Abstract – In the last few years the number of grid connected wind conversion systems (WECS) has increased rapidly. The most commercialized WECS technology is the doubly-fed induction generator (DFIG) that offers operational and economical advantages over other ones. Nevertheless, this system has as the main drawback the high susceptibility to grid disturbances, for example, voltage sags. In this work it is presented a 25kW test bench which emulates a WECS using the DFIG technology for tests under symmetrical and asymmetrical voltages sags. The design of the main components is shown: the power filter, signal conditioning board, control structure and the voltage sag generator. The first experimental results are also shown and briefly analyzed.

Keywords - Doubly-fed Induction Generator (DFIG), Wind Conversion Systems (WECS), Voltage Sags, Turbine Simulator and LCL Filter.

I. INTRODUCTION

The massive investments in renewable energy have reduced the prices of the electrical energy generated from these sources, becoming competitive in comparison with the traditional sources. One of the most competitive renewable technologies is the wind energy conversion system (WECS). The number of wind power plants worldwide has increased so fast in the last few years. Brazil has more than 2GW of installed power, a small number when compared with the top five countries (China 75GW, USA 60GW, Germany 32GW, Spain 23GW and India 18GW) [1], but the number of wind power plants are growing fast.

There are different WECS technologies using different types of generators. The most common technologies are the synchronous generator using full scale converters (FC-SG) and the doubly-fed induction generator (DFIG), both depicted in Fig. 1. The main advantage of the DFIG is the use of a converter connected to the rotor dimensioned for just 30% of the machine rated power, so reducing the equipment costs when compared with the FC-SG which employs a full converter. Nevertheless, the DFIG topology has two main disadvantages: the use of a gearbox, which is a fragile part in the whole system, and the direct connection of the stator to the grid, increasing the system susceptibility to network disturbances, such as voltages sags. The synchronous generator can be constructed with high pole number, eliminating the gearbox, and the full scale converter decouples the generator and the grid [2].

Within this context, it is important to study the WECS behavior during grid disturbances. In the last few years several papers on this topic have been published, studying the voltage sags impact on the WECS and developing some strategies to improve the low voltage ride-through capability (LVRT) as required in the modern grid codes [3], [4].

Papers [5]-[9] analyze the DFIG behavior during voltage sags using mathematical modeling and show simulation and experimental results. Based on the system behavior, other papers focus the studies on the proposal of different solutions for the LVRT improvement of the DFIG technology [8], [10]-[15]. The impact of the voltage sags on the FC-SG and ride-through solutions are addressed in [2], [16]-[21].

Most of the previous papers prove their developments using experimental results obtained in small power test benches (<5kW). In this context, this work presents the design of a test rig using a 25kW DFIG for voltage sags studies and the future development of new control strategies to improve its LVRT capability.

This work is focused in the design of the test bench since the details of the prototypes used in the literature are not
generally described. Furthermore this test bench has higher power than the ones generally used in the literature, representing advantages, as: better signal-to-noise ratio, higher inertia, smaller stator and rotor resistances, etc.

The text is organized as following: Section II is dedicated to describe the general structure of the test bench and its components, in Section III the DFIG classical modeling and the control strategy are described, Section IV show some experimental results and finally in Section V the conclusions and the proposal of future works are presented.

II. THE TEST BENCH

The test bench presented in this work represents a WECS with the DFIG technology. Fig. 2 depicts the prototype diagram. In the following subsections each component will be described.

A. Generator and Converter

The generator is a wound rotor induction machine manufactured by VEM, model SPER225M4HW. The parameters are listed in Table I. This machine has no especial construction characteristics and the power was chosen based on the available converter rated power. It is supposed to operate with speeds varying between +30% slip (1260RPM) and -30% slip (2340RPM).

The power converter is constituted of two three-phase converters from Semikron connected in the so called back-to-back configuration, as depicted in Figure 1(b) and 2. The rotor side converter (RSC) has three IGBT’s modules (arms) of 1200V, 63A (SK60GB128). In the grid side converter (GSC) the modules are 1200V, 35A (SK30GB128). The converter also includes a chopper (SK30GAL123) for the DC-link overvoltage protection. The IGBT’s are commanded through dual IGBT drivers (SKHI20opA).

The wind turbine is mechanically coupled to the generator through a gearbox in real WECS. Since the objective of the test bench is the studies related to the electrical part, the wind turbine is replaced by a simulator. The turbine simulator has the advantage of testing the generator under different operation (power) conditions independent of meteorological conditions (wind speed).

The turbine is emulated using a 37kW squirrel cage induction motor manufactured by Voges which is controlled by a commercial back-to-back converter ABB 380V/42A. This converter receives an external reference signal to control the machine torque.

The wind turbine torque is calculated through [22]:

\[ T = \frac{1}{2} \rho \lambda^{2} \beta \sqrt{p} C_{p} \left( \lambda \beta \right) \]

where \( \rho \) is the air density (typical value 1.225Kg/m³), \( A \) is the swept area of blades (m²), \( R \) is the rotor blades radius (m), \( V \) is the wind speed (m/s), \( C_{p} \) is the power coefficient, \( \beta \) is the blade angle (degrees) and \( \lambda \) is the tip-speed ratio given by:

\[ \lambda = \frac{\omega R}{V} \]

with \( \omega \) being the turbine angular speed (rad/s). In the literature several models are proposed to calculate the power coefficient \( C_{p} \). One of the most used models is given by [22]:

\[ C_{p} = \left\{ \begin{array}{ll} 0.5 \left( \frac{\lambda}{20} + \sqrt{1 + \left( \frac{\lambda}{20} \right)^2} \right) & \text{for } \lambda \leq 12 \smallskip \lambda = \frac{\omega R}{V} \end{array} \right. \]

with \( \lambda \leq 12 \) and \( \lambda > 12 \).

Since the rotor voltage is much smaller than the grid voltage, the RSC has the higher current capability. Due to the high difference between grid and rotor voltage, in order to reduce the DC-link voltage (used=450V), improving the modulation index on the rotor side, it is used a 380/220V transformer for the connection of the GSC to the grid.

On the other hand, the grid voltage reduction diminishes the maximum converter power. In fact the maximum active power (unity power factor) flowing through the converter is approximately 8kW (\( \sqrt{3} \times 220V \times 25A \)), since 25A is the IGBT rated RMS current with 80°C. Therefore, in this configuration operating the generator with the maximum slip of -30% the test bench can handle only 26.5kW (8kW/0.3). For safety reasons the rated power of the prototype was set to 25kW for now.

B. Turbine Simulator

The wind turbine is mechanically coupled to the generator through a gearbox in real WECS. Since the objective of the test bench is the studies related to the electrical part, the wind turbine is replaced by a simulator. The turbine simulator has the advantage of testing the generator under different operation (power) conditions independent of meteorological conditions (wind speed).

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\[ \lambda = \frac{1200 \sqrt{3}}{V} \]

with \( \lambda \) being the turbine angular speed (rad/s). In the literature several models are proposed to calculate the power coefficient \( C_{p} \). One of the most used models is given by [22]:

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with \( \lambda \leq 12 \) and \( \lambda > 12 \).

Since the rotor voltage is much smaller than the grid voltage, the RSC has the higher current capability. Due to the high difference between grid and rotor voltage, in order to reduce the DC-link voltage (used=450V), improving the modulation index on the rotor side, it is used a 380/220V transformer for the connection of the GSC to the grid.
\[ C_p(\lambda, \beta) = 0.22 \left( \frac{116}{\lambda} - 0.4\beta - 5 \right) e^{\frac{12.5}{\lambda}}, \] (3)

where:
\[ \lambda = \left( \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right)^{-1}. \] (4)

With the restriction of power being 25kW and choosing a typical wind speed range for a turbine with such power (4-10m/s), the blades radius is calculated based on Eq. (1). Furthermore, it is necessary to emulate a gearbox and chose the gear ratio based on the maximum generator speed (2340RPM). Table II shows the turbine parameters and Fig.3 depicts the power characteristics for different wind speeds with fixed blade angle \( \beta = 0^\circ \).

### Table II – Turbine Parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius (R)</td>
<td>5.45 m</td>
</tr>
<tr>
<td>Rated Wind Speed (V(_{\text{nom}}))</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Cut-in Wind Speed (V(_{\text{cutin}}))</td>
<td>4 m/s</td>
</tr>
<tr>
<td>Gear Ratio</td>
<td>21.12</td>
</tr>
<tr>
<td>Rated Power</td>
<td>25 kW</td>
</tr>
<tr>
<td>Rated Speed (high speed side)</td>
<td>2340 RPM</td>
</tr>
</tbody>
</table>

![Fig. 3. Emulated turbine power for different wind speeds and \( \beta = 0^\circ \)](image)

The pitch control (\( \beta \)) is not represented in the turbine simulator, because, as mentioned, the electrical part is of main interest. Other effect not represented is the shaft torsional oscillations.

Eq. (1)-(4) are implemented in a dSpace 1103 platform, described in Section II.E, where the torque reference for the turbine simulator is calculated using a wind speed (V) profile set by the user.

### C. LCL Filter

The LCL filter function is to reduce the harmonics produced by the switching of the converters, being of great importance for the overall system performance. This filter is designed to ensure the harmonic level within the range recommended by the standard [23].

The procedure for the choice of the parameters uses the converter power (\( P_c \)), the rated peak secondary transformer voltage (\( e_{r1} \)), the grid frequency (\( f_g \)) and the switching frequency (\( f_s \)).

The filter inductor is calculated as a function of the maximum current ripple and can be obtained as [24]:

\[ L_1 = \frac{e_{r1}}{2\sqrt{f_g f_s}}, \] (5)

The inductor value at the converter side (\( L_r \)) is related to the transformer inductance (\( L_1 \)) by the parameter \( r \) as seen in (6).

The value of the capacitor is limited by the allowed reduction of the power factor through the parameter \( \alpha \) \( (\alpha = 5\%) \) as shown in (7) [24].

\[ L_r = rL_1 \] (6)

\[ C_r = \frac{0.08 L_1}{2n_f f_s^{0.5}} \] (7)

The \( r \) value is calculated by (8), where \( \alpha = L_1 L_r \omega_0 \). This equation represents the current attenuation as a function of the calculated parameters:

\[ L_1 \] (9)

Usually, the attenuation value is chosen to be 20\%, in order to achieve good practical results [24]. The resonant frequency of the filter, \( f_{\text{res}} \), must be in an interval which is not affected by the grid frequency nor the switching frequency. Normally, it is between ten times the grid frequency and 50\% of the switching frequency \( (10f_g < f_{\text{res}} < 1/2f_s) \). The resonant frequency is calculated by [24]:

\[ f_{\text{res}} = \frac{L_1 + L_r}{L_1 L_r C_r} \] (9)

The value of the damping resistor \( R_d \) is initially defined as twice the value of the capacitor’s impedance at the resonant frequency [24]. The higher \( R_d \), the higher the filter damping and the gain at the resonant frequency is reduced. The best value for the resistor is chosen by considering the filter dynamics, the resonance and the generated losses [25].

Considering the equations above and performing some simulations, the values of the designed LCL filter are presented in Table III.

### Table III – LCL Filter Components Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor ( L_1 )</td>
<td>2mH</td>
</tr>
<tr>
<td>Capacitor ( C_r )</td>
<td>20\mu F</td>
</tr>
<tr>
<td>Resistor ( R_d )</td>
<td>3\Omega</td>
</tr>
</tbody>
</table>

For the inductors construction, iron powder cores with distributed air gap were used. It was chosen the E-type core from Micrometals, model E610-29. Details about the calculation of the necessary turns can be found in [26].

### D. Voltage Sag Generator

For the experimental tests it is necessary the emulation of voltage sags in the test bench. Two equipments were used for
For the symmetrical voltage sag tests, the ISG recommended in the standard IEC61400-21 [27] is used, which is depicted in Fig. 4. When the switch "S" is closed the currents flowing through \( Z_2 \) cause a voltage drop in \( Z_1 \) which represents a voltage sag in the terminals of the system "WT", calculated as:

\[
sag(\%) = \frac{Z_2}{Z_1 + Z_2} \times 100\%.
\]

Several combinations of \( Z_1 \) and \( Z_2 \) are possible. Due to restrictions in the size of the inductors two 1.2mH and one 0.3mH inductors were constructed, permitting the test of different levels of voltage sags. These inductors also present a medium tap which divides by two the total impedance. Since the impedance is low, the reactors are supposed to operate with currents around 1000A without saturation.

![Impedance sag generator](image)

The IPC is a commercial equipment, used of asymmetrical voltages sags test, following the IEC6100 standard [28]. It can control the sag level, duration and start time, allowing a wide variety of tests.

### E. Measurement System and Control Platform

The control strategies, described in the next section, the signal command logics, the turbine simulator algorithm and the software protections are implemented in a dSpace 1103 controller board. This platform is designed to meet the requirements of modern rapid control prototyping and it is used worldwide in the main university and industry research centers. Its main features includes an 1GHz processor, 50 bit-I/O channels, 36 A/D channels, 8 D/A channels, a slave DSP, 10 PWM outputs, etc.

The dSpace platform was employed in the test bench for two main reasons: the processing and memory capacity which permit the implementation of complex control strategies (next step in the development) and its Real-Time Interface in conjunction with the software ControlDesk permits the recording of several variables with a high sampling rate.

These features meet the requirements for the voltage sags studies intended with the test rig. Furthermore, the programming is simple and can be performed using the Matlab/Simulink or the C language. Latter programming technique was used.

For the control of the generator is necessary to measure the rotor (RSC) currents, the stator currents and the GSC currents, as illustrated in Fig.2. Furthermore, the DC-link voltage, rotor voltage and the low voltage side of the transformer (GSC voltage) are also measured. For this purpose it is used the current LEM LA-55P/SP1 and voltage LEM LV-25P transducers. These are Hall Effect sensors and are employed due to its good linearity, high bandwidth and great accuracy.

The output of the transducers (measurement signal) is a 0/25mA current signal. In order to minimize electromagnetic interferences (EMI) the transducers are localized close to the measured signals and the measurement signals are transmitted in current until the conditioning board (Fig.2).

The signal conditioning board is responsible for the conversion of the measurement for an adequate voltage level (±10V). This voltage was chosen in accordance with the input level of the A/D converter of the dSpace platform. Before the A/D conversion, there is a filtering stage to prevent aliasing. This anti-aliasing filter has 3 kHz of cut-off frequency, since the sampling rate was set to 6 kHz, and it is implemented via an Universal Active Filter (UAF42 chip). This chip is largely used in active filter implementation, due to the good precision of its internals capacitances, and so its smalls deviations of the designed filter’s cut-off frequency. Furthermore, the Besel topology was chosen because of its linear phase response and so its excellent pulse response with minimal overshoot. For circuit safety, the filters outputs are limited to -10/+10V using Zener diodes and the signals supply the A/D converter of the dSpace. Fig. 5 depicts the measurement signals transmission.

The control algorithm runs with the same rate of the signal sampling (6kHz), generating the voltage reference signals for the converters. The dSpace has a PWM dedicated module which calculates the outputs based on the voltage reference signals. These outputs are 0/5V digital signals that must be converted to 0/15V digital signal in accordance to the gate-drive circuit input. This conversion is made by the signal conditioning board using n-channel MOSFET (2N7002), due to its very fast switching, and so minimal delay of reference signal.

Fig. 6 shows some pictures of the test bench emphasizing the main components.

![Signal Conditioning Board](image)

### III. DFIG CLASSICAL CONTROL STRATEGY

For the first voltage sag tests it was implemented the classical DFIG control, depicted in Fig. 7 which shows the block diagram of the control structure for the two converters:

- Grid side converter (GSC): internal loops controlling the currents flowing through the filter using the grid voltage...
angle orientation and external loops controlling the dc-link voltage and the reactive power;

- Rotor side converter (RSC): internal loops controlling the rotor currents using the stator voltage angle orientation and external loops controlling the active and the reactive stator power.

In order to estimate the grid voltage angle for the control orientation, it used the PLL proposed by [29]. This PLL is based on a “Dual Second Order Generalized Integrator” (PSOGI) which decomposes the positive and negative sequence components of the voltage. Therefore, this PLL is robust for unbalanced voltage conditions as expected.

For the control adjustment it was used the techniques of "Modulus Optimum" and "Symmetrical Optimum" [30]. More details about the system modeling and the tuning process can be found in [31].

It is important to mention that the classical control strategy was first tested, because it is more employed in commercial equipments. Just this strategy, as highlighted hereafter, cannot guarantee the LVRT capability. For this purpose, commercial equipments also use the so called crowbar device. Improvements of the classical strategy will be the future works with the test bench presented in this paper.

IV. EXPERIMENTAL RESULTS

This section presents some experimental results of the test bench. The objective here is to show the operation and the voltage sag tests. The complete explanation of the results is not addressed in this work.

For the first test it was considered a 50% three-phase voltage performed with the ISG, as depicted in Fig. 8. The generator was operating at synchronous speed (1800RPM) generating 10kW.

Fig. 9 shows the rotor current phase A. This is the main variable to be analyzed during the voltage sag, because it reaches high values that can trip or even damage the RSC. In the Fig. 9 one can notice that the first peak current is almost the converter rated current. The rotor currents oscillate with the grid frequency (60Hz) due to the flux natural response, fact explained in [5] and [8].

![Fig. 6. Test bench pictures](image)

Another important variable to be analyzed is the DC-link voltage. One can see in Fig. 10 that during the sag this voltage increases, so it is necessary the use of the discharge chopper for safety operation of the test rig during the tests.

For the unbalanced test it was considered a 65% phase-to-phase voltage sag (Fig. 11) with the generator operating at 2070RPM. Fig. 12 depicts the rotor currents, showing the high peak values compared with the peaks before the sag. These high values can be explained by the flux natural response and also by negative sequence component [6]. Fig. 13 shows the dq rotor currents used by the control. One can see that just the mean values of the currents are controlled.

Through these results it is possible to see that dSpace platform permits the record of several variables, fact extremely important for the posterior analysis of the data.

V. CONCLUSIONS

In this work the design and selection of the main components of as 25kW WECS test bench were described. This prototype was built for voltage sag tests presenting the
DFIG technology, since this type of generator is very susceptible to this kind of disturbances. The first experimental results were shown in order to show the system operation and point out the main variables of interest. The next step in the studies will be the analysis of the results and the development of new strategies to improve the system ride-through fault capability. Therefore, the future works intend to contribute for the integration of wind turbines to the grid, attending the modern grid codes.

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