Voltage dip generator for testing wind turbines connected to electrical networks

C. Veganzones [a,*], J.A. Sanchez [b], S. Martinez [a], C.A. Platero [a], F. Blazquez [a], D. Ramirez [a], J.R. Arribas [a], J. Merino [a], N. Herrero [b], F. Gordillo [a]

[a] Department of Electrical Engineering, ETSII, Universidad Politecnica de Madrid, C/Jose Gutierrez Abascal 2, 28006 Madrid, Spain
[b] Department of Civil Engineering, Hydraulics and Energy, ETSICCP, Universidad Politecnica de Madrid, Ciudad Universitaria, s/n, 28040 Madrid, Spain

Keywords:
Wind power generation
Grid code
Fault ride-through capability

A B S T R A C T

This paper describes a new voltage dip generator that allows the shape of the time profile of the voltage generated to be configured. The use of this device as a tool to test the fault ride-through capability of wind turbines connected to the electricity grid can provide some remarkable benefits: First, this system offers the possibility of adapting the main features of the time–voltage profile generated (dip depth, dip duration, the ramp slope during the recovery process after clearing fault, etc.) to the specific requirements set forth by the grid operation codes, in accordance with different network electrical systems standards. Second, another remarkable ability of this system is to provide sinusoidal voltage and current wave forms during the overall testing process without the presence of harmonic components. This is made possible by the absence of electronic converters. Finally, the paper includes results and a discussion on the experimental data obtained with the use of a reduced size laboratory prototype that was constructed to validate the operating features of this new device.

1. Introduction

One of the determining factors for achieving significant reductions in atmospheric CO_2 emissions is to integrate the largest possible number of renewable energy sources into electrical power systems. Currently, wind farms constitute a significant percentage of the generating capacity in several countries. In Spain and Germany, wind farms surpass 20% of the total installed power, representing more than 10% of the annual electrical energy demand [1]. That has led to situations in which more than 50% of the total instantaneous demand of the electrical system has been met by wind generation [2]. In this regard, the technical operators of these electrical systems have expressed concerns about the ability of wind farms to participate in the dynamic regulation of the network like conventional power plants do, particularly during contingencies, without compromising safety, reliability, and service quality. This concern increases with the rate of penetration of wind generation in the system [3,4].

The dynamic performance requirements to be met by wind farms when facing the network contingency called "voltage sag" are especially relevant. This is due to the fact that, in certain circumstances, it has been noted that this disturbance could cause the simultaneous shutdown of large numbers of wind generators connected to the electrical system [5,6]. For this reason, the new voltage dip ride-through capability requirements for wind farms are one of the most important changes imposed by new grid codes. As a result, many power system operators in Europe have established new operating procedures which define the characteristics of the voltage–time response that wind farms must be able to tolerate during the contingency, in terms of depth, duration and profile, and the requirements to be met regarding the exchange of active and reactive power during the disturbance [7–13]. Fig. 1 shows various voltage–time profiles set by some of these operators.

Nowadays, compliance with these requirements is verified by using simulation models for each type of wind turbine, with appropriate details to be integrated as part of the dynamic stability studies of the power system to which they are connected. Thus, the analysis of the dynamic response to voltage dips by wind turbines with Synchronous Generator and Full-power Converter technology (SGFC) is described in Refs. [14,15]. An analysis for wind turbines with Doubly-Fed Induction Generator technology (DFIG) is described in Refs. [16,17] for various control alternatives. A similar study for Fixed Speed Induction Generator technology (FSIG) can be found in Refs. [18,19].

However, to validate the simulation models, the wind generators must be subjected to field or laboratory tests which reproduce, as faithfully as possible, the voltage–time profile established by the

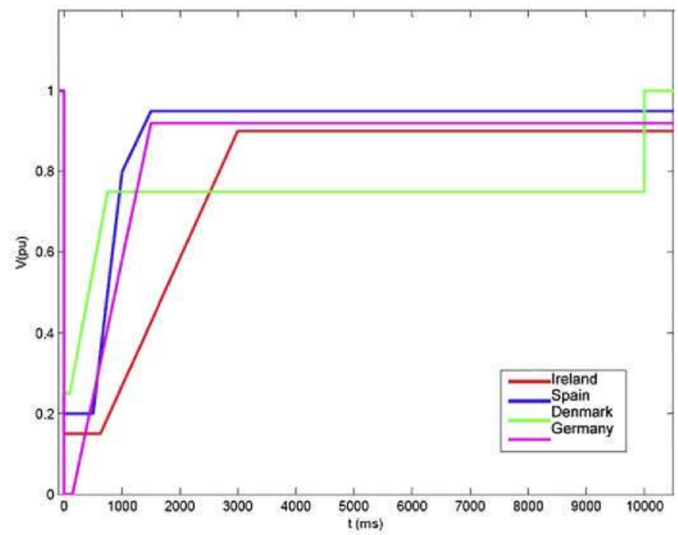

Fig. 1. Voltage sag patterns of several European grid codes.

different voltage dip patterns (Fig. 1). To do this, devices capable of generating a voltage whose time profile meets these requirements are needed.

These voltage–time patterns (Fig. 1) begin with a steep drop from the rated value to very low voltage levels (25–0%). They differ in the sag duration and in the slope of the subsequent voltage recovery phases once the fault is cleared. Most of the voltage dip generators found in the literature, and analyzed in this article, can reproduce the initial abrupt voltage drop and maintain the values shown in the deep zone of the sag. However, they are not able to reproduce the slow voltage rise during the recovery period after fault clearance, thereby producing a rectangular-shaped voltage-time profile. Thus, as described in Ref. [20], a voltage dip generator with a rectangular profile is presented, where the sag depth is adjustable in discrete steps by means of voltage dividers and a tapped transformer. In the prototype described in Ref. [21], the depth is regulated by the combined action of a controlled static switch and a controlled step-down transformer. A device with similar characteristics is presented in Ref. [22], consisting of a transformer and switchable impedances connected in series. In Ref. [23], this regulation is performed using an autotransformer with taps. Finally, in Ref. [24], the regulation is achieved by the combined action of an IGBT switched device with a tapped transformer.

The authors have developed two new voltage sag generators with a programmable voltage–time profile. This programmability makes it easily adaptable to most grid codes. One of these devices uses synchronous machines [25], and the other uses an induction regulator. This paper presents the last one. A prototype of this voltage sag generator has been constructed. This prototype is fully scalable and, since it is not based on power electronics, all of its components are available at any applicable power range.

The paper is organized as follows: Section 2 describes the constitution and operation of the proposed device. Section 3 explains the operational procedure to be followed in order to generate a particular voltage sag time profile. Finally, Section 4 shows the results obtained using a laboratory prototype of the proposed voltage sag generator in order to experimentally validate the actual operation of the device.

2. Description

Fig. 2 shows a diagram of the proposed device. Basically, it consists of a three-phase induction regulator with a control mechanism to modify the shaft position (S-DEC). The induction regulator connects the device under test to the network by means of a set of contactors (S-CNX). The system can be complemented with two tapped transformers if voltage adaptation is needed (S-ADT).

The operation of all these devices is controlled by a programmable logic controller (S-PLC). The shape of the "voltage dip" to be generated can be programmed in the PLC. To follow this reference, the PLC controls the operation of the contactor set (S-CNX) and generates the angle setpoint input to the control mechanism for the shaft position regulator (SM).

The device works because of the ability of the induction regulator (MA) to modify the output voltage phasor (modulus and phase) as a function of the shaft angular position (α). Fig. 3 shows the connection diagram for the induction regulator windings.

The induction voltage regulator (MA) has the same electromagnetic structure as a wound-rotor induction machine. It has two three-phase windings: one of them is placed in the rotor ($R_{1\text{-N}}$, $R_{2\text{-N}}$, $R_{3\text{-N}}$), and the other in the stator ($S_{1\text{-}11}$, $S_{2\text{-}22}$, $S_{3\text{-}33}$). The wye rotor winding is wired in parallel with the power source by connecting its terminals (R_1, R_2, R_3) to the corresponding phases (D_{I1}, D_{I2}, D_{I3}). However, the stator windings ($S_{1\text{-}11}$, $S_{2\text{-}22}$, $S_{3\text{-}33}$) are connected in series with the respective phases of the power supply (D_{I1}, D_{I2}, D_{I3}), behind the rotor connection points [26].

Fig. 4 shows the phasor diagram, which depicts the voltage phasors corresponding to the rotor and the stator windings for one of the phases (phase 1), when connected as described above, and for the case where both windings have the same number of turns. Two cases are represented corresponding to two different angular positions (30°, 150°) of the rotor shaft.

In this figure we note that the phase voltage output of the induction regulator ($U_{\text{MA-out}}$) is the result of the vector sum of two phasors: first, the voltage phasor induced in the rotor winding (U_{R_1N}), and second, the voltage phasor in the corresponding stator winding ($U_{S_1S_{11}}$), i.e.:

$$\vec{U}_{(\text{MA}_{\text{out}})_1} = \vec{U}_{(\text{D}_{\text{O1}})N} = \vec{U}_{R_1N} - \vec{U}_{S_1S_{11}} \tag{1}$$

Moreover, the position of the rotor shaft (α_{r-s}) sets the relative position between the rotor and stator voltage phasors. This establishes a relationship between the angular position of the shaft (α_{r-s}) and the phase difference between the stator and rotor voltage phasors, and, thus, with the output voltage ($U_{\text{MA-out}}$).

Therefore, the voltage at the output terminals of the induction regulator ($U_{\text{MA-out}}$) can be expressed in terms of the input voltage ($U_{\text{MA-in}}$) and the shaft angular position (α_{r-s}) according to:

$$U_{\text{MA-out}} = U_{\text{MA-in}} \sqrt{2[1 - \cos(\alpha_{\text{rs}})]} \tag{2}$$

Hence, by appropriate regulation on the shaft angular position, the desired time profile for the output voltage can be achieved. The PLC (S-PLC) generates the time profile of the intermediate command signal for the shaft angular position (α_{ref}). This signal is calculated by a controller that is also implemented in the PLC, so that the output voltage follows the desired time profile for the voltage sag (v_{ref}), as defined in the previous section. The controlled servomotor (SM) implements the regulation of the shaft position.

The system is completed with the inclusion of a contactor-based automatic connection system (S-CNX, see Fig. 2). This allows for the proper switching sequence needed to connect the wind generator under test to the voltage sag generator in the right conditions. It features a set of four three-phase fast contactors (KT.1–4) and two single-pole contactors (KB.1–2) that enable the system to be safely connected and disconnected during the test using hardwired programmed logic control. The chronological sequence is as follows:

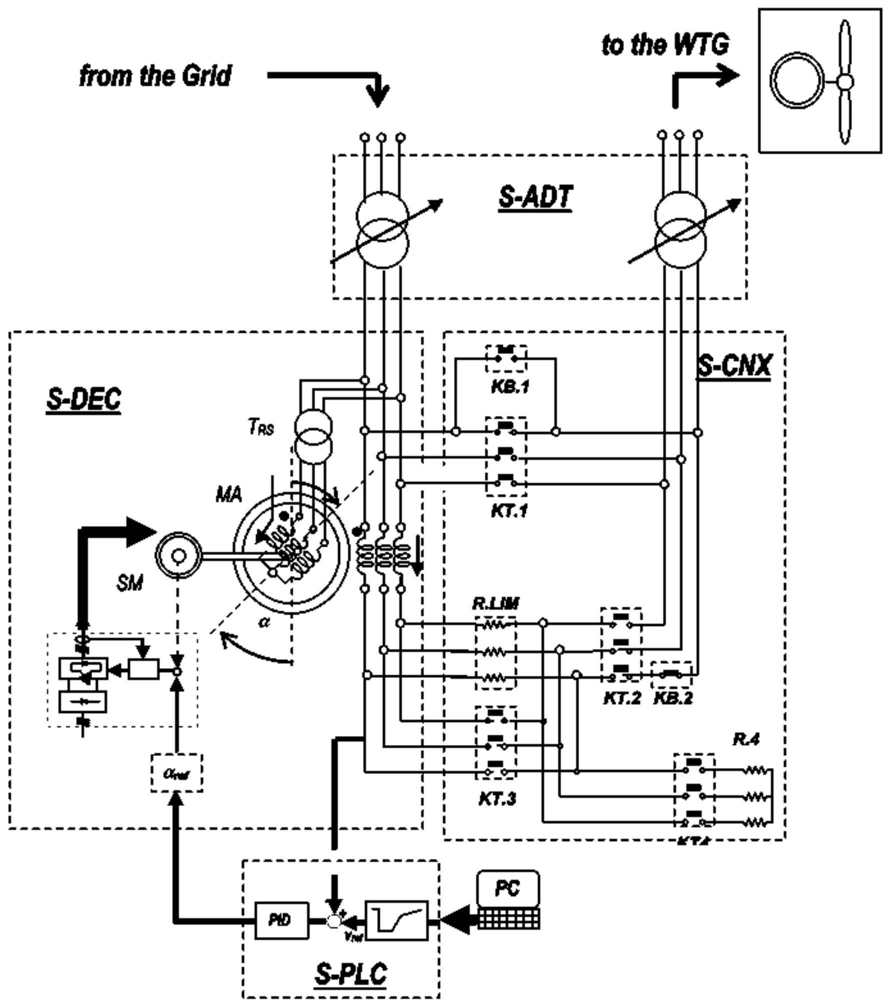

Fig. 2. Schematic of the voltage dip generator system.

- At the initial stage, contactor (KT.1) is closed, and contactors (KT.2), (KT.3), and (KT.4) are open. This means that the wind generator under test is directly connected to the network at nominal voltage.
- The switching sequence begins with the contactor (KT.2) closing, which limits the inrush current through the insertion of a resistor (R.LIM) during the first instants. Then the resistor is bypassed when the contactor (KT.3) is closed. Simultaneously, the contactor (KT.4) is closed only for a moment, which forces a steep voltage drop by introducing a low resistance to ground (RT.4) that accelerates the transient response of the induction regulator windings.
- At the end of the switching sequence, the contactors (KT.2) and (KT.3) remain closed, and the other two (KT.1 and KT.4), open, so that the voltage in the wind generator under test becomes regulated by the action of the induction regulator ($U_{MA\text{-}out}$).

Unbalanced voltage sags due to phase-to-phase faults can be generated with the same sequence plus the activation of the normally open contactor (KB.1) and the normally closed contactor (KB.2).

3. Operational procedure

This section presents the operational procedure to be followed in order to generate the particular voltage sag time profile corresponding to the low voltage ride-through requirements for wind generators of the grid code of the Spanish operator. Fig. 5 shows this profile [11].

This procedure is performed in three sequential steps. The first two are completed prior to the test, and the third is where the actual test is carried out.

3.1. Initialization step

Before running the test, adjustment and calibration of the device must be completed to suit the particular conditions of the test. To do this, the S-DEC device, but not the wind generator under test, must be connected to the network. These functions include: voltage adaptation between the wind generator and the voltage regulator, identification and positioning of the initial angle of the induction regulator shaft, and characterization of the voltage profile to be generated during the test. To do this, the following operations must be performed on different subsystems:

- S-CNX subsystem. No contactor is energized, they remain in the rest position. Thus, the sag generator is powered from the network but disconnected from the wind generator under test, and is therefore operating under no-load. Thus, the module is ready to execute the later switching sequence
- S-ADT subsystem. The rated voltage of the wind generator and the induction regulator are adapted by adjusting the transformer tap changer.

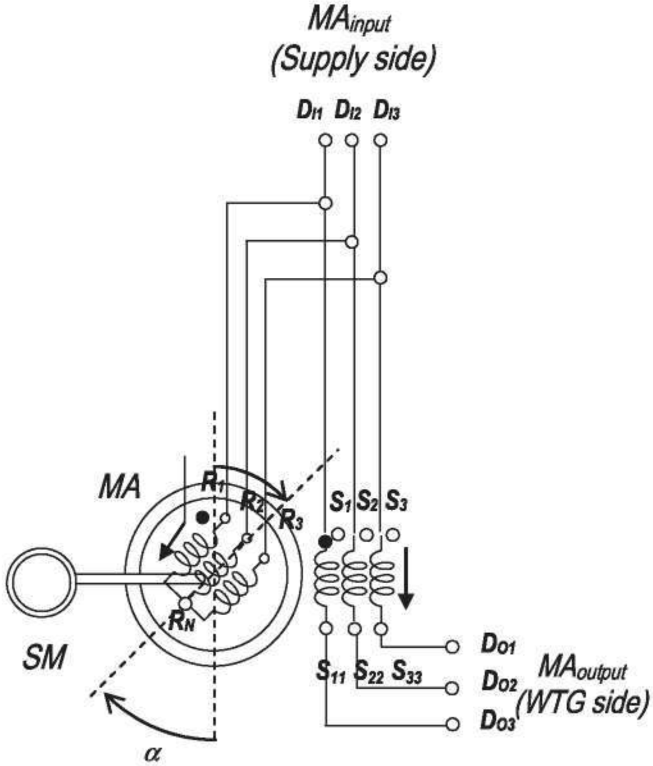

Fig. 3. Schematic of the induction regulator.

- S-PLC subsystem. The induction regulator is calibrated in three steps. First, the angular positions corresponding to minimum and maximum output voltage ($U_{\text{MA-out}}$) are identified. Second, the rotor is placed in the angular position $\alpha_{\text{ref-0}}$ corresponding to the voltage level at the bottom of the sag (0.2 p.u., in this case). Starting from this initial reference value, the control system will then dynamically adjust the reference during the test. Finally, the PLC is programmed with the data that define the desired time voltage profile (sag depth, intervals, recovery ramps, etc.).

3.2. Setting without charge

Keeping the induction regulator disconnected from the wind generator to be tested, the operation of the overall system is

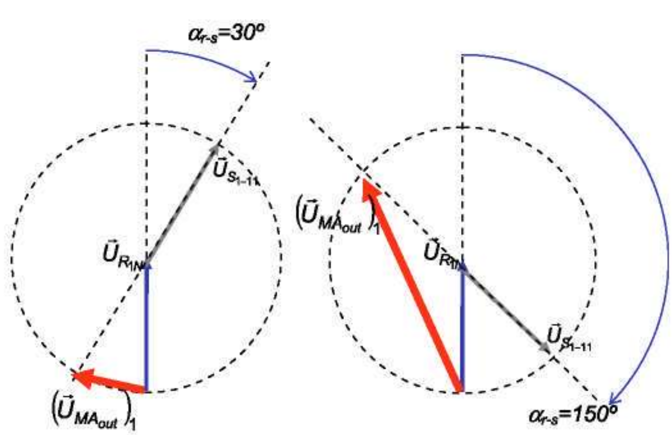

Fig. 4. Representation of voltage phasor diagram in the induction regulator windings for two angle shaft positions: $\alpha_{r-s} = 30°$ (left), $\alpha_{r-s} = 150°$ (right).

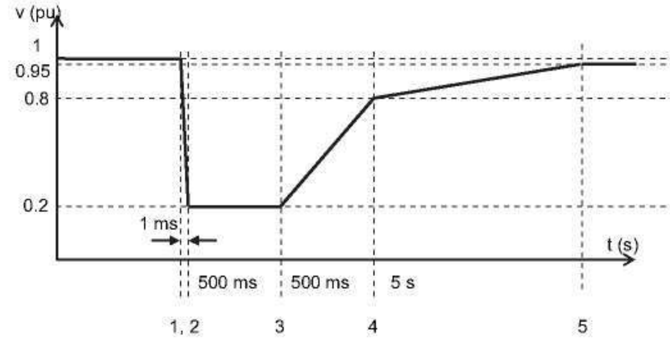

Fig. 5. Grid code Spanish operator voltage sag time profile for low voltage ride-through requirements for wind generators.

checked. Also, the voltage and angle controllers are adjusted to optimize the response of the control system so that it follows the desired voltage–time profile.

3.3. Test procedure

The following describes in detail the performance of each of the subsystems, for the periods defined along the test process depicted in Fig. 5.

- S-CNX subsystem. Over time period "1–2", corresponding to the start of the process, this subsystem manages the switching protocol sequence of the contactors described above in order to adequately connect the wind turbine (WTG) from the network rated voltage to the sag generator voltage preset in step A.
- S-DEC and S-PLC subsystems. Over time period "2–3" (500 ms), corresponding to the deep part of the voltage dip, the programmable logic controller (S-PLC) keeps the shaft angle around the starting position so as to keep the voltage at the induction regulator output constant, at around 20% its rated value. Over the next time period, "3–4" (500 ms), corresponding to the first stage of voltage recovery after the sag, the S-PLC device regulates the output voltage of the induction regulator such that it tracks the recovery shape of the ramp voltage, from 20% up to 80% of its rated value. During the next period, "4–5" (14 s), this system keeps track of a new ramp voltage–time recovery, from 80% to 95% of its rated value. At this point, the test concludes. Next, the S-CNX subsystem reconnects the wind generator to the network, following

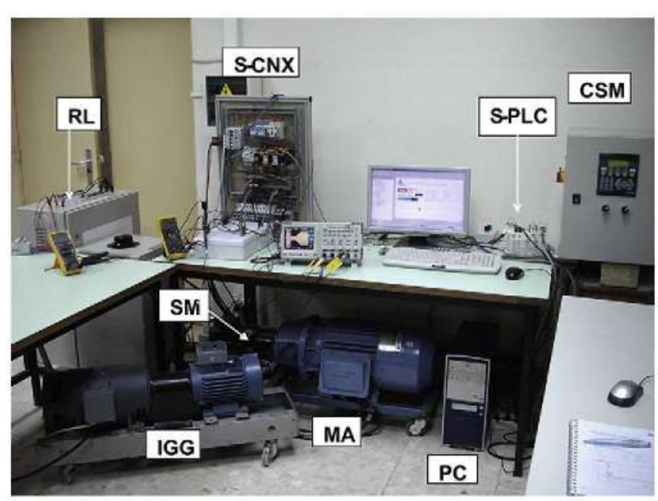

Fig. 6. 5 kV A Reduced-size voltage dip generator prototype.

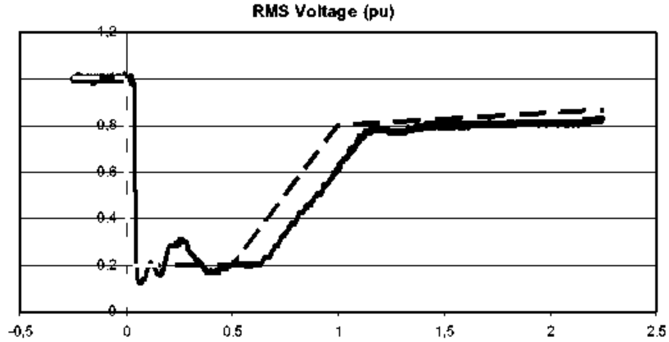

Fig. 7. Result of no-load test experiment: rms voltage–time profile; reference value (dashed line), actual value (solid line).

a contactor switching protocol sequence similar to that described above.

4. Voltage dip generator laboratory scaled prototype. Results

A 5 kV A prototype of a voltage sag generator was developed to validate the experimental operation of the proposed device. Fig. 6 shows a picture of this laboratory prototype. The main components of the voltage dip generator system can be identified as follows:

- An induction regulator (MA), employing a 5-kV A 400-V wound rotor asynchronous electrical machine.
- A controlled servomotor for the shaft position control system, consisting of a PLC controlled 10 Nm PM motor (SM).
- The voltage control system, labeled (S-PLC), handled by a PLC connected to a PC by an USB port.

The following describes the tests that were performed to validate this prototype and discusses the results. In these tests, the voltage–time profile represented in Fig. 5 was programmed as the reference "voltage sag" signal. The "voltage dip generator" device should regulate its output voltage to adjust to this reference signal.

Considering the type and nature of the equipment connected to the output of the dip generator device, three different kinds of test were conducted:

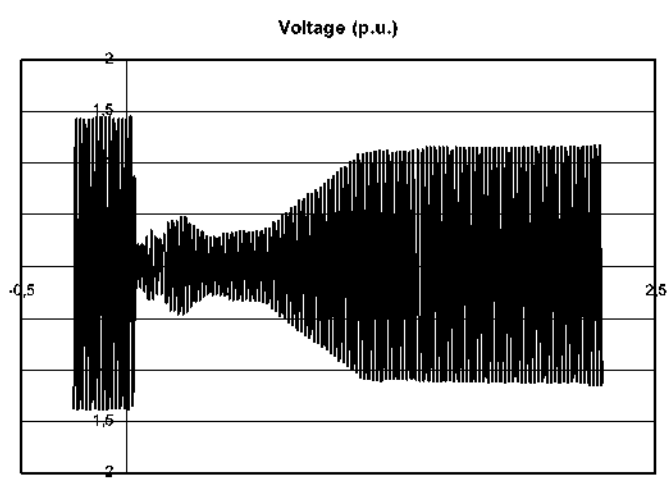

Fig. 8. Result of no-load test experiment: Voltage–time waveform profile.

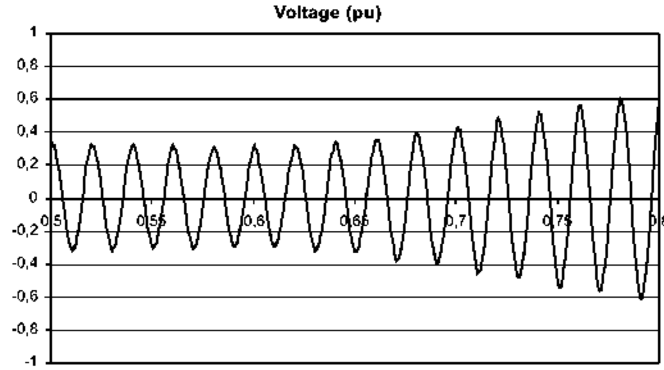

Fig. 9. Result of no-load test experiment: Close-up of voltage–time waveform profile: during the voltage recovery ramp.

- No-load test: the output device remains open.
- Resistive load test: the output device is connected to a rheostat (RL) (see Fig. 6).
- Generator test: the output device is connected to an asynchronous generator system (IGG) (see Fig. 6).

4.1. No-load test

During this test the sag generator input is connected to the grid voltage and the output is left open circuited. The objective of this test is to check the operation of the control system and the setting of the control parameters.

The dashed line in Fig. 7 shows the rms value of the voltage sag reference signal that was programmed into the PLC. The solid line superimposed on this signal represents the actual voltage–time response. Fig. 8 shows the time profile of the voltage waveform during the test process. Fig. 9 shows a close-up of this voltage waveform during the first 300 ms at the beginning of the voltage recovery ramp.

These results show that the generator achieves very acceptable tracking of the reference signal, although, obviously, following each abrupt change in the signal, there is a delay and an oscillation in the response. Additionally, they verify that the voltage waveform remains sinusoidal at all times.

4.2. Resistive load test

In this test, a variable resistive load is connected to the sag generator output. The purpose of this test is to observe the effect of

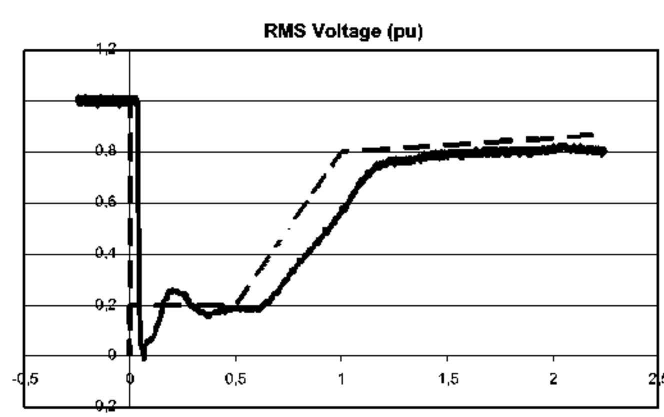

Fig. 10. Result of resistive load test experiment: rms voltage–time profile; reference value (dashed line), actual value (solid line).

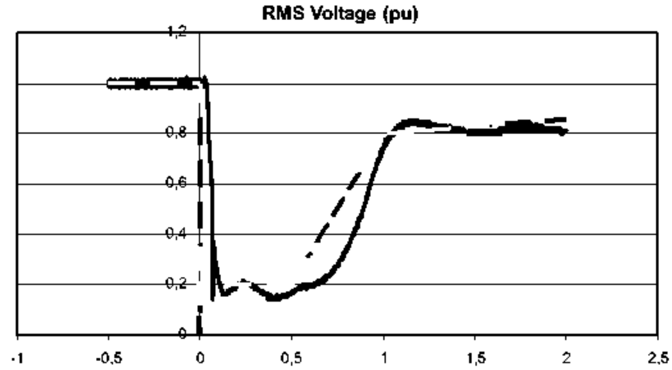

Fig. 11. Result of induction generator test experiment: rms voltage–time profile; reference value (dashed line), actual value (solid line).

the current flow through the windings of the induction regulator on the response of the system.

Fig. 10 shows the reference signal (dashed line) for the desired rms value of the dip generator output voltage and the trace of its actual time response (solid line) when connected to a resistive power load of 0.5 p.u.

These results indicate that the action on the contactor KT.4 (see Fig. 2), shorting the voltage applied to the load through a small resistance immediately following the dip, reduces the effect of the delay that would otherwise result from the long time constant associated with the parameters of the induction regulator windings during the switching transient. The insertion of this resistance allows the voltage drop to be abrupt.

Moreover, it appears that the response of the system, when faced with an abrupt change in the reference voltage signal, offers an adequate compromise between overshoot and delay.

4.3. Generator test

In this test, the output of the voltage sag generator is connected to the electrical generator of a scaled fixed-speed wind generator (IGG, see Fig. 6). This scaled wind generator consists of a 1-kW squirrel cage induction machine driven by a controlled dc motor that emulates the wind turbine behavior. Fig. 11 shows the reference signal (dashed line) for the desired rms value of the dip generator output voltage and the trace of its actual time response (solid line) when the test is performed at the wind generator rated power.

Note the delay shown in the figure for the dynamic response of the system when confronted with steep changes in the reference voltage. This is due to the time constant introduced by the transient impedance of the asynchronous generator.

5. Conclusions

A new system for generating voltage dips has been presented, and its viability for testing the low voltage ride-through capability of wind generators demonstrated. Its ability to reproduce the time profile of a real voltage dip, particularly the voltage recovery ramps, is remarkable. Nevertheless, some aspects of its performance need to be improved, and further research has to be conducted, particularly in terms of:

- Developing an adaptive control system so that the response best fits the desired setpoint signal, especially taking into account the wide variability of the generator operating point during the test.
- Improving the design of the induction regulator so that its dynamic response is faster and the internal voltage drop is minimized.

Acknowledgements

This work was funded by the Spanish Ministry of Education and Science and by the Ministry of Science and Innovation under research grants PN-ENE2005-06299 and PN-ENE2009-13276, respectively.

References

[1] Executive Committee for the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems of the International Energy Agency (2009, July). IEA Wind Energy Annual Report 2008 [Online]. Available from: http://www.ieawind.org.
[2] AEE Press Releases (2010, January 5). Wind energy has consolidated as the third technology of the power system [online]. Available from: http://www.aeeolica.es.
[3] Tsili M, Papathanassiou S. A review of grid code technical requirements for wind farms. IET Renewable Power Generation September 2009;3(3): 308–32.
[4] Veganzones C, Martinez S, Blazquez F. Large scale integration of wind energy into power systems. Electrical Power Quality and Utilisation Magazine April 2005;1(1):15–22.
[5] Atienza L. Wind energy development in Spain. In: Presented at MIT Energy Club, Boston, MA; April 3, 2009.
[6] Rodriguez JM, Alvira D, Baares S. The Spanish experience of the grid integration of wind energy sources. In: Presented at 2005 IEEE Russia Power Tech, St. Petersburg, June 27–30; 2005.
[7] Regulation TF 3.2.5. Wind turbines connected to grids with voltages above 100 kV. Denmark: Elkraft System and Eltra. Available from: http://www.energinet.dk; November 2004.
[8] Regulation TF 3.2.6. Wind turbines connected to grids with voltages below 100 kV. Denmark: Elkraft System and Eltra. Available from: http://www.energinet.dk; May 2004.
[9] Grid connection regulation for high and extra high voltage. E.ON Netz GmbH. Available from: http://www.eonnetz.com/pages/ehn_de/Veroeffentlichungen/Netzanschluss/Netzanschlussregeln/ENENARHS2006eng.pdf; April 2006.
[10] The grid code issue 3, revision 16. Warwick CV34 6DA: National Grid Electricity Transmission Plc. Available from: http://www.nationalgrid.com; 30 May 2006.
[11] Requirements on voltage dip ride-through capability of wind farms. REE, grid code PO 12.3. Available from: http://www.ree.es; October 2006.
[12] Grid code. Version 2.0. EirGrid. Available from: http://www.eirgrid.com; January 2007.
[13] REA generating plants connected to the high and extra high voltage network. Berlin: Verband der Netzbetreiber – VDN. Available from: http://www.vdnberlin.de/eeg_hh_en.asp; August 2004.
[14] Sanchez JA, Veganzones C, Martinez S, Blazquez F, Herrero N, Wilhelmi JR. Dynamic model of wind energy conversion systems with variable speed synchronous generator and full-size power converter for large-scale power system stability studies. Renewable Energy June 2008;33:pp1186–98.
[15] Abbesa M, Belhadja J, Bennania AA. Design and control of a direct drive wind turbine equipped with multilevel converters. Renewable Energy May 2010; 35(5):936–45.
[16] Santos-Martin D, Rodriguez-Amenedo JL, Arnalte S. Providing ride-through capability to a doubly fed induction generator under unbalanced voltage dips. IEEE Transactions on Power Electronics July 2009;24(7):1747–57.
[17] Flannery PS, Venkataramanan G. Unbalanced voltage sag ride-trough of a doubly fed induction generator wind turbine with series grid-side converter. IEEE Transactions on Industry Applications September/October 2009;45(5):1879–87.
[18] Ledesma P, Usaola J, Rodriguez JL. Transient stability of a fixed speed wind farm. Renewable Energy July 2003;28(9):1341–55.
[19] Rahimi M, Parniani M. Dynamic behavior and transient stability analysis of fixed speed wind turbines. Renewable Energy 2009;34(12):2613–24.
[20] García Gracia M, Lepea Andía D, et al. "Voltage sag generation equipment for wind power plant, controls and regulates short-circuit power detected by to-be-tested electric or wind power generators, for voltage and power values higher than predetermined values". Int. Patent WO2008125718-A1; October 2008.
[21] Li J, Liang L, et al. "Power network's voltage-dip generator, has thyristor transmitting motion signals to control running situation of reducing transformer through by-pass use thyristor, and start-up use thyristor to change amplitude of input voltage". China Patent CN101119074-A; Feb. 2008.

[22] Llorente JI, et al. "Gamesa innovation and technology, S.L. Low-voltage dip generator device". Int. Patent WO2006106163-A1; Oct. 2006.
[23] Garnacho F, Rodríguez JL. Procedimiento de medida de la respuesta de aerogeneradores ante huecos de tensión con la unidad móvil ULISES. Revista Energía 2006;32(191):91–8 (in Spanish).
[24] Mceachern A, Tangney B. "Voltage sag generator for AC power system, has switch connecting output and input and includes electromechanical switch contacts and insulated gate bipolar transistor switch in parallel". U.S. Patent US2003230937-A1; July 2004.
[25] Platero CA, Blazquez F, Ramirez D, Veganzones C, Arribas JR, Martinez S, et al. "Banco y método de ensayo de equipos eléctricos frente a huecos de tensión". Spanish Patent ES 2 325 902 B2; Oct. 30, 2008.
[26] Slemon GR, Straughen A. Electric machines. Toronto (CA): Addison-Wesley Pub.; 1980.