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New Platform for Experimental Education in Electrical Generation Based on Wind Energy Systems*

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In this paper, the development of a physical platform and the description of a specific methodology to be employed for experimental teaching in wind energy electrical generation in the 'Electrical Generation with Renewable Energy Sources' course, within the Electrical Engineering educational program at the Universidad Politecnica de Madrid, is presented. The developed platform has a reduced-size wind turbine to which some different types of scaled-size electrical generation systems can be coupled. The instructors can easily configure the specific structure of this platform for each laboratory session. A regulated electric fan is employed to generate and control the speed of the wind that is incident on the wind rotor. Students can configure the session specifications and are able to control the execution of each experiment, as well as to analyze the results in a comfortable way using user-friendly interface software. This paper also describes, as a case study, the application of the proposed methodology in one of the laboratory sessions.

Keywords: electrical engineering education; electric machines; wind energy

INTRODUCTION

RECENT STUDIES CONCLUDE that the massive emission of greenhouse gases (CO_2, CH_4, NO_x . . .), mainly caused by human activity, is a determining factor in climate change and its undesirable consequences [1]. A very significant part of these gas emissions are produced by the combustion process of coal, fuel or gas produced in thermal power plants for electric generation. To achieve gas emission reduction targets, the governments of the most developed countries are promoting a massive introduction of power plants with renewable energy sources, such as wind power or solar energy, in the electrical systems [2]. As a consequence, significant results have been achieved of late. For example, the contribution from wind energy to the combined electricity demand of countries such as Germany or Spain is now 19.9% and 9.8%, respectively [3].

This situation has led to an increase in demand for renewable energy courses that prepare engineers to work in this relatively new field [4], and many renewable energy education initiatives have been developed in universities around the world [5]. In particular, the Universidad Politecnica de Madrid (UPM) has included, since the new curriculum of the Electrical Engineering degree was implemented in the year 2000, a specific subject, called 'Electrical Generation with Renewable Energy Sources'.

The peculiar characteristics involved in these electric generation systems pose some additional difficulties for the student of Electrical Engineering, who has to assimilate the new concepts and the operational modes introduced in the analysis of these generation technologies, as compared with the traditional ones [6]. For this reason, it is very advisable to complement the theoretical sessions by carrying out experiments using a physical prototype and following a specific methodology. Furthermore, hands-on laboratory sessions are an easy approach to many advanced topics and let students acquire skills that will bevaluable for their later careers.

The introduction of new courses in wind energy electrical generation systems in the Electrical Engineering educational program is very recent and, consequently, few references can be found to any educational benches that allow for wind generation experiments. Of special interest is the educational system developed at the Vaasa University in Finland and the pedagogical methodology employed in it [7], based on the Constructivism theory, where modeling and simulation is a principal method selected for education, and labora-

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tory works also remain an important part of the studies. In this case, as in the system presented in this paper, the educational platform has been developed based on a model created from the composition of scaled prototypes used in research studies to verify the operation of new control strategies for different wind energy systems technologies [8].

In this paper, a versatile wind generation training platform is presented, as well as the specific methodology associated with its use in the experimental teaching sessions of the 'Electrical Generation with Renewable Energy Sources' undergraduate course. This new tool has been adapted progressively; taking into account the educational experience obtained by teaching this subject over the last four academic years.

As stated in [7], for educating about wind power it is important to have available equipment nearby. With small-scaled wind power plants the characteristics of wind power and the new ideas of students are demonstrated at the campus. The platform presented in this paper also has a reduced-size wind turbine. As the objective is to teach bulk wind generation, the educational platform is chosen to be as close as possible to the wind generation systems used in industrial wind plants. This has led to the use of a three-bladed horizontal turbine instead of the vertical one used in [7]. An additional feature is the possibility of coupling the most common electrical generators used in wind farms (induction, doubly-fed induction and synchronous direct driven generation systems).

The software employed in the control of this platform was developed in the Matlab environment. It allows one to use different regulation strategies for each wind generation system, and different values for the fundamental parameters of these regulation systems, a key factor in a pedagogical platform.

Instead of being exposed to the natural behavior of the wind [7], and for safety reasons, the platform is located in an area surrounded by campus buildings, protected from high wind speeds. In addition, this leads to another relevant educational feature, the possibility of generating the desired wind conditions for each test, independent of the weather. This is accomplished by means of a fan drive by a fully controlled induction motor.

To summarize, from the educational point of view, the main contribution of this platform is the combination of the aforementioned characteristics, i.e., the interchangeability of generation systems and control schemes and the ability to generate the desired wind conditions.

The physical structure of the platform is described below. Its use in a course on 'Electrical Generation with Renewable Energy Sources' and the pedagogical methodology applied in it, are then described, along with some preliminary results on learning effectiveness. As an example of application, a detailed description of the execution of one of the proposed sessions is described in the Appendix.

STRUCTURE OF THE EDUCATIONAL PLATFORM

The developed educational platform is schematically represented in Fig. 1.

The platform has a reduced-size Wind Turbine (WT). Three different types of Electrical Generator (EG) (induction squirrel cage machine, wound rotor induction machine, and multipole permanent magnet synchronous machine) can be coupled to the WT shaft, through a suitable mechanical coupling system (MC). Connected to the output of the generator, the platform has a configurable Electronic Power Conditioner System (EPC),

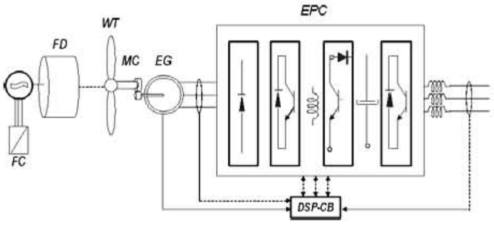

Fig. 1. General layout of the educational platform.

Fig. 2. Outdoor part of the educational platform.

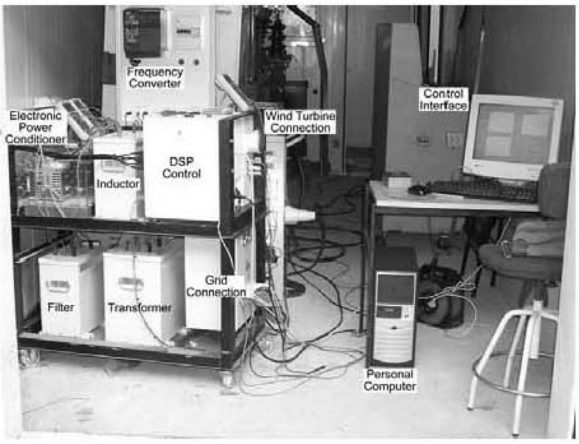

Fig. 3. Indoor part of the educational platform.

composed of several electronic converters, which controls the particular generation system in use. A programmable Digital Signal Processing Control Board (DSP-CB) is used to implement the different control strategies and algorithms that best suit the different configurations of the wind system. The system also has a Fan Drive (FD) with an induction motor, regulated through a Frequency Converter (FC), used to establish the desired wind speed conditions.

The part of the platform constructed outside can be seen in Fig. 2, in a picture taken during a session with the students, with the WT in the foreground and the FD in the background. The indoor part is shown in Fig. 3.

All the elements were selected taking into account the special circumstances of the educational use, as stated in the Introduction. The main components are described here.

- The Wind Turbine (WT) has three blades, each 0.7 m long, with an aerodynamic profile made with epoxy and fiberglass. Figure 4 shows a detailed view. It is worth noting that this is not an adequate configuration for small wind turbines in terms of efficiency, but the pedagogical objective is to reproduce a scaled version of large wind generators, which is the topic of the course.
- The electrical generators are three-phase special machines: 4 poles, 350 W and 230 V, for the induction squirrel cage and the wound rotor induction generators; and 10 poles, 350 W and 48 V, for the multipole permanent magnet synchronous machine (as shown in Fig. 4).
- The EPC is an IGBT educational power electronics module from SEMIKRON [9]. It can be configured for each experiment to obtain different converter topologies. Figure 5 is a diagram of the electronic devices available, together with a photograph of the module. The system also has a 50 mH dc inductor and a 2300 μF, 800 V, electrolytic capacitor.
- The DSP-CB, used to control the EPC system, has a TMS320F2812 fixed point DSP [10]. The hardware environment for the controller is a Spectrum Digital eZdsp F2812 module [11], and an interface board has been specifically developed for the control of the EPC [12]. The DSP Board can be programmed directly from the Matlab programming environment, through standard Matlab-Simulink blocks and a specific Matlab toolbox [13].
- In order to perform the control system analysis, the platform is completed with a graphical interface that permits a nonadvanced computer user to change some control parameters and to view their effect on the behavior of the system. In this respect, note that the objective is not to teach computer engineering but electrical engineering. Figure 6 shows a screen capture of the interface developed with the Matlab Toolbox 'Graphical User Interface (GUI)' [14], an easy object-

Fig. 4. Detailed view of the wind generation drive.

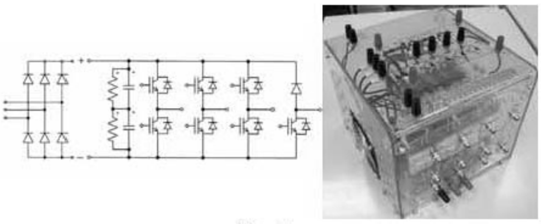

Fig. 5. Electronic power conditioner. Diagram and picture.

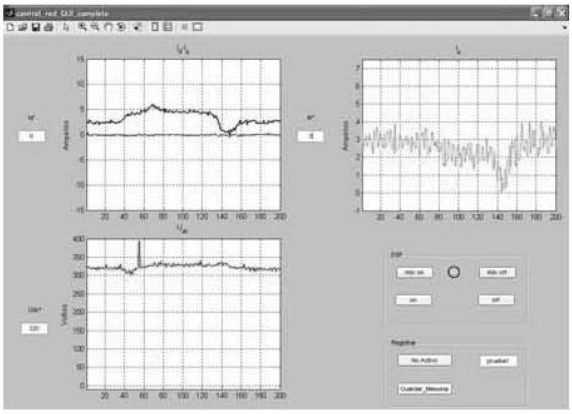

Fig. 6. Graphical interface of the educational platform.

oriented language that allows one to create custom interfaces, with push buttons, sliders, pop-up menus, mean values, etc.

INTEGRATING THE USE OF THE PLATFORM IN A COURSE

Currently, the study of wind generation systems within the Electrical Engineering degree at UPM (see Fig. 7 for the sequence of courses), is carried out as part of the ‘Electrical Generation with Renewable Energy Sources’ course (semester 8). In particular, wind generation systems subjects are taught for 52 hours, with 40 hours for theoretical learning and 12 hours for practical training.

Classroom sessions

The theoretical contents of the wind generation part of the course are divided into 40 classroom sessions, each lasting one hour. These sessions are conducted in a traditional lecture-based way and aim to cover the theoretical aspects of electrical generation from wind energy.

Laboratory sessions

Previous to the inclusion of the educational platform, laboratory sessions consisted of computer simulations. Although this methodology is advantageous in several aspects (related to theoretical insight, equipment cost, and time and space flexibility) [15], a lack of hands-on laboratory sessions was identified early on by the instructors, and also by the students. A first attempt to improve the teaching methodology was to complement the computer simulations with a visit to a wind farm. This is very illustrative and, indeed, the visit remains a part of the course. Also, it made more obvious the need for having physical equipment available in the laboratory to carry on interesting educative experiences that cannot be performed in an industrial wind plant. As a consequence, it was decided to develop a new system that fulfilled these educational needs. The result was the platform described in the previous section.

Sem. 1	General Physics I, Calculus I, Algebra I, Engineering Graphics I Drawing I, Chemistry I, Computer Science
Sem. 2	General Physics II, Calculus II, Algebra II, Engineering Graphics II, Chemistry II, Mechanics I
Sem. 3	Advanced Physics I, Materials, Mechanics II, Advanced Calculus, Statistics, Thermodynamics I
Sem. 4	Differential Equations, Ad. Physics II, Circuit Theory I, Strength of Materials I, Thermodyn. II, Economics
Sem. 5	Strength of M. II, Fluid Mechanics I, Machines Theory, Systems Theory, Electrical Machines I, Materials II
Sem. 6	Heat Transfer, Fluid Mech. II, Electronics I, Electrical Machines II, Automatic Control I, Circuit Theory II
Sem. 7	Specialized Mathematics, Electronics and Automatic Control, Industrial Engineering, Industrial Electronics, Electrical Machines Control, Power Systems I
Sem. 8	Thermal Engineering, Material Technology, Structures, Manufacturing I, Power Systems II, **Electrical Generation with Renew. Energy Sources**
Sem. 9	Project Engineering, Electrical Technology, Transport Technology, Electrical Installations, Electrical Energy Generation, Control of Electric Drives
Sem. 10	Project Engineering, Electrical Technology, Transport Technology, Electrical Installations, Electrical Energy Generation, Control of Electric Drives

Fig. 7. Semester sequence of courses in Electrical Engineering at Universidad Politecnica de Madrid.

Once available, the teaching methodology of laboratory sessions was completely revised to take advantage of the new equipment. The students must now complete their experimental training by carrying out the following four sessions using the developed platform:

1. Determination of aerodynamic coefficients versus tip speed ratio of the wind rotor.
2. Operation of the two fixed-speed windings induction generator system.
3. Operation of a variable speed wind turbine with doubly-fed induction generator system.
4. Operation of a variable speed wind turbine with full converter synchronous generator system.

More detailed information about the structure and the main contents of one of the laboratory sessions can be found in the Appendix.

Each session lasts 3 hours and is undertaken by 12 students under the guidance of two instructors, according to the following methodology:

- At the beginning of the course, the students are provided with a lab guideline that contains the description and the objectives of each session, as well as an explanation of the main technical details.
- Before each laboratory session starts, the students must prepare their plan of execution; they also have to pass a ten-minute quiz concerning the contents of the lab guideline, which must have been studied in advance. The inclusion of this test has proven to be a valuable pedagogical tool for the further development of the session because it ensures that almost all the students (those who pass the test) have a similar knowledge about the fundamentals of what they are going to do, and are sufficiently informed about safety aspects.
- The students, distributed in three groups each of four people, are to mount the equipment and connect the measurement instrumentation at the beginning of the laboratory session. At this point, the experience has revealed some difficulties with the number of students per group, related to inadequate task distribution.
- Before the execution of each part of the session, and for no more than 10 minutes, the instructor explains and remarks ion the objectives and details of the experiment, and also insist on safety issues.
- The students, guided by the instructors, must follow the session handling the equipment and taking measurements. At this stage, the main

pedagogical role of the instructor is as coach. The instructor uses Problem Based Learning (PBL) methodology to force the students to learn the fundamental principles in the context of solving a problem, by asking leading and open-ended questions [16].

- Finally, after the session, each student team must process the results of the session and must draft a short report about it. The learning assessment is based on this report and the previous systematic observation.

Preliminary pedagogical assessment

Although it is not the objective of this paper to present a formal assessment of the educational methodology used in the laboratory sessions, it could be catalogued as PBL, and there is plenty of information available on this topic, for instance [17]. The use of the described platform has only been implemented very recently and there are no significant quantitative results available. However, the qualitative impression obtained by the instructors is that students are more motivated during laboratory sessions. Preliminary results on effectiveness assessment also show an improvement in the students' opinion about the usefulness of the new laboratory sessions in understanding the principles of electrical generation with wind energy. This indicator has evolved from a mean value of 3.55 out of 5, in the previous four years, to 4.1, in the last year. Although this is not very significant, because it has been only one year since the implementation of the renewed laboratory sessions, it is a positive early indication of improvement.

CONCLUSIONS

The educational platform described fulfills the special needs of hands-on laboratory sessions in the topic of electrical generation from wind energy. In contrast with computer simulations, it allows a closer representation of real wind generators and their associated technical problems. Its use, along with an adequate learning methodology, leads to a better understanding of the fundamental principles involved.

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APPENDIX

Case study. Report and results of the laboratory session no. 4: full converter variable speed WG system

As an application example of this educational platform, this Appendix presents a short report of one of the laboratory sessions: Operation of a variable speed wind turbine with a full converter synchronous generator system. It contains a brief description of the setup and, for the three parts of the session, a collection of measurements obtained during the course of a real session, the analysis of the results and the conclusions drawn.

Setup description

Figure 8 shows a detailed scheme of the composition of the overall system, including the structure of its regulation system, and Table 1 gives additional information about the system parameters.

In this case, the wind turbine is directly coupled to a Permanent Magnet multipole synchronous generator (PM). The regulation of the system is achieved through a double electronic converter composed of a Rectifier-Chopper (CH) and an Inverter (INV).

The set CH is composed of a three-phase diode rectifier and a dc/dc converter. It controls the electromagnetic torque (M) of the PM generator by means of the regulation of the dc link current (I_{dc}). The rotational speed measurement (O) establishes the torque reference value (M_{ref}), through the dc link current reference ($I_{dc\text{-}ref}$), in order to follow the 'tracking of the optimal power point' control strategy (SPMP).

The Inverter (INV), which is composed of a three-phase IGBT full-bridge converter, controls the active and reactive power injected into the grid through the direct (i_d) and quadrature (i_q) components of the current injected into the grid, respectively. The current direct component, i_d, is controlled by keeping the dc voltage level at the capacitor ($U_{dc\text{-}ref}$), and the current quadrature component, i_q, is controlled by means of the reference value of the reactive power (Q_{ref}).

Part 1: Generator test

The objective of the test is to experimentally determine the values of parameters *RGSIP* and *LGSIP*. The winding resistance of the PM generator, *RGSIP*, can be measured directly by connecting an ohmmeter to the output of the PM generator in open-circuit.

The value of the d-axis synchronous inductance of the PM generator, L_{GSIP}, is obtained from the test schematically represented in Fig. 9, where a variable resistor is connected to the PM generator, in order to test for different operating conditions. The instrumentation used to carry out measurements is also shown, represented by dotted lines.

Taking into account that the electro-motive force, E, can be expressed in terms of the rotational speed, as determined in a previous session (Session 1, part 2) and, hence, in terms of the generated frequency, f, the value of *LGSIP* is can be determined as:

$$L_{GSIP} = \sqrt{\frac{E^2 - (U + R_{GSIP} I)^2}{(2\pi f I)^2}}.$$

As an example, Table 2 shows three series of measurements (corresponding to three different values of the variable resistor) taken during a laboratory session.

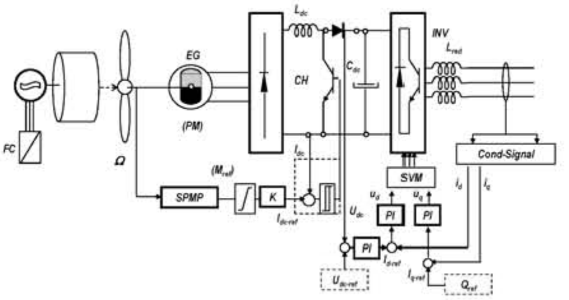

Fig. 8. Variable speed wind generation system with full converter synchronous generator.

Table 1. Main parameters of the system

L_{GSIP}	R_{GSIP}	L_{red}	R_{red}
50 mH	4 O	16 mH	0.3 O

L_{dc}	C_{dc}	$K_{Idc\text{-}ref}$	*SPMP*
100 mH	23.5 mF	0.75	8×10^{-8} x^2

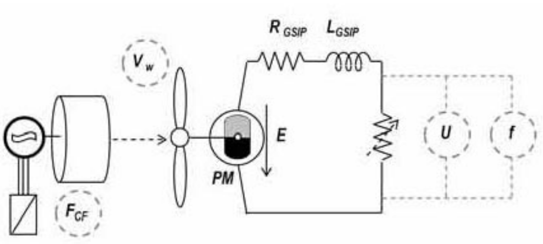

Fig. 9. PM generator test.

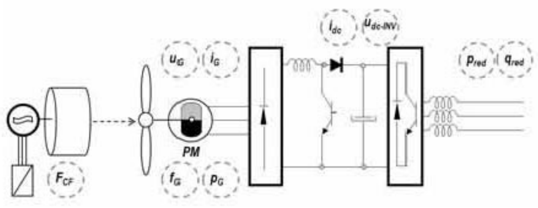

Fig. 10. Layout of the WG steady operation test.

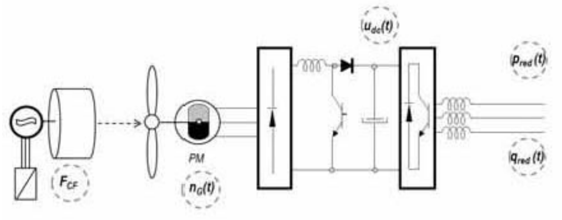

Fig. 11. Magnitudes recorded during transients.

Table 2. Example of measurements from PM generator tests

Series	*f* (Hz)	*U* (V)	*I* (A)
1	80	97.5	0.54
2	70	72.0	1.54
3	63	49.2	2.43

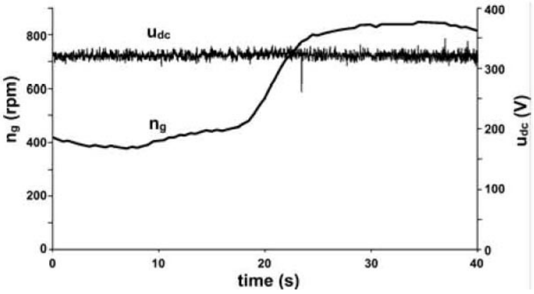

Fig. 12. Records of the time evolution of *ng*(*t*) and *udc*(*V*) during a ramp variation in the incident wind speed.

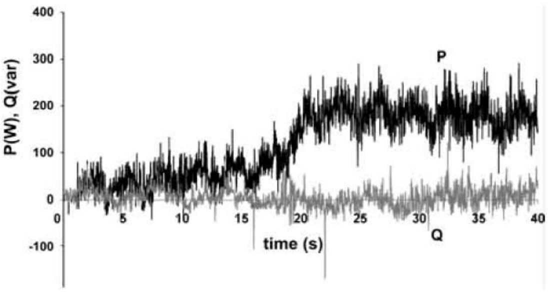

Fig. 13. Records of the time evolution of *Pred*(*t*) and *Qred*(*t*) during a ramp variation in the incident wind speed.

Part 2: WG steady state operation test

In this part of the session, the whole wind generation system is connected to the electric grid and exposed to a constant wind speed, with constant reference values. Different electrical and mechanical magnitudes are measured, as shown in Fig. 10 by the dotted lines. As an example, Table 3 shows some measurements for three different wind speeds, when the reference value of the reactive power injected into the grid is set to zero.

The results of Table 3 show a correct operation of the inverter control which, on the one hand, maintains 'null' the value of the reactive power (Q_{red}) required for the generation system, and, on the other hand, maintains the voltage of the dc capacitor ($U_{dc\text{-}INV}$) at a constant value, with any power production situation level. It should be noted that the converter efficiency () is greater under higher winds and rotational speeds.

Part 3: WG transient operation test

In this part of the session, the wind generator is also connected to the electric grid, but the interest is focused on the transient response system to sudden changes. In particular, two different situations are studied: the response to a wind variation and the response to a change in the reference value of the reactive power. The developed educational platform allows the recording of the time evolution of the most significant variables, represented in Fig. 11 by dotted lines.

In actual wind generation, the magnitude of the wind speed is continuously changing, so it is worthwhile to show the students the behavior of the WG under these circumstances. In the laboratory experiment, a ramp evolution in the wind speed is studied, forced by the fan drive, FD. Figure 12 shows a record of the transient evolution of the rotational speed, $n_g(t)$, and the dc link voltage at the capacitor connections, $u_{dc}(V)$. The corresponding records for the active and reactive grid powers, $P_{red}(t)$ and $Q_{red}(t)$, are shown in Fig. 13.

Table 3. Some results of WG steady operation tests

Wind (m/s)	f_G (Hz)	U_G (V)	I_G (A)	P_G (W)	I_{dc} (A)	U_{dcIN} (V)	P_{red} (W)	Q_{red} (var)	η (%)
6.0	41	40	1.2	72	1.4	315	26	0	36
7.8	60	55	1.7	122	1.9	315	100	0	81
9.3	79	70	2.3	212	2.5	315	169	0	80

From these records the students are asked to write a report about the session, including the results that can be inferred. For instance, some conclusions are:

- The wind speed change causes slow and smooth change in the rotational speed, *ng*(*t*), from 400 rpm to 800 rpm.
- The reference value of dc current, *Idc-ref*(*t*), (not shown in the figures) increases from 1 A to 3.8 A, in order to follow the SPMP control strategy.
- The system tries to increase the dc capacitor charge, but the inverter control system maintains the value of the dc link voltage around 320 V.
- As a consequence, the active power injected into the grid increases from 25 W to 190 W, as slowly as the rotational speed.
- The inverter control system is able to keep the value of the reactive power injected into the grid at 0 var, according to its reference value.

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