A Scientific Approach in Wind Energy Courses for Electrical Engineers

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***Abstract*— Teaching and research are joint activities at University level, but in many cases it is found that both activities have a poor connection. While the scientific method based on well-known steps is commonly applied at research level, this methodology and the associated know-how are rarely integrated in degree courses. This work describes the integration of theory, simulation, lab-scale experiments and industrial developments in wind energy courses for electric engineers. The proposed methodology reuses the knowledge from the research that is performed at University level to bring the students the latest industry developments and scientific trends with a scientific approach in multidisciplinary wind energy courses.**

***Index Terms*— Wind energy conversion systems, power electronics, electrical machines, simulation tools.**

I. INTRODUCTION

The increasing role of power electronics in electric drives and power systems, the new concepts associated to the smart grids, the steady increase in the penetration of renewables energies or the new generation of hybrid, plug-in and battery electric vehicles are good examples of the trendy applications where industry is demanding engineers with a multidisciplinary knowledge. Even though degree curricula at University level are gradually including these new trends and paradigms into the electrical engineering field, the knowledge is still segmented in specific topic associated to traditional subjects. Traditional courses of electric machines, power electronics and automatic control are of course essential, but we can also take advantage of the multidisciplinary nature of these emerging applications to provide the students with multi-topic courses [1-3]. Wind energy is a good candidate to achieve this goal since it requires knowledge on electric machinery, power electronics, digital signal processing, control theory and mechanical engineering, to name a few [4-6]. As a starting point the topic itself is known to be a center of interest for the students since the wind energy technology is the most mature among renewables and Spain is also leading the development of wind energy conversion systems (WECS) worldwide [7,8]. Apart from being a hot and multidisciplinary topic, it is also an ideal topic to follow a top-down approach. Opposite to the procedure in other subjects, the application-oriented approach of the course allows starting the lectures with the description of the application, descending later on to the underlying mathematical description and modeling. The course is further enhanced with a methodology that promotes hands-on activities through the synchronous creation of wind energy simulators.

The aforementioned methodological considerations are integrated into a scientific approach that aims to let the students follow the same steps that are commonly used at research:

- Theory: students are provided with the updated background of wind energy conversion systems.
- Simulation: the students build themselves a simulator for a full-power WECS based on two-level voltage source converters (VSCs) and permanent magnet synchronous generators (PMSGs).
- Lab-scale experiments: the students get to know how the simulation software can be executed in a real test rig with industrial elements.
- Industry products: A visit to real WECS is finally done to let the students see the final industrial product.

With this approach the students follow the R&D steps that are common in the design of a new industrial product. This procedure provides a full picture of the role of Engineers and at the same time reuses the knowledge that University professors already have in their research activities. Consequently, the scientific approach adds values to the students training bringing them knowledge and resources from the University research. The different aspects of the proposed methodology are summarized in Fig. 1.

II. DESCRIPTION OF THE COURSE

This course has been developed within the framework of a specialization course at the University of Malaga (UMA), Spain. These specialization courses provide undergraduate and graduated engineering students with an opportunity to approach to theory and applications of novel industrial developments, updating their professional skills.

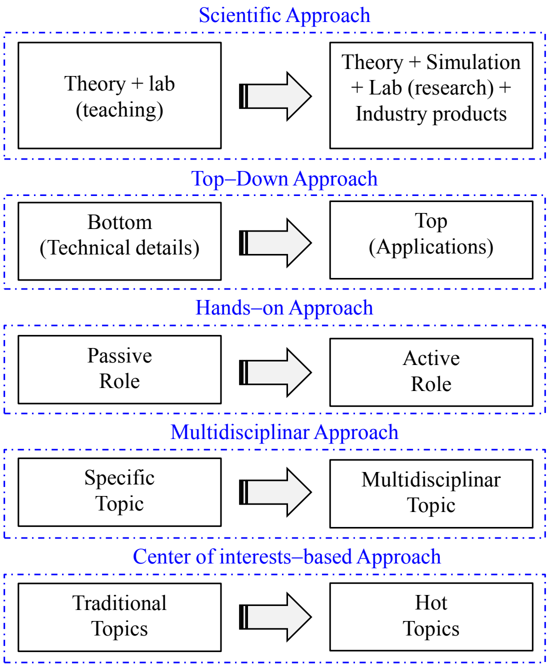


Fig. 1: Methodological approach of the wind energy course.

The course has been structured following a top-down approach [1], beginning with an overview of the wind energy technological status, following with the simulation of a WECS and ending with the experiments both in a lab-scale prototype and industrial product. Opposite to other pedagogical approaches that provide the student with ready-to-use simulations [9]-[11] and didactic materials in the lab, the experience promotes *i)* hands-on learning by asking the students to build their own simulators step-by-step following an inclusive strategy and *ii)* the contact with industrial product in a research lab and industrial WECS. Although the use of simulations and lab-teaching in power electronics [9] and electrical machines [10] is common in University teaching, most of the methodologies do not provide a proper multidisciplinary context, do not allows the students to build their own simulations and do not bring the student closer to the research and development at industry. From the methodological point of view, the course follows a combined strategy that includes both direct lectures with hands-on working in a simulation and experimental environment.

The course lasts for a period of 40 hours and consists of three parts:

- Part 1: theoretical background of wind energy and description of the technological status of the WECS (power electronics, electrical generators and topologies).
- Part 2: simulation of a full-power WECS with a permanent magnet synchronous generator, two-level IGBT-based voltage source converters, PI-based field oriented control (FOC) and carrier-based pulse width modulation (PWM).
- Part 3: experiments in a lab-scale research lab, where a full-power WECS is used for research purposes, and in already installed industrial WECS.

Table I summarizes the content of the three parts of the course and table II describes the competences that are obtained at each stage (theory, simulation and experiments).

TABLE I: COURSE CONTENT AND SCHEDULE

Objective	Part 1: Lecture	h
Get to know the wind energy situation worldwide	Wind Energy Situation	1
Obtain a general knowledge of non-electrical WECS issues	FAQS about WECS	3
Review the basics about EM and PE for WECS industry	Electrical machines and converters	3
Acquire consciousness of the wide range of technologies	WECS topologies	2
Understand the new requirements of the TSO	WECS regulation in Spain	1
Evaluate DFIGs performance in WECS	Partial-power WECS	2
Understand the advantages in offshore and onshore WECS	Full-power WECS	3
Review industry developments and foreseeable trends	Future Trends in WECS	2
Objective	**Part 2: Simulation**	**h**
Review the bidirectional flow in Matlab-Simulink	Matlab/Simulink introduction	3
Use of functions, cascade simulations and power curves	Wind Simulation	3
Use of plot options and review of gear and gearless WECS	Gearbox Simulation	1
Simulink implementation of differential equations	Mechanical system Simulation	2
Practical notions of PI tuning, 3D representation	PMSG model and control	4
Practical notions of modulation and control	VSI model and PWM design	4
Promote student creativeness and joy	Free time for simulation	2
Objective	**Part 3: Experiment**	**h**
Technology overview	Description of the lab	2
Understand how to execute simulation code on real-time system	DSP code generation	1
Understand the physics of the generator control	Experiments on the electrical drive	1
Provide the students with an idea of the industrial products	Visit to low- and hi-power WECS	2

TABLE II: COMPETENCES TO BE DEVELOPED DURING THE COURSE

Competence	Lec.	Sim.	Exp.
Basic knowledge of WECS	X		
Simulation skills		X	
Active role and Autonomous learning	X	X	
Environmental concern	X		X
Connection of technical knowledge	X	X	X
Creative thinking		X	
Cooperative attitude		X	
Awareness of industrial concerns	X		X
Critical judgment	X	X	
Initiative and problem-solving skills		X	
Long-life learning	X	X	X

III. THEORETICAL BACKGROUND.

In the first part, the lectures start with the general concepts of wind energy and end with the current trends at the wind energy industry (see table I). During the lectures the technical content is gradually increased and the focus is placed on the topologies, power electronics and electrical machines selected by different manufacturers. The students have the opportunity to review the gearless direct-drive multi-pole choice of *Enercon*, the medium speed permanent magnet generators with back-to-back 2L-VSCs used by *Gamesa*, the 3-level Neutral Point Clamped (NPC) VSIs used by *Multibrid* (now *Areva*), the diode-rectifier with boost stage used by *Vensys* or the doubly-fed induction generator for off-shore applications developed by *Repower* to name a few. Notice that lectures' content is close to market trends in nowadays wind generation systems [8]. Since the choice of each manufacturer is always a trade-off between different features, the course reviews electrical machines and power electronics characteristics within the specific context of WECS. Fortunately, the variety is so wide that the course can cover many aspects of interest for electric/electronic engineering students or professionals.

This first part of the course includes the main theoretical content and it is lectured alternating class speech, technical videos (from manufacturers and institutions) and tests/questions. It is industry oriented and focused on issues of interests for electric/electronic engineers.

To summarize, some of the main features of part 1 are:

- The theoretical explanation provides a context that includes non-electric/electronic multidisciplinary aspects
- Industrial aspects are emphasized showing wind energy manufacturers' catalogues and videos where some of the hottest technical aspects in the field can be identified.
- It is shown the wide variety of technical solutions, including the Gamesa G132 generator model and all the technical solutions adopted by Vestas and other manufacturers.
- Teacher-centered methodology is broken including more than 100 test questions and short problems within the lectures and building a competition among groups of students.

Further details on the theoretical content can be found in [x].

IV. SIMULATIONS

In the second part of the course a specific topology is selected and the students are challenged to build in Matlab/Simulink a wind energy conversion system (see table I). The student has to build the whole simulation starting from the scratch, with no pre-built black or blue boxes, aiming to promote the development of simulation skills and hands-on work. The simulation follows an inclusive strategy where every new element in the simulation is connected to the previous ones until the whole WECS is simulated. For the sake of generality, the course avoids specific toolboxes and builds every element from its mathematical model. The system selected for simulation includes a permanent magnet synchronous generator (used by *Gamesa* in its late developments) because of the simplicity of the equations and its industrial interest, a 2-level voltage source inverter and standard FOC with PWM.

The first step is the selection of a specific topology from the wide variety shown in the first part of the course. The choice is made on the basis of promoting simplicity and industrial interest. Although the horse of the wind energy industry has been the DFIG in partial power topologies, new developments (e.g. Gamesa G-132) are selecting PMSGs and using multiphase machines [8]. Since the mathematical model of such generators is simpler, PMSG was therefore selected for the simulation. Low voltage ride through requirements are also pushing wind energy industry to full-power topologies and the most widely used type of converter in WECS is the 2-level VSC. Based on that premises, the final topology selected to challenge the students is a full-power topology with back-to-back converters and a PMSG. Although the gearbox is optional depending on the number of poles of the PMSG, it is included in the simulation for the sake of completeness. The generator-side analysis has been included in the lab sessions with sequential steps:

- **Matlab/Simulink intro**: .m files are executed from Simulink using Matlab and S-function blocks and .mdl files send simulation data to Matlab using *to file* and *to workspace* blocks. Bidirectional connection Simulink-Matlab and Matlab-simulink is thus exemplified to introduce the software.
- **Wind Simulation:** since the course is oriented to electric/electronics engineering students, the simulation of the wind is built from the empiric relations of (1) that provide the power/torque curves as in Fig. 2. Tip speed ratio, maximum power point tracking (MPPT) and pitch control, are reviewed and discussed.
- **Gearbox simulation**: the gearbox is considered to be lossless for the sake of simplicity. The rotational speed of the low-speed shaft in the blades is transformed to provide the proportional high-speed at the generator shaft.

$$P_m = \frac{1}{2}\rho_a A_s V_w^3 C_p(\beta,\lambda) \qquad \lambda = \frac{V_t}{V_w} = \frac{R_t \omega_t}{V_w}$$

$$C_p(\beta,\lambda) = 0.73\left(\frac{151}{\lambda_1} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)e^{-\frac{18.4}{\lambda_1}} \qquad (1)$$

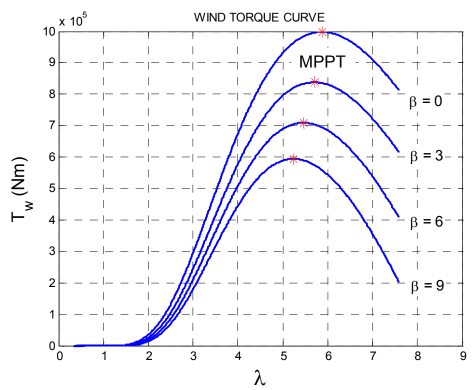


Fig. 2. Wind torque as a function of the tip speed ratio and pitch.

▪ **Mechanical system simulation:** the rotational equation of the wind generator (2) is implemented next. The students implement a differential equation in Simulink for the first time, writing the equation in state-space form to avoid derivative blocks.

$$\frac{d\omega_{turbine}}{dt} = \frac{1}{J}\left(T_{turbine} - T_e\right) \quad (2)$$

▪ **PMSG model and control:** the permanent magnet generator model and control are both included in the same stage because the generator without control easily leads to simulation divergence. The PMSG is implemented in Simulink using (3) using the parameter of a 2MW PMSG well-defined in [7].

$$\begin{aligned} \frac{di_d}{dt} &= \frac{1}{L_d}\left(u_d + \omega_{elec} L_q i_q - R i_d\right) \\ \frac{di_q}{dt} &= \frac{1}{L_q}\left(u_q - \omega_{elec} L_d i_d - R i_q - \omega_{elec}\lambda_m\right) \quad (3) \\ T_e &= \frac{3}{2} P\left(\lambda_m i_q - \left(L_d - L_q\right) i_d i_q\right) \end{aligned}$$

The field oriented control (FOC) is also implemented in Simulink using (4), which includes the PI controllers, the feedforward decoupling terms (e_d and e_q) and the zero d-current (ZDC) criterion. The inverter is considered as ideal ($v_d = v_d^*$ and $v_q = v_q^*$) until the next stage.

$$\begin{aligned} i_q^* &= k_{pn} \cdot \left(n_t^* - n_t\right) + k_{in} \cdot \left(\int \left(n_t^* - n_t\right)\right) \\ v_d^* &= k_{pf} \cdot \left[i_d^* - i_d\right] + k_{if} \cdot \left[\int \left(i_d^* - i_d\right)\right] + e_d \\ v_q^* &= k_{pt} \cdot \left[i_q^* - i_q\right] + k_{it} \cdot \left[\int \left(i_q^* - i_q\right)\right] + e_q \quad (4) \end{aligned}$$

At this stage, the students are asked to start the wind generator, simulate sudden wind gusts, include noise in the current measurements and evaluate the impact on the control performance, modify the pitch angle during the simulation and make multiple simulations in cascade (from .m file) and plot 3D figures (Fig. 3).

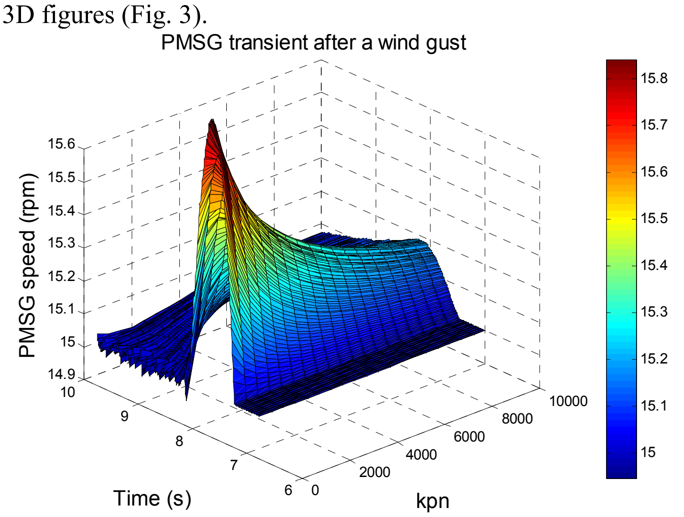


Fig. 3. Transient of the PMSG after a wind gust using different values of the PI speed loop controller defined in (4).

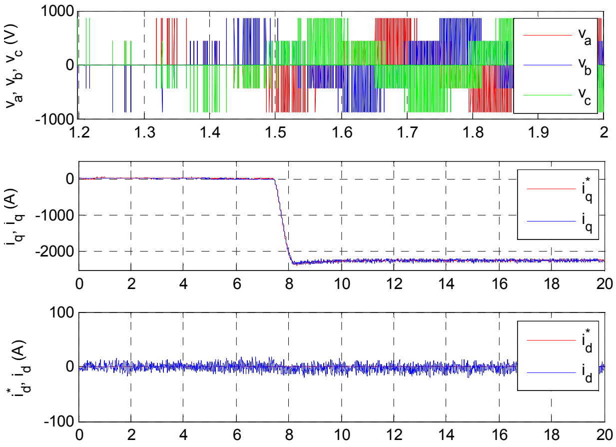


Fig. 4. Stator voltage and d-q currents with PWM supply.

▪ **VSC model and PWM design:** at this stage the students include the real stator voltages provided by the voltage source converter (VSC) and implement a carrier-based pulse width modulation (PWM) scheme. Stator phase voltages are calculated from the switching functions S_i and the value of the DC link voltage. The applied PWM scheme is carrier-based method with a triangular carrier signal at 1 kHz. The students are then asked to test the WECS with PWM supply (Fig 4), modify the DC link voltage to review the modulation index explanation, modify the switching frequency to evaluate its impact on the system performance, calculate the total harmonic distortion (THD) and the spectrum of the generated stator currents, using the PowerGui from the SimPowerSystems toolbox.

▪**Creative simulation time:** students are asked to propose their own simulation features and WECS performance, aiming to promote deep understanding, creative thinking and students' initiative [17].

At the end of these seven steps the students have successfully implemented the generator-side control. Each stage includes an input/output box and all boxes are finally connected in the complete system (see Fig. 5). The main features of part 2 can be summarized as follows: the whole simulator is built step by step by students (starting from the scratch to promote simulation skills), the selected WECS is as simple as possible, approaching the student to industry standards (e.g. FOC, PWM), the full-power WECS configuration has a wide technological variety and includes useful concepts for electric/electronic engineers (e.g. modulation index, THD, inner and outer control loops, transients, noise, etc.), the simulation is directly connected and reinforces the concepts included in the theoretical part of the course, implementation has a low cost for the School of Engineering.

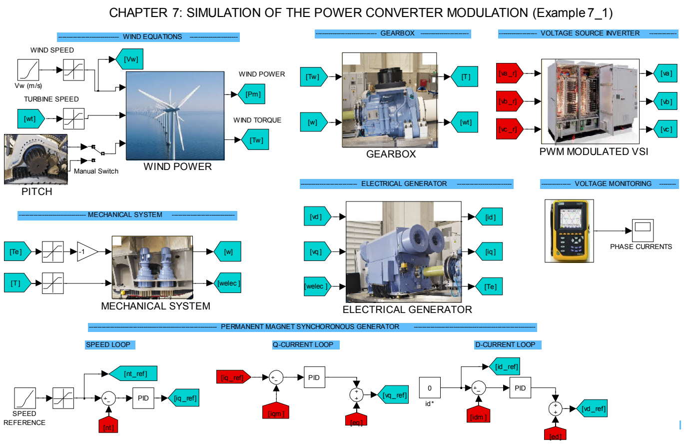


Fig. 5. Transient of the PMSG after a wind gust using different values of the PI speed loop controller defined in (4).

V. TEST RIG AND EXPERIMENTS.

The scientific approach is completed bringing the students closer to the real elements of the WECS. In this manner the students deeply understand the R&D steps that include the analysis of the state-of-the-art technology, the proposal of a new strategy, the simulation of the idea, the testing stage in a lab-scale prototype and the extension to demonstrators/ products. The cost of this part is practically zero since the resources from the research activities are reused to provide students with an updated knowledge. This part 3 of the course encompasses different steps:

- Description of the test rig: opposite to standard lab teaching where the equipment is non-industrial, the test rig shown in this part includes industrial products from Semikron, Siemens or Texas Instruments to name a few. Even though didactic material has its own advantages, approaching engineering students to real products also has an added value. The test rig is shown in Fig. 7 and includes a wide variety of elements: two-level (machine-side) and three-level VSCs (grid-side), DC (load/wind emulation) and 6-phase induction machine (generator), LC filters, step-down transformer, DSP, etc.

  The test rig includes some industrial products and other elements designed at UMA within the framework of R&D projects: two level VSCs are Semikron SKS22F modules and three-level VSC uses Semikron switches but the PCB has been built at UMA (Fig. 6d). The 6-phase IM has been designed and rewounded at UMA (Fig. 6b) from a standard 3-phase machine. DSP is a TI TMS320F28335 but the PCBs have been designed at UMA (Fig. 6a, patent 201400981). Current and speed measurements are taken with four hall-effect LEM LAH 25-NP sensors (with an accuracy of the ±0,5%) and a GHM510296R/2500 digital encoder, respectively.

All elements are shown and fully described to students, also indicating the process to integrate the equipments into the lab-scale WECS. There is a significant difference between theory/simulations and implementation, and this part of the course is devoted to let the students realize about these differences.

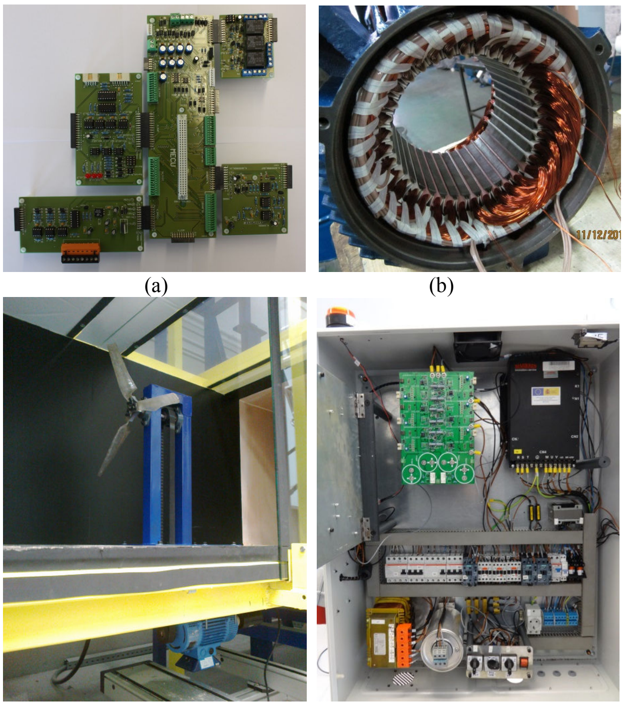
- DSP code generation: At this stage the code of the FOC is downloaded to the DSP using two different approaches:
  - From Matlab/Simulink: the code is compiled using the real time workshop. The students have the chance to see how the code from the simulation from part 2 can be directly executed in the DSP performing a real-time high-performance control.
  - From C code: alternatively the code can be directly written and optimized in C (this is the procedure used at research) and then complied to DSP code for real-time implementation.

This part of the course is used to briefly explain concepts relate to real-time control and the importance of the execution times. As an example, the times used at FOC and model predictive control (MPC) are compared.

- Experiments on the electrical drive: at this stage some experiments are shown to students, including the speed regulation from the FOC strategy or the synchronization and connection to the grid. For security reasons this part of the course remains only demonstrative and students are not allowed to do hands-on work on the test rig. The impact of the controllers tuning, switching frequency and parameter detuning is shown to the students, confirming some of the results that they could check at the simulation stage.
- Visit to low- and high-power WECS: The school of engineering at UMA has two low-power (kW-range) wind energy conversion systems (vertical- and horizontal-axis) on the roof of the building. The power from these WECS is used to charge a set of batteries and the MPPT control is performed by commercial equipment that cannot be accessed and modified. However, it is a good chance for student to see an industrial installation with a built-in control. A visit to high-power (MW-range) is also done when possible. The students are only allowed to visit the base of the wind mill but the wind company also provides explanations and technical details that are insightful.

VI. CONCLUSIONS

Educational innovations at engineering degrees typically require time and material resources that sometime are not available. However, it is possible to amortize the efforts done at the research stage by University staff to improve the lectures. Specifically, it is possible to bring the scientific approach to students by including advanced state-of-the-art theory concepts, use of simulation tools (Matlab/Simulink), research test rigs (with industrial elements) and finally industry products. This procedure brings benefits to the students because they can get to know the different steps at R&D from the idea to the final product. At the same time it is less time-consuming for lecturers since they can reuse know-how from their research activities. If this is performed using the students' centers of interest (e.g. wind energy) where they can have an active role in a top-bottom structure, it is possible to create a multidisciplinary course that enhances the students motivation and skills.



(a) (b) (c) (d)

Fig. 6. Test rig elements.

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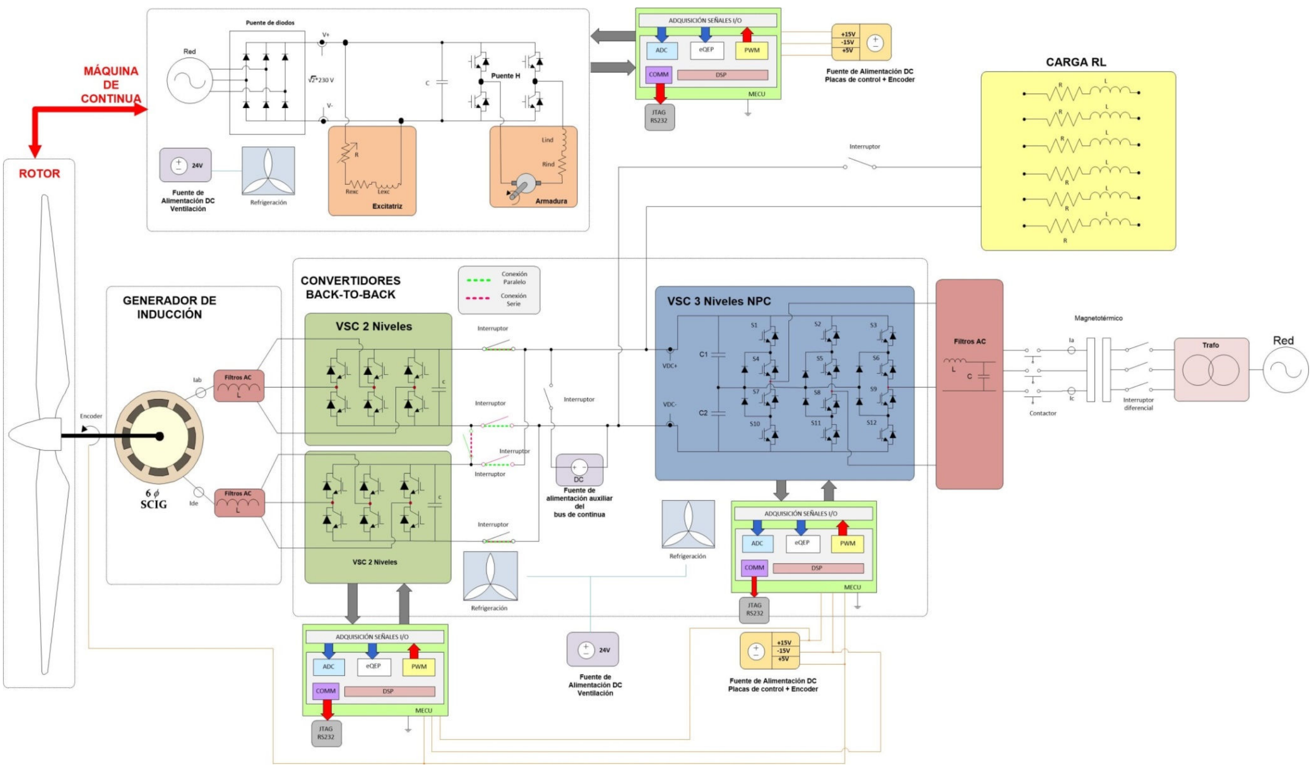

Fig. 7. Scheme of the experimental rig with six-phase induction generator and 3-level NPC grid-side VSC.