Low scale grid emulator test bench for in-house validation of high power converters oriented to offshore

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Abstract. This paper presents a low scale test bench to generate grid faults and disturbed grid voltage conditions to test grid connected converters. The test bench is applied to improve design aspects and control code developments for offshore wind converters. By using a low scale replica of the original offshore converter, with same control code and control electronic elements (Converter Control Unit) of the original one, new control code developments and design aspects are easier to test and integrate. For that purpose, the whole system (test bench and the equipment under test) is modelled and transferred to a simulation environment. Thus, with the procedure of simulation, test and prove, the new Ingecon wind MV100 family has been adapted to offshore applications. Case examples of the performed control developments and results are also shown.

1. Introduction

Power grid emulators have been spreading in recent years in order to test distributed renewable generation systems [1]. Voltage source based power grids can emulate extreme grid disturbances as voltage faults and recreate any operating point of the grid. These characteristics make grid emulators an excellent way to validate the capability of any equipment upon specific grid operator requirements.

Offshore wind turbines are bigger than onshore and are connected to inter-turbine grids several kilometers away from shore. The definition of these grids can vary significantly from one location to another and their definition is not as clear as in onshore. Thus, new design and control challenges arise in offshore environments, which push further wind turbine technology: New control techniques, new designs and new operational modes.

Offshore environment is not friendly for onsite tests, so those new solutions have to be well tested before their implementation in real wind turbines. For that purpose a grid emulator can play a key role. Furthermore, to develop those designs and control code challenges, a testing procedure using a grid emulator can help to ensure both, the correct integration of the improvements in the wind turbine and the wind turbine in the grid. That's why more specialized and sophisticated power labs are being developed oriented to test offshore wind turbines [2] [3].

As they are more specialized and have bigger rated power, those labs are more expensive. In this context, to face a long design process with big design challenges, a low scale test bench is proposed. To perform fault tests with a grid emulator, at least 50% more rated power than the equipment under test (EuT) is convenient. Considering a product family up to 10 MW (see table 1), the proposed test bench is scaled to 300kVA in order to optimize the cost and operability of the system.

Table 1. Output power range of MV100 product family.

	GRID				MACHINE
Rated Power Overload	Target WT power [kW] simultaneity 0,9/0,9	Target WT power [kW] simultaneity 0,9/0,95	Target WT power [kW] simultaneity 0,95/0,95	Target WT power [kW] Vn@PF=1	Target WT Power [kW] Vn@PF=0,95
INGECON WIND MV100 5600	9100	9600	10100	11200	11400
	10000	10600	11200	12400	12500
INGECON WIND MV100 4600	7500	7900	8300	9200	9300
	8300	8700	9200	10200	10300
INGECON WIND MV100 3400	5500	5800	6100	6800	6800
	6200	6500	6900	7600	7600

If the low scale grid emulator test bench is located in an in-house power laboratory and the whole system (test bed and the equipment under test) has been modelled and transferred to a simulation environment. Then, the product developing process is quite shorter and it is performed with more guarantees. Furthermore, if after the commissioning of the wind turbine any unexpected issue is reported, the grid emulator can be used to recreate the event in a controlled environment in order to improve the wind turbines performance.

2. Characteristics of the test bench

The proposed test bench has 3 main parts: Grid emulator to replicate easily grid conditions, a simple turbine environment (Drive-generator + Simple Wind Turbine Control) and low voltage / power MV100 replica. In this section the structure and characteristics of the first two are described. The third part is related to the equipment under test, so it is explained in the next section. The main scheme of the test bench is shown in figure 1.

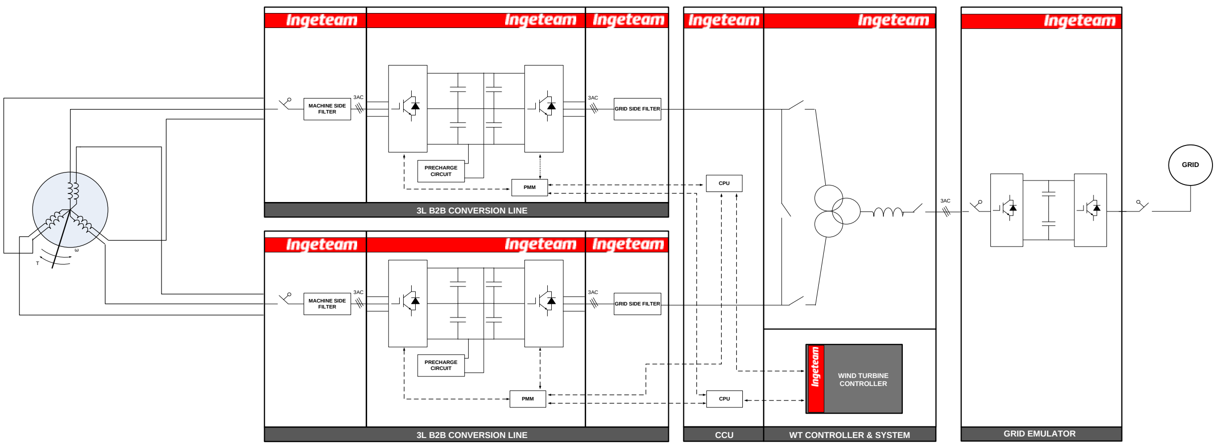


Figure 1. Low scale test bench scheme.

2.1. *Grid Emulator*

The power system of the grid emulator is composed by two three level N.P.C ('Neutral Point Clamped') converters based on IGBTs. These two converters used as a voltage amplifier, are comprised with a front-end rectifier and a back-end inverter. Therefore, the EuT (Equipment under Test) side converter generates a predefined voltage and frequency profile, while the GSC (Grid side converter) only has the task to keep the DC bus voltage within acceptable levels. As it is a three level N.P.C converter, a control technique in order to keep in balance the bus capacitors is also implemented.

As the reference voltages to the EuT side converter are generated according to the user specifications, to behave in a very specific way. The current control loops of the converter are bypassed and only the maximum current is limited with protection purposes. The characteristics of the grid emulator are listed in table 2.

Table 2. Characteristics of the grid emulator.

Rated Power	735 kW
Max Current	650 A
Output voltage	690 V
DC bus voltage	1100 - 1500 Vdc
Modulation	PWM 5 kHz
Cooling	water

2.2. *Drives-generators and additional elements*

Besides a grid emulator, a generator to generate active power is needed to reproduce any operational point of the offshore wind turbine. For that purpose, several generator options are available (see figure 2 b): A SCIG (squirrel cage generator), a synchronous generator and a multi-phase PMG (permanent magnet generator). From those generators available, only the multi-phase PMG has been used in the product development process. As a generator needs torque to generate power, each generator has its own drive.

To recreate in a more accurate way the wind turbine connection to the grid, the test bench is equipped with a transformer and a main contactor (see figure 2 a). This allows testing transformer energization, redundancy and many operational modes. Related to this, a simple wind turbine level Control (WTC) system is also implemented in order to test dynamic operations.

Additionally, an inductor with several taps is also available to configure the grid impedance. This way it is possible to configure short circuit power and adjust it to the desired ratio (see figure 2 c).

(a) *(b)* *(c)*

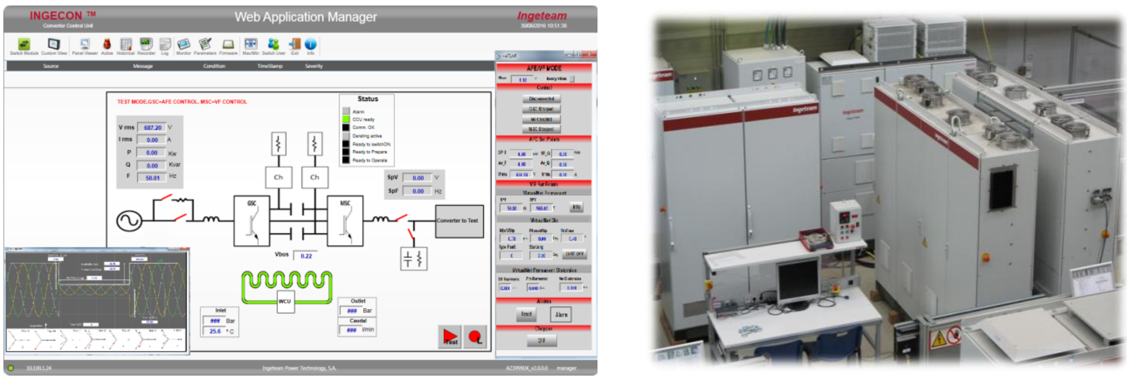
Figure 2. *(a)* Main transformer and contactor. *(b)* Drives and generator and *(c)* configurable grid inductor.

Table 3. Drive-generators and emulated grid characteristics.

Transformer connection possibilities	YΔ, ΔY and YY
Available generators	Synchronous, SCIG and PMG
Grid impedance possibilities (μH)	100,150,250,300,400,450,550

2.3. Operational Characteristics

The interface between the grid emulator and the user is performed through a web client (see figure 3 a). The web client is linked to the PLC which will be the responsible to command the DSP by sending the voltage references. Voltage references are generated according to user's specifications. So, basically the PLC is responsible for collecting and processing the data introduced by the user and for feeding the DSP with the correct voltage references, in order to create the grid conditions specified by the user.



(a) *(b)*

Figure 3. *(a)* Overview of the web client to command the grid emulator and *(b)* overview of the low scale test bench.

In short, in this platform is possible to test equipments under the following grid conditions:

- Symmetric and asymmetric voltage dips.
- Voltage dips with specific start phase-angle and phase-angle jumps
- Grids with high negative sequence component in steady state.
- Frequency deviations.
- Grids with high harmonic components.
- HVRT up to 1.5 per unit.
- Flicker.

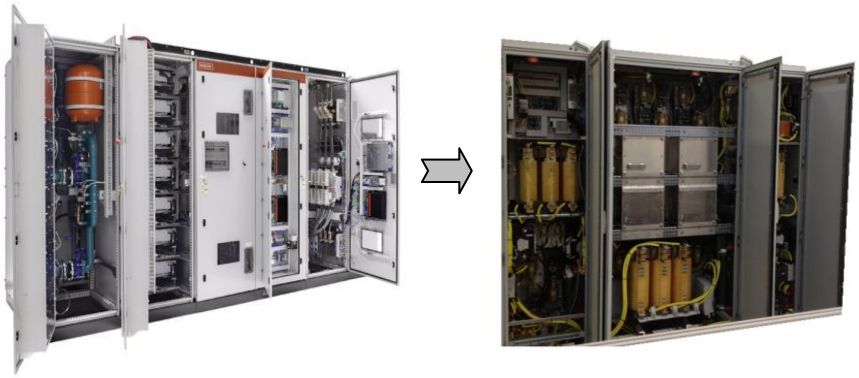
In order to test transient characteristics properly, the converter control is capable of applying the disturbance specified by the user in the instant of the wave specified by the user. For example, a one-phase voltage dip can be generated when the sinusoidal voltage is crossing zero or when it is in its maximum value.

3. Characteristics of the power converter under test

A down-scaled replica of the MV100 is used as EuT in the test bench. This replica is composed of two 3L-150kVA converter lines with an output voltage of 690V. The converter is based on IGBTs and it has natural convection cooling. Both converter lines have been equipped with redundant control logic to improve availability.

The main purpose is to test a system as close to the real one as possible. For this purpose, the control hardware and the control code in the real equipment and the scaled one are the same, with the same control logics, auxiliary equipment and input/output signals.

As regards the power circuit, the components of the main power circuit are scaled maintaining the same per unit value. To make the EuT more flexible, the inductors of the system have several connection points to configure different inductivity values. This allows configuring the power circuit of the EuT to represent the whole range of converter product family (5 – 10MW).



(a) (b)

Figure 4. *(a)* Overview of the MV100 cabinet and *(b)* overview of the low scale replica.

4. Validation process

As important as developing new software capabilities is integrating them into the control code. A new code development can have interactions with other code parts or previous developments. Thus, correct integration of them is a key issue. Furthermore, the control code is in constant evolution since, it has to be adapted to: new environments, new requirements, new regulations, new products, new hardware, etc. To validate new firmware versions or new software package versions a grid emulator and a scaled version of the power converter is an ideal environment that allows testing those before the implementation in real systems.

The grid emulator test bench is located in-house, close to the code developers and the whole system (test bench and the equipment under test) have been modeled and is available in a simulation environment. Thus, the code developer only has to manage / keep updated one code for three different scenarios: Electromagnetic simulation (Matlab, PSCAD…), test bench and the real equipment (see figure 5). Each one of the scenarios has its purposes, its advantages and drawbacks.

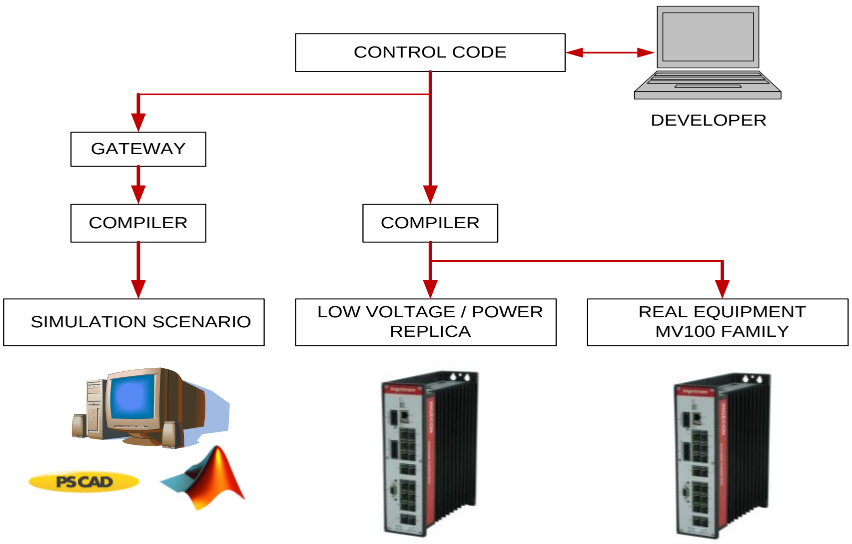


Figure 5. Main scheme of the simulation, test and prove process.

The simulation analyses are oriented to evaluate electromagnetic transients. Thus, the real control codes of the fastest devices are implemented in the simulation scenario: FPGA and DSP level code. The PLC has more slow dynamics compared to the previous ones, so, a simplified version of the PLC is used in the simulation scenario. This does not affects to the simulation accuracy, because simulation run time is often smaller than 20 s.

Once the control code has been upgraded, debugged and tested in a simulation environment, the second stage of the validation process starts. The same code is compiled (using another compiler) and uploaded to the CCU (Converter Control Unit) of the low scale replica in the test bench. This time, with the real PLC code, real measurement devices, communications, real internal clock for digital devices, background code, memory mapping, etc.

In this stage, to verify the correct integration of the new firmware, a generic validation plan (or sequence) or specific validation plan can be used. So depending on the area and impact of the code modification the most suitable validation plan is chosen. A generic validation plan includes tests for almost every requirement in the grid codes, but it is not tested in depth. That's why the generic validation plan has been used only for small code changes, since it is easier to test and it can be even a pre-programmed sequence. On the contrary specific validation plan (or sequence) is focused in a specific aspect. For specific validation, as much tests as possible are performed and the code is better tested. Of course, here comes the dichotomy between fast validation (fewer tests) and more reliable validation. The answer of the dichotomy is always a subjective choice.

Once the control code (or a design modification) has been validated by using a simulation tool and the low scale test bench, the third and last stage of the validation comes. In this stage, the validation is performed in a high power testing laboratory with the real equipment. For this last stage, thanks to a more reliable and previously tested code. The time needed is quite shorter and the probabilities to have no adequate results, which may require design changes, are reduced.

5. Case examples

Ingeteam has used this test bench to adapt the new MV100 product family to offshore environment. In the development of this product family many parts of the control code and design aspects have been developed. The final configuration and capabilities of the product are specific for each client and developed according to their requirements, but Ingeteam has developed new solutions to be ready for the upcoming challenges.

For example, as a major control code change which affects to the whole control strategy: New FOM (Filter Oriented Modulation) has been developed for this new product family. Offshore applications, often MV, require high output power. So, modulation techniques are a key issue as less commutation frequency allows bigger output power.

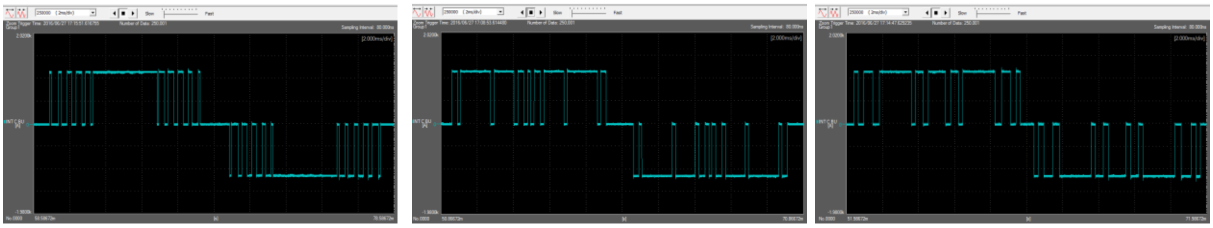
Another code part that has been developed is the upgrade of the control code related to LVRT (Low Voltage Ride Through) operation. This modification has been tested due to regulation changes. Any change related to LVRT has to be well tested as it is the most or one of the most difficult aspects of the grid codes to meet [4]. Besides those examples, many more developments have been made as: Transformer energization, redundancy, evaluation of the parallelization of 2 converter lines, generator control optimization…

5.1. New Filter Oriented Modulation

As it was mentioned before, to obtain more output power, one of the fields to improve technologically is modulation. By reducing the commutation frequency, more power can go through the converter, at least considering the same hardware.

Increasing commutation frequency, usually better THDs (Total Harmonic Distortion) are obtained and faster control responses. Nevertheless, considering the output filter and characteristics of the application, the modulation can be improved or optimized. This way, it is possible to obtain better output current THDs even reducing the commutation frequency.

The new FOM is a modulation that considering the filter characteristics and operational characteristics, gives the best performance. To develop tools and to tune modulation technique criteria, the scaled test bench had been used. The down-scaled test bench has several filter options (many different capacitors) and configurable inductor values. So it provides configurability and flexibility to perform several tests and evaluate different modulation-filter configurations as a whole. Even to evaluate how they behave upon voltage faults, asymmetric grid voltages, grids with high harmonic content, etc. The following figure shows as an example, 3 different modulations tested in the test bench, each one with a different filter configuration.



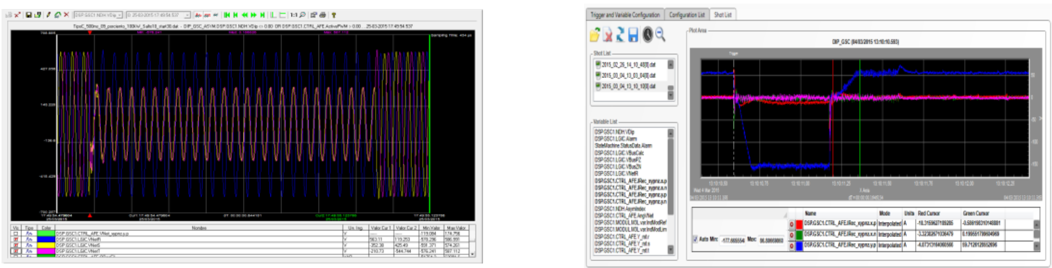
(a) *(b)* *(c)*

Figure 6. Several modulations tested by using low scale test bench. *(a)* 1100 Hz commutation frequency *(b)* 900 Hz commutation frequency and *(c)* 900 Hz commutation frequency.

5.2. LVRT control code upgrade

Grid codes are changing continuously in the same way the LVRT requirements do [5]. One of the latest changes is related to how the negative sequence current have to be managed during asymmetric grid faults. This requirement is included in some grid codes such as VDE AR-N 4120 [6]. So in order to fulfill those new requirements the control code has to evolve.

To test and validate the fulfillment of those new requirements and implement the changes to the MV100 product family, the test bench presented in this paper had been used. With the test bench, it is possible to generate in a controlled way and with repeatability any type of voltage fault, with the desires start phase-angle or phase-angle jump. Thus, new control techniques can be tested fast and with a lot of flexibility. When the time for real equipment certification comes, the process can be easier, as it is validated already in a down-scaled version. In figure 7 a voltage dip generated with the grid emulator is shown and magnitudes of the injected currents to the grid (in sequences).



(a) *(b)*

Figure 7. Some results obtained with the low scale test bench. *(a)* Voltages at grid emulator terminals during a fault and *(b)* measured currents in sequences.

6. Conclusion

The designs and control developments validated using the test bench had been compared / confronted with the results of the real equipment. Results obtained in a power laboratory with enough rated power. At the power laboratory of Indar (an Ingeteam brand) located in Beasain (Spain). This power laboratory can test equipments up to 12 MW, so, it is suitable to test MV100 product family. The performed tests have shown successful results and the time required to test the real equipment was quite shorter than previous occasions.

Defining a protocol which includes the most exigent scenarios and tests, every aspect of the wind turbine control can be verified in a short period of time, new control features can be easily, fast and without additional cost tested in house, making sure that the new features have a good integration in the control code

Another beneficial effect of developing this test bench, where the whole system has been transferred to a simulation scenario, is the improvement of the simulation models. By comparing the results of the test bench with the results in the simulated scenario, more accurate and validated simulation models of the converter can be achieved. These models can be used by the wind turbine manufacturer to optimize the wind turbine and its transmission system.

Finally, as an additional advantage of developing this test bench, it can be highlighted its capacity to provide an easy way to continue improving the product. If after the commissioning, any unexpected issue is reported, the test bench provides a simple way to reproduce the event in a controlled environment, in order to evaluate the causes and take the required actions to correct the problem.

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