# Firmware development methodology designed to simplify wind turbine converter validation and certification

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As more wind energy is connected to the grid, ensuring the correct electrical performance of the wind turbine is critical, to maximise production and also ensure the safe operation of the grid. The power converter is the active component connecting the turbine to the grid. As the interface between the two, the power converter is designed to function to meet the needs of the generator side and the grid side.

Following power converter installation, unwanted firmware behaviour can have serious consequences, from impact on production, leading to reduced revenues, to non-fulfilment of grid code requirements. It can even lead to damage to other turbine components, resulting in higher operational and maintenance costs.

Ingeteam's robust firmware development methodology has been developed to minimise onsite validation and certification and has several key benefits:

- Enables the ability to track the desired functionality from specification to validation.
- Allows for establishing requirements for various functionalities, including converter protections and emergency sequences, fieldbus communications, dynamic behaviour, power quality (PQ) response, fault ride-through (FRT) and dynamic response.
- Enables determination and defining of the proper validation environment for every stage of the development and functionality of the power converter, allowing for testing of functionality, from individual code debugging to partial code software-in-the-loop (SiL) simulation, to full controller testing in hardware-in-the-loop (HiL) simulation.
- Allows automation of test execution to ensure the validity of a solution upon multiple external conditions, such as grid variations and grid code fulfilment for example.

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Through this methodology process, any issues found during the validation stage are quickly fed back into the development stage to be corrected.

## Validation procedure

The firmware development is based on a procedure where the focus is set on the definition and successful execution of the validation tests. The ultimate goal is to verify and demonstrate that the customer's requirements are fully met.

Therefore, the procedure highly relies on the definition of the tests and on the platforms used during the validation.

The present article focuses on steps 2 and 3, where the iterations for the firmware qualification are performed.

## Test definition and execution

As a test-based validation approach, a critical aspect of the procedure is the correct definition and tracking of the requirements and the test sequences. The replicability of the test plans is essential for an iterative validation of new firmware releases and must be automated as much as possible for this purpose.

The first step involved in the validation procedure involves the definition of the tests forming a test plan, and the programming of the execution of such tests. For that purpose, Ingeteam has developed a web-based test automation tool that manages the execution of the tests.

The first step involves the definition of the test cases, based on a database where the test requirements, project-specific parameters and test acceptance values are indicated. An important part of this step is to define the target system where each test will be executed, being SiL or HiL the available targets.

Once the tests are defined, they are fed into the automation tool, which performs the execution of the tests. Based on the target defined in the previous step, the correct system is launched, meaning that the tool launches the SiL model or the HiL system based on the pre-definition for each of the tests. It is important to note that the targeted system must have a dedicated API available for this purpose.

After the test cases are executed, the results are post-processed in order to check that the acceptance values are met for each of the test cases, independently of the targeted system.

All the post-processed information is used to issue an acceptance report, which acknowledges the fulfillment of the performed test cases.

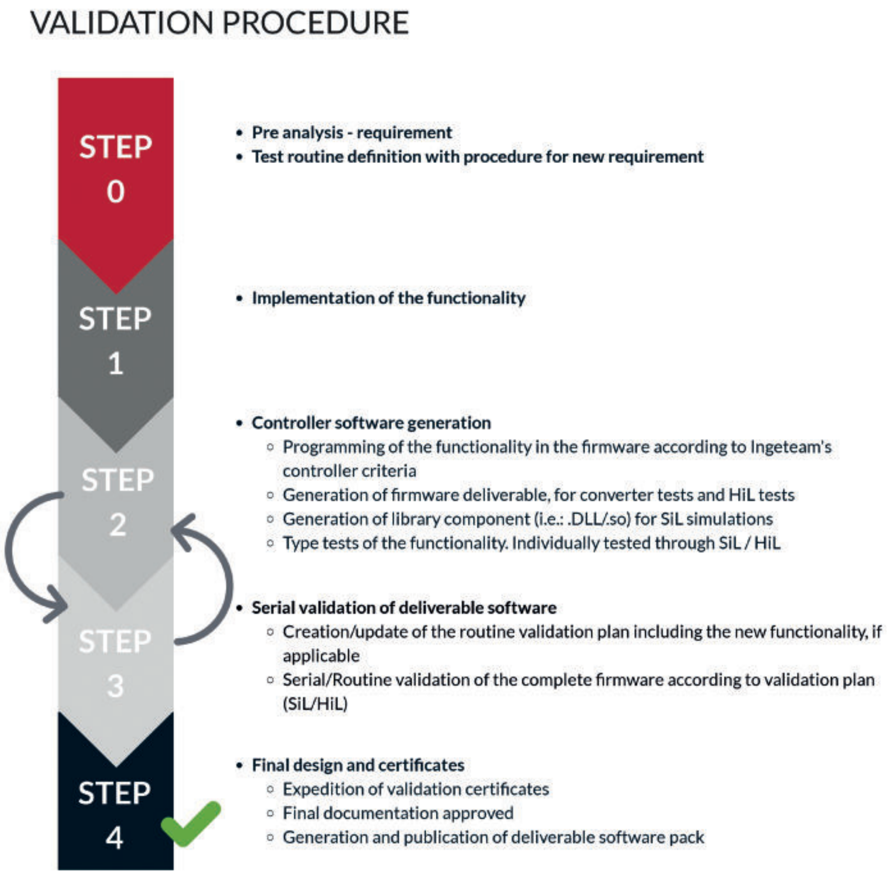


Figure 1. Validation procedure, from request to release

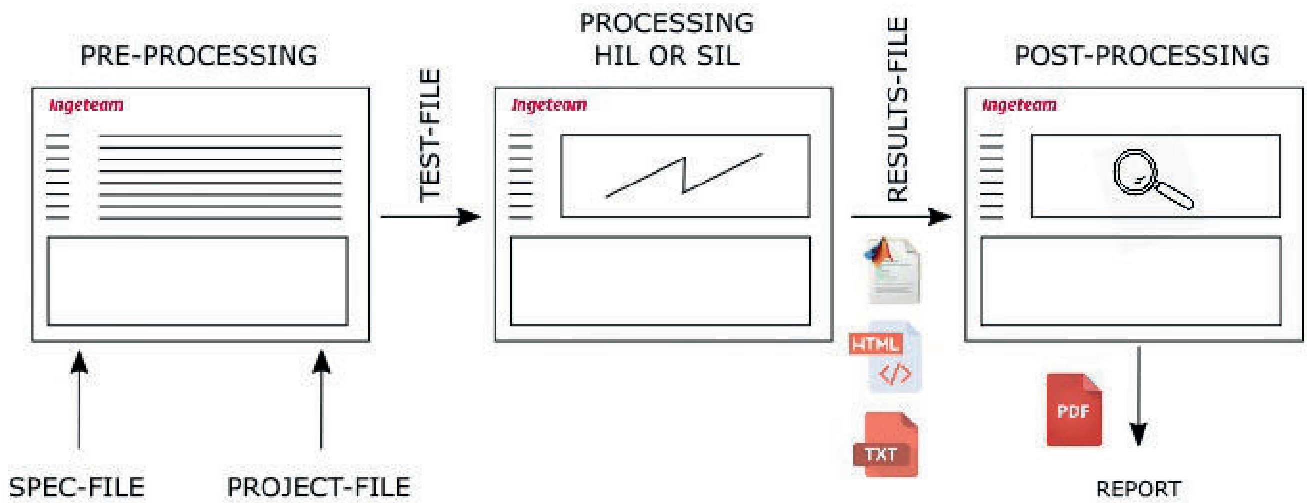


Figure 2. Test Automation Tool steps

| # | CATEGORY | # | REQUIREMENT TO VALIDATE | #SUB | SUB-REQUIREMENT TO VALIDATE | TEST DEFINITION | ACCEPTANCE CIRTERIA | TARGET SYSTEM *(HIL/SIL)* |
|---|---|---|---|---|---|---|---|---|
| 1 | PUNTOS OPERACIÓN (PO) | 1.1 | LA TURBINA HA DE SER CAPAZ DE FUNCIONAR PERMANENTEMENTE EN LOS PUNTOS DE OPERACIÓN INDICADOS | 1.1.1 | SOPORTAR VALORES DISTINTOS A LOS NOMINALES EN TENSIÓN, FRECUENCIA, POTENCIA Y VELOCIDAD | Velocidad (p.u.), potencia (p.u.), tensión (p.u.), frecuencia (p.u.) | LA TURBINA PERMANECE EN SU PUNTO NOMINAL SIN DAR ALARMA Y SIN CAMBIAR SUS POTENCIAS ACTIVA Y REACTIVA | HIL/SIL |
| 1 | PUNTOS OPERACIÓN (PO) | 1.1 | LA TURBINA HA DE SER CAPAZ DE FUNCIONAR PERMANENTEMENTE EN LOS PUNTOS DE OPERACIÓN | 1.1.2 | PUNTOS DE OPERACIÓN INCLUYENDO POTENCIA, VELOCIDAD, REACTIVA DE ESTÁTOR, REACTIVA DE ROTOR, TENSIÓN | Potencia (p.u.), velocidad (p.u.), reactiva estátor (p.u.), reactiva rotor (p.u.), tensión (p.u.) | EL EQUIPO ES CAPAZ DE ALCANZAR LOS SETPOINTS DE POTENCIAS REQUERIDOS DE FORMA PERMANENTE. | HIL/SIL |
| 2 | FRT | 2.1 | LA TURBINA DEBE SOPORTAR LA SUB SIN DESCONECTARSE | 2.1.1 | - | Tensión (p.u.), duración sub/sobretensión (s), potencia (p.u.), fase | LA TURBINA SOPORTA LA SUB SIN DAR ALARMA, ADEMÁS PRESTAR ATENCIÓN A LOS TRANSITORIOS DE CORRIENTE Y TENSIÓN ALCANZADOS EN GENERADOR, CONVERTIDOR Y TRANSFORMADOR Y GOLPES DE PAR EN EL TRAN MECÁNICO | HIL/SIL |
| 2 | FRT | 2.1 | LA TURBINA DEBE SOPORTAR LA SOBRETENSIÓN SIN DESCONECTARSE | 2.1.2 | - | Tensión (p.u.), duración sub/sobretensión (s), potencia (p.u.), fase | LA TURBINA SOPORTA LA SOBRETENSIÓN SIN DAR ALARMA, ADEMÁS PRESTAR ATENCIÓN A LOS TRANSITORIOS DE CORRIENTE Y TENSIÓN ALCANZADOS EN GENERADOR, CONVERTIDOR Y TRANSFORMADOR Y GOLPES DE PAR EN EL TRAN MECÁNICO | HIL/SIL |
| 3 | CALIDAD RED (CRED) | 3.1 | POWER QUALITY | 3.1.1 | ARMÓNICOS SEGÚN IEC61000-2 y 61800-3 | Potencia (p.u.), límite THC (%) | EL THC CALCULADO DEBE ESTAR POR DEBAJO DEL LÍMITE | HIL/SIL |
| 3 | CALIDAD RED (CRED) | 3.1 | POWER QUALITY | 3.2.1 | ARMÓNICOS IEEE | Potencia (p.u.), límite THC (%) | EL THD DE CORRIENTE Y TENSIÓN CALCULADO DEBE ESTAR POR DEBAJO DEL LÍMITE | HIL/SIL |
| 4 | CURRENT LIMITS (CURRLIM) | 4.1 | DAR POTENCIA EXTRA DURANTE CIERTO TIEMPO | 4.1.1 | - | Potencia extra (kW), tiempo de sobrepotencia (s) | SE TIENE QUE PODER DAR LA POTENCIA EXTRA DURANTE EL TIEMPO ESPECIFICADO | HIL/SIL |
| 5 | SOPORTAR PERTURBACIONES (PRTB) | 5.1 | LA TURBINA HA DE FUNCIONAR CORRECTAMENTE CON LAS PERTURBACIONES DEFINIDAS | 5.1.1 | SOPORTAR VALORES DISTINTOS A LOS NOMINALES EN TENSIÓN, ASIMETRÍAS Y FRECUENCIA | Variación tensión (p.u.), frecuencia (p.u.) | LA TURBINA PERMANECE EN SU PUNTO NOMINAL SIN DAR ALARMA Y SIN CAMBIAR SUS POTENCIAS ACTIVA Y REACTIVA | HIL/SIL |
| 6 | LÍMITES TÉRMICOS (TERM) | 6.1 | LÍMITES TÉRMICOS | 6.1.1 | - | Temperatura de operación, Temperatura ambiente | SE TIENE QUE COMPLETAR EL ENSAYO SIN ALARMAS Y DANDO LAS POTENCIAS REQUERIDAS | RT |
| 6 | LÍMITES TÉRMICOS (TERM) | 6.2 | LÍMITES TÉRMICOS | 6.2.1 | DERATING EN POTENCIA ACTIVA A ALTAS TEMPERATURAS AMBIENTE | Temperatura ambiente (ºC), temperatura inicio derating (ºC), pendiente derating (kW/ºC) | SE DEBE REALIZAR EL DERATING CON LA PENDIENTE ADECUADA | RT |
| 6 | LÍMITES TÉRMICOS (TERM) | 6.2 | LÍMITES TÉRMICOS | 6.2.2 | DERATING EN POTENCIA ACTIVA A ALTAS TEMPERATURAS COOL | Temperatura ambiente (ºC), temperatura inicio derating (ºC), pendiente derating (kW/ºC) | SE DEBE REALIZAR EL DERATING CON LA PENDIENTE ADECUADA | RT |
| 6 | LÍMITES TÉRMICOS (TERM) | 6.3 | LÍMITES TÉRMICOS | 6.3.1 | DAR ALARMA POR SOBRETEMPERATURA | Temperatura de operación, Temperatura ambiente | SE DEBE DAR ALARMA POR SOBRETEMPERATURA Y REALIZAR UNA PARADA SUAVE | RT |
| 7 | BDEW - Technical Guideline: Generating Plants Connected to the Medium-Voltage | 7.1 | PUNTOS DE OPERACIÓN | 7.1.1 | DIAGRAMA PQV | Tensión (p.u.), Potencia (cos phi) | | HIL/SIL |
| 7 | BDEW | 7.1 | PUNTOS DE OPERACIÓN | 7.1.2 | DIAGRAMA PF | Activa (p.u.), Frecuencia (p.u.) | LA POTENCIA SEBE DISMINUIR ANTE UNA SUBIDA DE FRECUENCIA ENTRE 50.2 Y 51.5 Hz | HIL |

Figure 3. Overview, test categories and target system

## Software-In-The-Loop validation

Ingeteam targets this validation through Software-In-The-Loop (SiL) models for the critical control software components and through Hardware-In-The-Loop (HiL) simulators for full software + hardware (controller) integration testing.

- SiL modelling consists of a detailed representation of the converter, generator, grid and control logics inside an EMT model, where the main control routines are compiled into an executable library (i.e.: .DLL) with the exact same source code that is deployed in the converter.

SiL modelling allows for detailed debugging down to individual breakpoints on the source code, supporting an in-depth testing of DSP's control routines.

SiL validation advantages include:

- Low-level debugging
- Flexible modelling non-dependent on hardware limitations
- Multiple controller instances
- Start from snapshot
- Execution from library component - no need for any hardware equipment (controller)

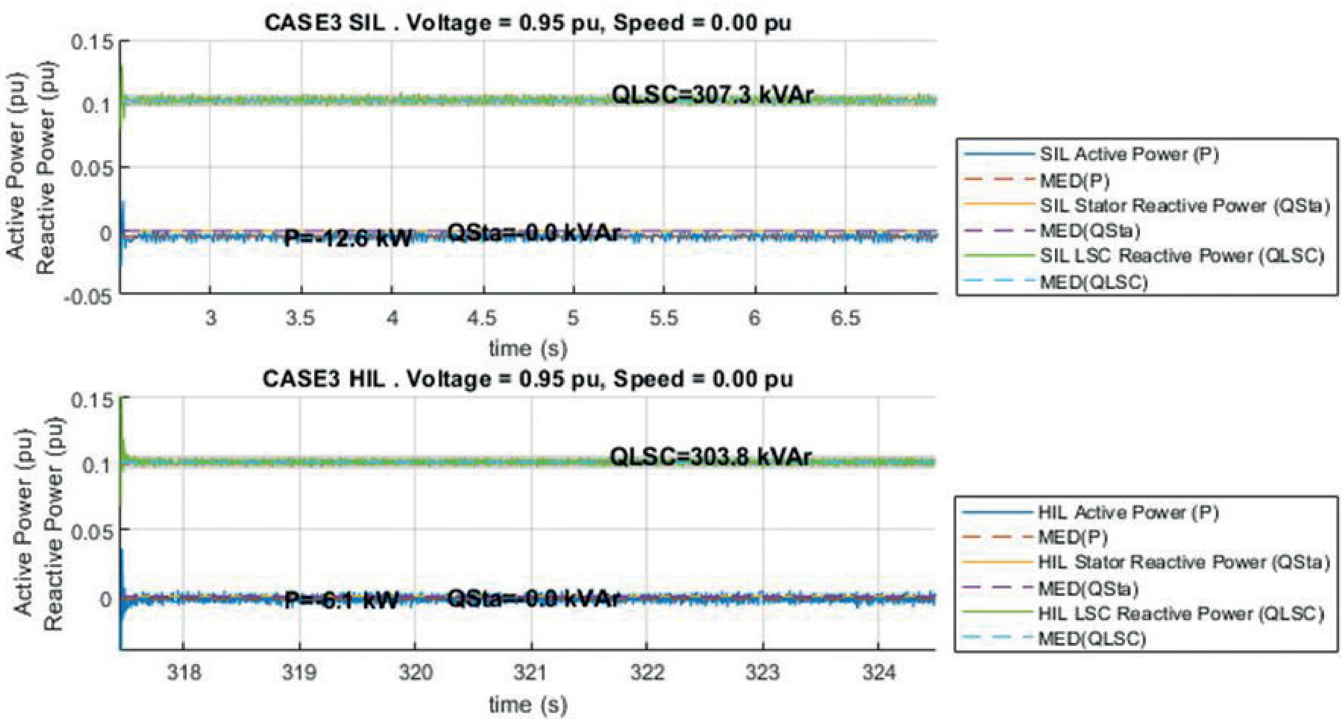


Figure 4. Post-processing of results for the same test case, executed both in HiL and SiL systems

- Direct integration in other platforms or higher-level models (i.e.: wind turbine models, wide-area grid models)

SiL validation limitations are:

- Non-real-time execution, long simulation times required, depending on model complexity
- Partial coverage of original source code. Focused mainly on the validation of the electrical control algorithms and modulations, not all the original firmware layers can be included in the executable library. Hardware abstraction layers, fieldbus communications, HMI and high-level logics, for example, are not part of SiL validation.

An accurate representation of the control dynamics is achieved by the flexibility of the time step selection, which typically ranges from <1μs. to 50μs., in a compromise between execution speed and electro-magnetic transient precision based on test requirements.

For example, in the case of high precision requirements such as harmonic spectrum compatibility, a low time step is required to obtain representative results:

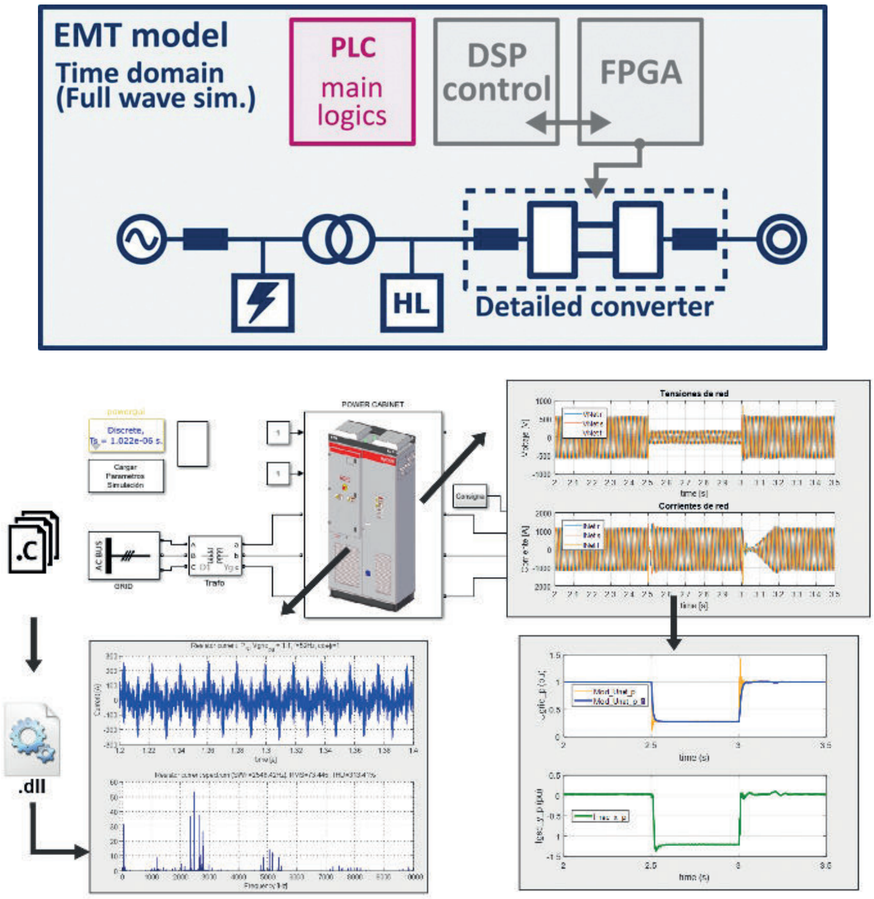


Figure 5. SiL EMT model overview

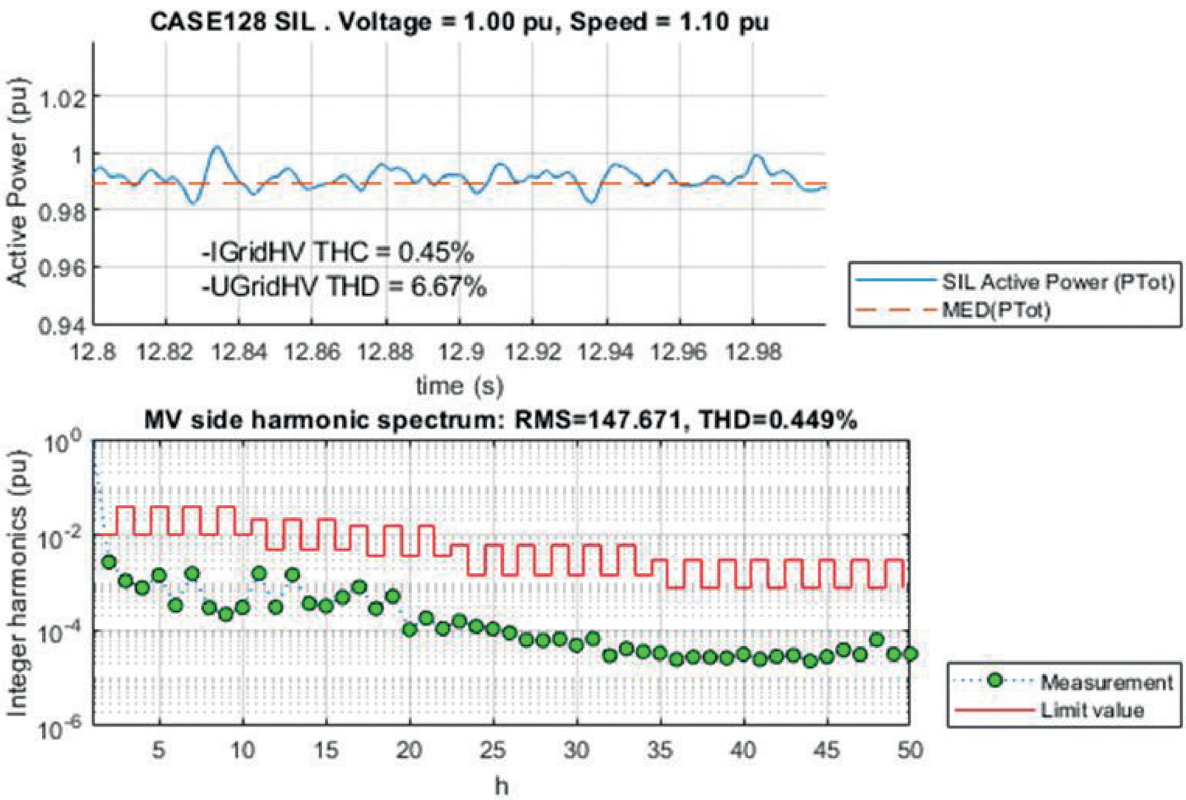


Figure 6. Harmonics compliance SiL test case, based on IEEE requirements

### Hardware-in-The-Loop validation

To overcome the limitations of SiL validation, a Real Time Simulation platform is included in Ingeteam's validation procedure, thus incorporating the real Converter Control Unit (CCU) for a full HiL validation.

The clear advantage of this step is that the firmware tested is exactly the same as the one released to production, running exactly in the same controller that is installed inside the converter.

HiL validation advantages include:

- Full coverage of converter firmware.
- Full coverage of controller's hardware (Digital & Analog I/Os, Fieldbus communications, encoder signals, HMI interfaces, etc.).
- Real Time execution. Two systems available depending on the required precision for the test under execution:
  - Processor-based models: Average time step of 40-50µs.
  - FPGA-based models: Average time step of 1-2µs.

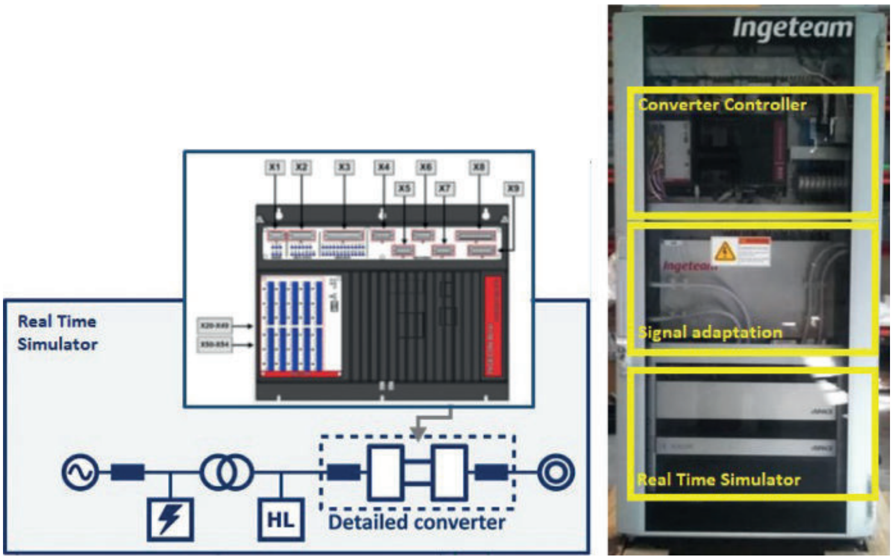


Figure 7. HiL system overview

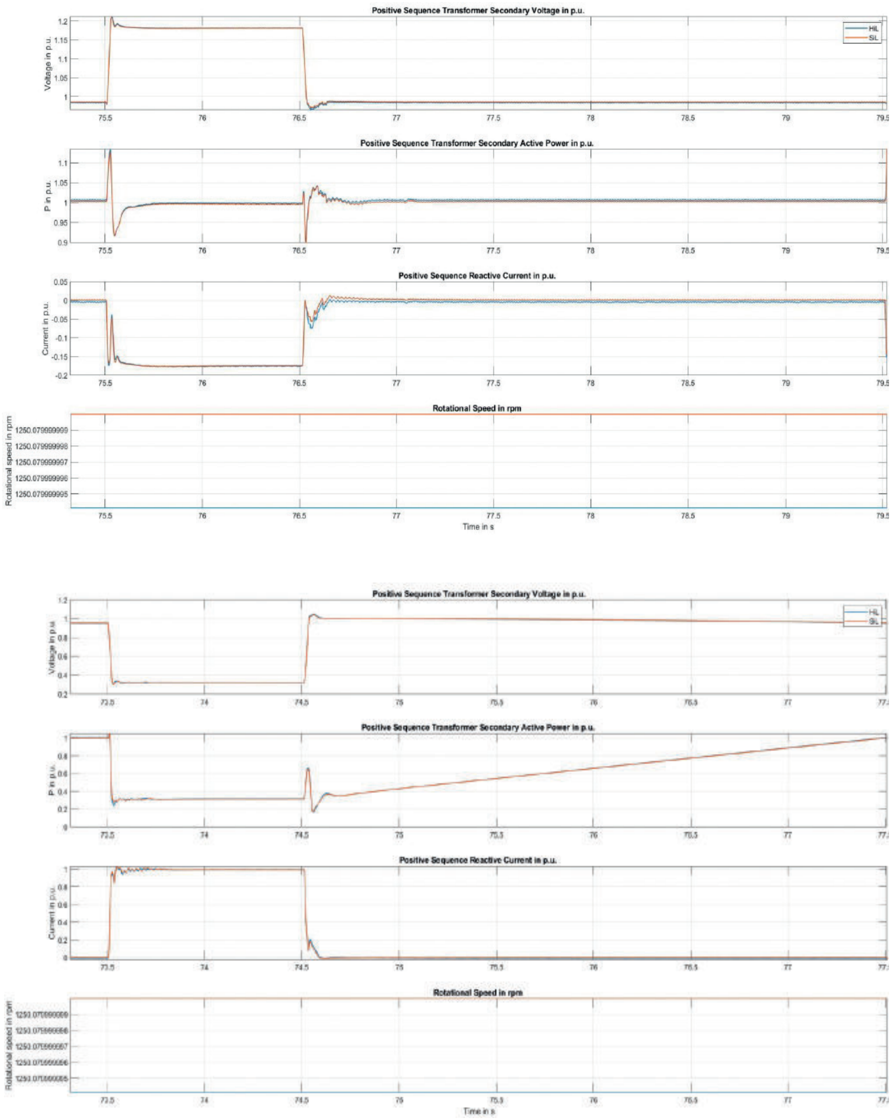


Figure 8. Ingeteam's dynamic response under SIL & HIL simulation for a three phase 120% overvoltage (left) and 30% undervoltage (right) cases.

### Correlation of results

For both SiL and HiL models to be trusted and to ensure that the compiled library component used in the SiL model and the real controller have an equivalent behaviour, the results of both models are always correlated to each other under the same test conditions. This ensures that the library component can be fully trusted when a HiL system is not available for controller integration.

The following example shows the correlation of a 120% overvoltage and a 30% undervoltage fault cases.

### Conclusions

Reliability is a key factor in all of Ingeteam's converter developments, and the validation process has been designed to ensure the highest level of reliability and optimization at every stage of firmware development.

With the increasing complexity of the firmware programmed in the converter controller, a detailed step-by-step testing and validation process is essential to guarantee a reliable firmware integration, prior to field deployment of the production code.

Ingeteam's robust firmware development methodology ensures that the controller and the production code are fully tested throughout the development stages, drastically minimizing the on-site validation and certification phase, reducing the time to market, and reducing the overall cost of the wind turbine.

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