hours, the students carried out their own research or simulations independently. Concerning laboratory experiments, the

manipulation was carried out in the presence of at least one of the teachers. Afterwards (if nothing changes in the electrical circuit), the students are free to continue manipulating independently.

Fig. 5 shows the process of presented PREX.

The PREX was organised in such a way as to work on each part from both, simulated and experimental point of view, in order to compare the two results and any differences. This approach in engineering sciences, which integrates the scientific approach, is familiar to students from the scientific stream in secondary school as shown on the CPGE (*Classes Préparatoires aux Grandes Ecoles* in French) [5], enables them to enter into a problem thanks to the simulation of all or part of a system, to define the expected behaviour and to test its response via manipulation. It thus allows the student to improve his

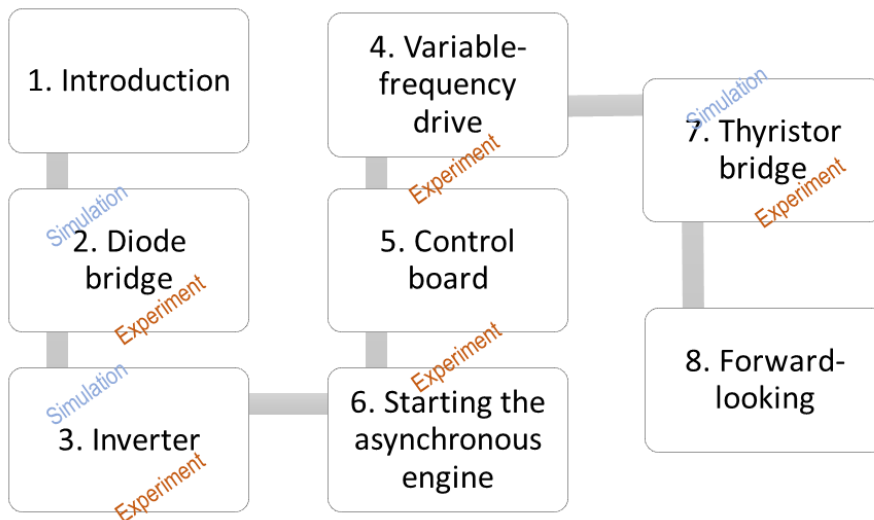


Figure 5 : PREX energy conversion process.

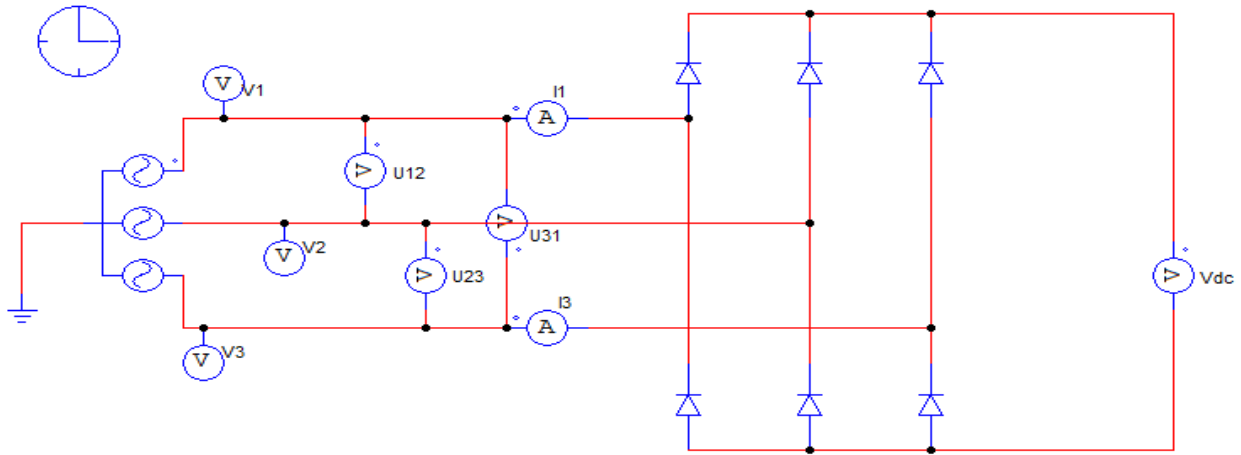


Figure 6 : Simulation of AC-DC conversion in PSIM software.

understanding of the system, by seeking to reduce the gain between the simulated system and the real one.

The understanding of the operation of the inverter and rectifier, and especially their function in relation to the motor speed variation, allowed the students to gain a prior understanding of the operating principle of a commercial variable-frequency drive.

The start-up and operation of the motor was exploited with the commercial inverter (Fig. 4), the different teaching systems (Figs. 2 and 3) and the deployment of a PWM type control board designed for this course (Fig. 12).

In the next section, each block is presented individually.

From a pedagogical point of view, the framework set at the very beginning of this article imposed a very precise structure for each session.

First of all, before each meeting, the student had access to the presentation and the topic, in order to allow him/her to increase the feeling of mastery of his/her learning as well as to search among his/her previously acquired competences for the tools to tackle the highlighted problem.

In addition, the teacher tried for each activity to find a balance between student self-discovery and teacher guidance towards the solution. This method seems to promote proceduralization in the learner [6], i.e. the ability to perform one or more tasks (procedural knowledge [7]).

Finally, as specified in the introduction of this article, this module should enable the student to acquire the ability to develop an experimental approach. Consequently, it will be possible to notice that in each session the students are led to compare the results obtained in simulation with those obtained experimentally and theoretically.

IV. EXTRACT FROM THE INSTRUCTIONS

In this section, we present an introduction to each session or group of sessions. Extracts of questions and possible answers are proposed (marked in italics) in this section.

1. AC/DC converter comparison between simulation and experience

After a general presentation of the system and its components, the students studied its behavior by simulation. The results obtained were explained using theory.

In session 2, only after having explored numerically the operation of the two converters (AC/DC and DC/AC), these results will be validated by measurements on the experimental bench.

Q3: Reproduce the circuit in Figure 6 on PSIM and display the time variation of all the voltage-measuring instruments used. *The time variation of the voltages in the circuit is shown in Figure 7.*

Q5: Perform a single-phase diode bridge on PSIM circuit with a parallel load resistor (4.6Ω) representing the next part of the circuit to be connected.

Q6: Compare the voltage and current values before the diode bridge with those after the diode bridge.

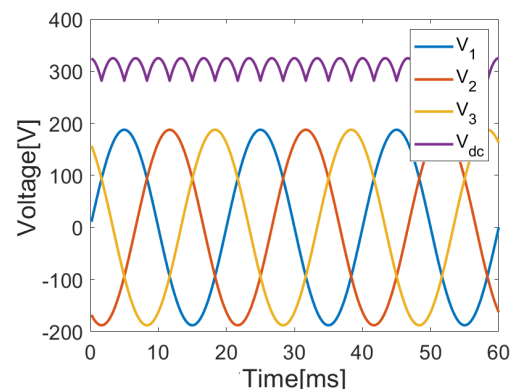


Figure 7: Voltage time variation in the circuit in figure 6.

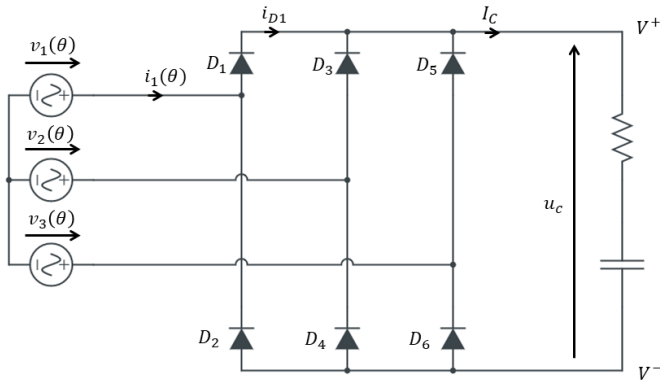


Figure 8: AC-DC converter scheme.

Q7: Add a parallel capacitor between the diode bridge and the resistor.

Q8: Vary the capacitance between the values 0.01mF and 100mF. Compare the voltage values before the diode bridge with those after the diode bridge according to the values of the capacitor.

Q11: Using the diagram in Figure 8, find the expression that relates the peak voltage of the three-phase supply to the average DC voltage at the rectifier output.

The input of the three-phase system is defined below:

$$\begin{cases} v_1 = V_m \sin(\omega t) \\ v_2 = V_m \sin(\omega t - \frac{2\pi}{3}) \\ v_3 = V_m \sin(\omega t - \frac{4\pi}{3}) \end{cases}$$

With $\omega t = \theta$.

Consider the interval $[\pi/6 - \pi/2]$, during which diodes $D1$ and $D4$ are conducting. The average DC voltage at the output of the rectifier $u_c(t)$ can be written as :

$$u_c(t) = v_1(t) - v_2(t)$$

$$\langle u_c(\theta) \rangle = \frac{1}{\frac{\pi}{2} - \frac{\pi}{6}} \int_{\frac{\pi}{6}}^{\frac{\pi}{2}} u_c(\theta) d\theta$$

After development [8], we obtain :

$$\langle u_c(\theta) \rangle = \frac{3\sqrt{3}V_m}{\pi}$$

This question allows the student to develop a critical thinking: he/she tries to interpret the result of his/her simulation by relying on this knowledge, acquired during the previous study cycle. On the other hand, if these notions have not been addressed or mastered, the format of the course allows pair work to compensate for the gap or a specific intervention by the teacher.

2. Inverter experiment and comparison with the simulation model

During this session the PWM ("Pulse Width Modulation") technique was exploited by the students. Below is an extract from the PREX booklet.

As can be seen in Figure 1, once the AC voltage has been transformed into a DC voltage, it is necessary to obtain, from the DC voltage, three sinusoidal AC voltages, each 120° out of phase with the others. To do this, we will use an inverter controlled by a technique called "Pulse Width Modulation" (PWM).

Q14: Draw a block diagram of a single phase inverter using a PWM.

Q15: Draw a block diagram of a three-phase inverter (phases out of phase by 120°) using a PWM.

Q16: For the two functional diagrams produced (Q14 and Q15), make two circuits on PSIM. Proposed simulation diagram of the three-phase inverter with control in figure 9.

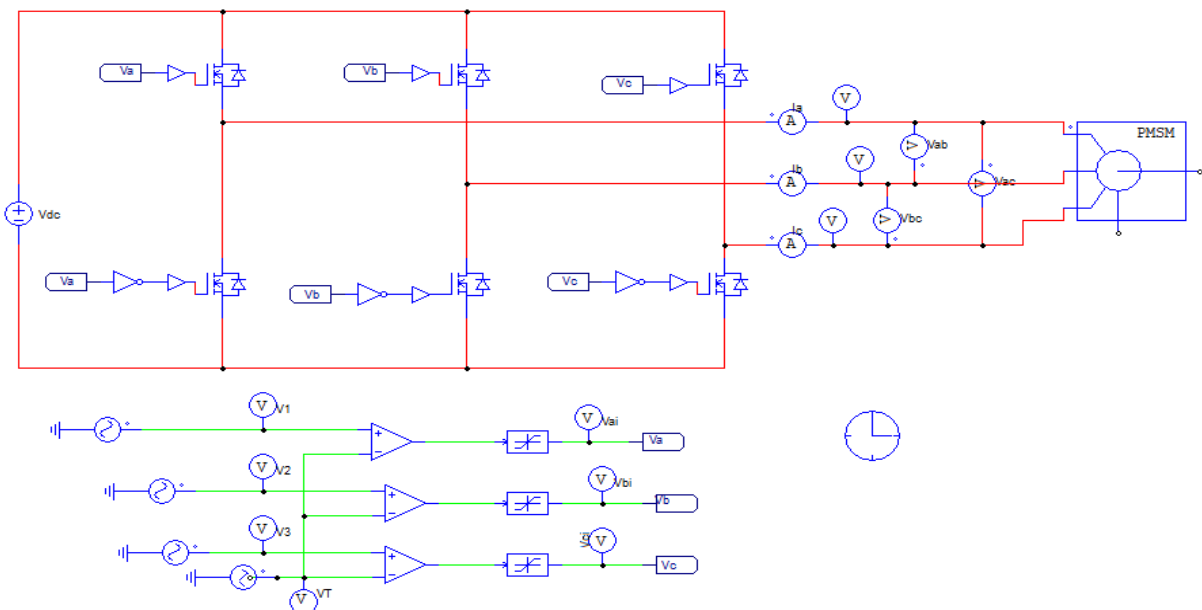


Figure 9: Simulation of the three-phase inverter with control under PSIM software.

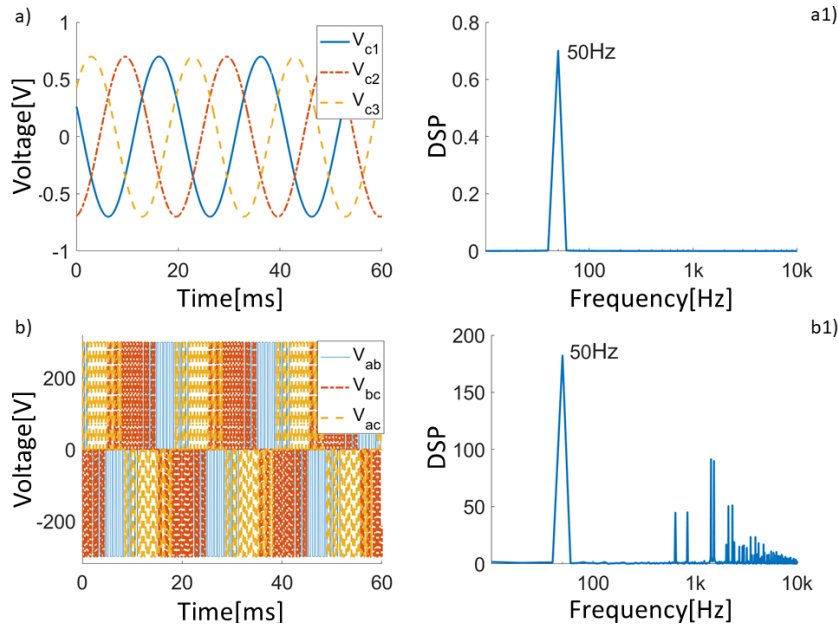


Figure 10: Results of the simulation of diagram in figure 9. a) PWM control voltages; b) Compound output voltages of the three-phase inverter; a1) Fourier transform (FFT) of the V_{c1} signal in figure a; b1) Fourier transform (FFT) of the V_{ab} signal in figure b.

Q17: Work on the three-phase inverter circuit and display the three line-to-line voltages at the output of the system (U_{ab}, U_{bc}, U_{ac}). Compare the system output signal with the PWM control signal using a FFT. *The required graphs are provided in Figure 10, where the acronym PSD stands for Power Spectral Density.*

Q18: Add a low-pass filter for each phase to observe the changes at the output signals.

Q19: Change the frequency of the PWM control triangle signal and compare it with the values of the total harmonic distortion (THD) of one of the three-phase currents at the output of the system. *The variation of THD with the frequency of the triangular PWM control signal is shown in Figure 11.*

Q20: Change the frequency of the three-phase control signal and check the effects on the system output signals.

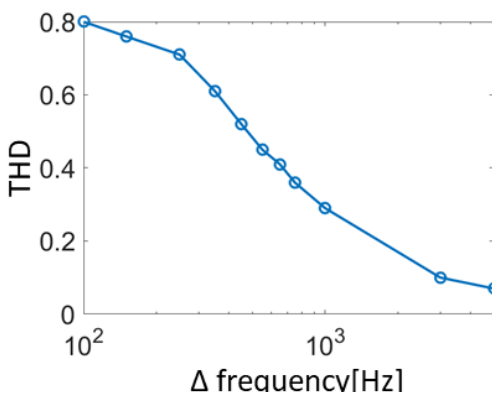


Figure 11: Variation of the THD as a function of the frequency of the triangular PWM control signal.

3-4. Proposal for an electronic board architecture; Handling of the board proposed by the teaching team

Students proposal: generation of the triangular signal based on two AOP (double threshold comparator + integrator). Three-phase signal generated digitally by a sine function (microcontroller programming).

The electronic board designed by the teaching team is shown in fig.12. It is powered by a 12V DC voltage source. It is possible to vary the frequency of the modulator and the carrier via potentiometers. The control signals of the three sinusoids and the triangular carrier can be viewed on the oscilloscope. It is also possible to visualise the logic signals sent to one arm of the inverter (0 = IGBT open, 1= IGBT closed) as well as the 0÷5V signals that control the system shown in fig. 2.

The students used the electronic board to validate the results obtained by simulation.

5-6. Comparison of commercial variable-frequency drive performance VS home-made systeml. Introduction to scalar motor control. Comparison of AC/DC converter performance diode bridge VS thyristor bridge

In the first of these two sessions, the students tested the electrical motor at start-up, in detail they observe the starting current on the oscilloscope. This allowed them to compare the value of the current drawn by the motor at start-up (I_d) with its nominal value (I_n) and to notice the proportionality factor between the two was $I_d=7I_n$.

In the PREX material, the team describes the techniques of varying the rotor resistance as well as

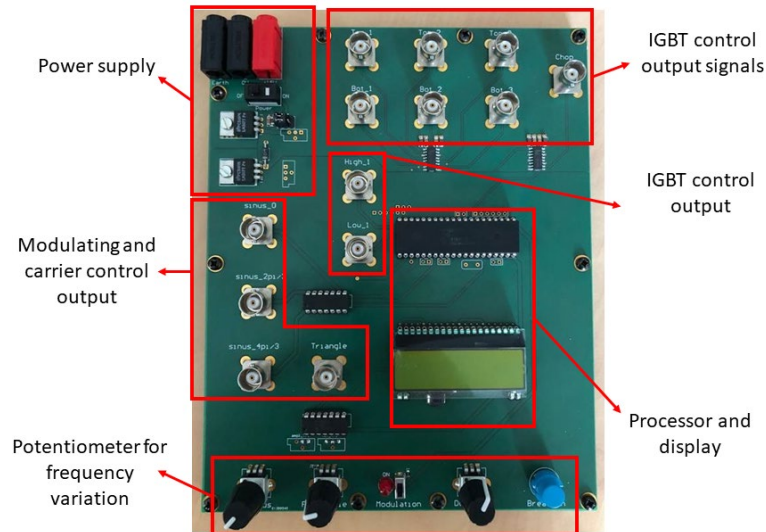


Figure 12: Layout diagram of the electronic board for PWM control.

varying the voltage and frequency to limit the starting current. This passage introduces the interest of using a thyristor bridge for AC/DC conversion, i.e. to modulate the average value of the rectifier output voltage.

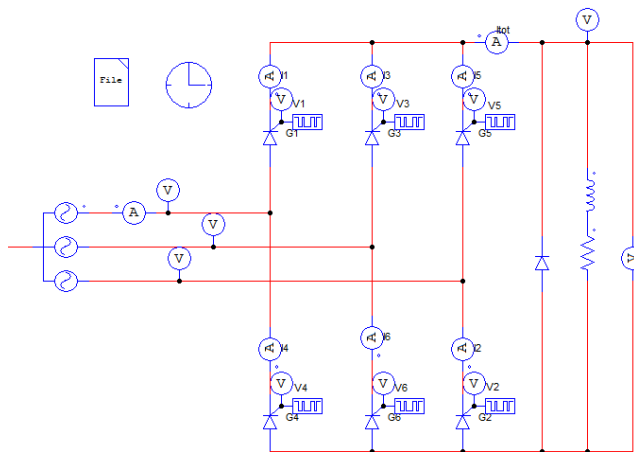


Figure 13: Simulation of the three-phase thyristor bridge using the PSIM software.

Q51: Draw a block diagram of a three phase thyristor bridge.

Q52: For the block diagram produced, make a circuit on PSIM. A block diagram of the AC/DC thyristor bridge is shown in Fig. 13.

Q53: Once the functional circuit is created, measure the DC output voltage as a function of the AC input voltages according to the chosen firing angle (α). In fig.14, the evolution of the average output voltage for an RMS voltage as a function of different values of the firing angle (α), with a range between 0° to 120° .

Q56: Using the simulations done on the thyristor bridge and the three-phase inverter, to combine the two simulations to

use the thyristor bridge to power the three-phase inverter on PSIM.

Q57: Evaluate the output voltages in the case with thyristor bridge connected to 3-phase inverter and compared to a diode bridge supply.

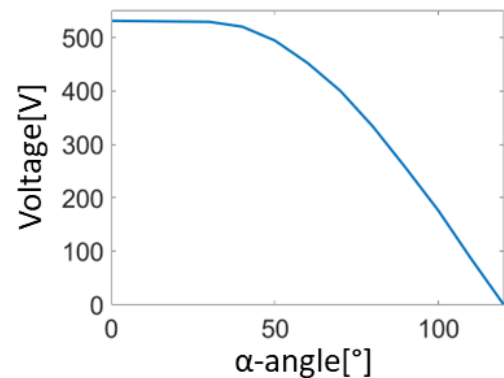


Figure 14: Average output voltage variation of the three-phase thyristor bridge as a function of the firing angle (α).

V. STUDENTS FEEDBACKS AND FUTURE DEVELOPMENTS

The students work was evaluated on the basis of three moments [9]:

1. A diagnostic assessment at the beginning of each session. This allowed the teacher to find out the level of the students through oral questioning. Moreover, a self-assessment of this type was made by the student before each session, working on the preparation part. An example of self-assessment is shown in Figure 15.
2. A formative assessment in the form of an oral presentation, prepared and presented in pairs. This allowed the students to begin to prepare for the summative assessment, while benefiting

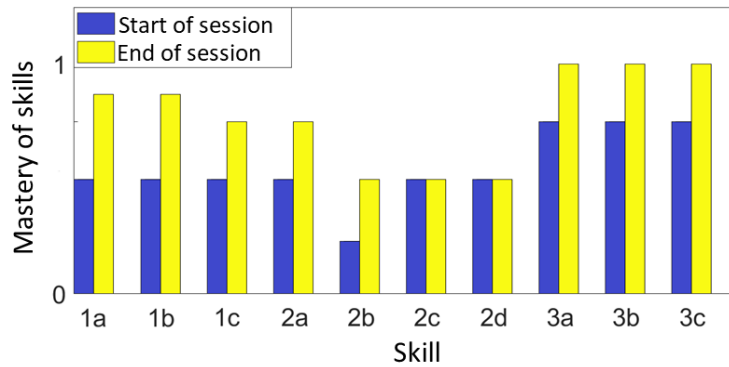


Figure 15: Example of students feedback on their perception of mastery before and after the Energy Conversion PREX.

from teacher feedback to improve and progress. This exercise also highlighted any areas for improvement.

- The course ended with a 20-minute oral presentation. This presentation took place in front of a jury of teacher-researchers (approximately eight members), including the one who directed the PREX. The other members were the leaders of the other proposed PREX from other fields.

Students were judged against the competences presented in Table 1, the same initial and final self-assessments.

An exchange with the students also highlighted possible points of improvement for the next PREX Energy Conversion session in 2023. They expressed an interest in programming the control of the electronic board. Based on this request, the writing of part of the control would be entrusted to the students (i.e. the generation of sinusoidal signals).

As regards the prospects of the teaching team, from a disciplinary point of view, a new version of the board has already been designed in order to carry out the scalar motor control [10]. This new version will make it possible to control the two converters in cascade in order to limit the motor starting current.

From a pedagogical point of view, it seems desirable to change the sequence of events with regard to the skills being worked on. The idea would be to make each student of the pair work on one of the two converters while they are in simulation and experimental validation via the systems of figures 2 and 3.

This would allow each student to work on the skills targeted by the module while saving time that will be devoted to the implementation of the scalar motor control. An exchange time will be recommended so that each student can present to the other the functioning of the converter studied, knowing that peer learning has several benefits for both the explainer and the learner [11].

In addition, a more rigorous follow-up of the students is envisaged, by taking the time at the beginning of the

module to make a more thorough assessment of the level of the students as well as by asking the jury to take the time to fill in the grid of competences during the oral defence.

In the long term, the team would like to set up a more effective system for evaluating the impact of this module on the student's progress in the course (both its usefulness and usability [12]), for example by means of anonymous questionnaires for the entire class or individual interviews.

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