Ingeteam

Robust Firmware Development For Wind Applications Through HiL/SiL Validations

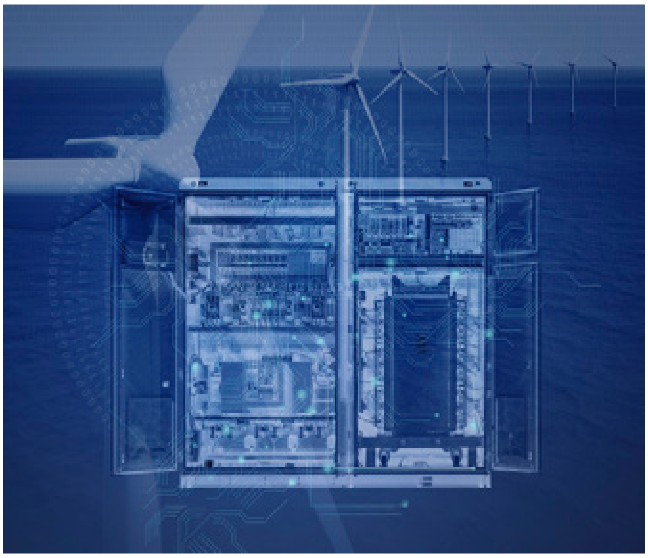
EDUARDO SANZ

Ingeteam Power Technology, Sarriguren, Spain

1. Introduction

As more and more wind energy is added to transmission networks, ensuring the correct electrical behavior of wind turbines is critical, not just for the wind turbine itself but also to ensure the safe operation of the electrical grid. The power converter is the main active component connecting the wind turbine to the grid. As such, its operation must be reliable and deterministic, and the firmware programmed into the converter's controller must be thoroughly tested and validated during its development.

Detection of unwanted firmware behavior after its installation on the wind turbine can have serious consequences, from unavailability of the production, to non-fulfillment of grid code requirements or even damage to the turbine components.



A proper firmware development methodology allows the following:

· To track the desired functionality from specification to validation.

· To set the requirements for each of the functionalities: converter protections and emergency sequences, fieldbus communications, dynamic behavior, Power quality (PQ) response, fault ride-through (FRT) dynamic response, etc.).

· To determine and define the proper validation environment for every stage of the development and functionality, depending on the critical nature of the functionality and the available technology. The functionality, not implementation, is tested from individual code debugging to partial code Software-in-the-Loop (SiL) simulation, to full controller testing in Hardware-in-the-loop (HiL) simulation.

· To automate test execution to ensure the validity of a solution upon multiple external conditions (grid variations, SCR factors, grid code fulfillment, SSR/SSCI evaluations, etc.)

Through this methodology, any issues found during the validation stage are quickly fed back into the development stage to be corrected and ensure that the firmware loaded in the converter has a robust behavior prior to production and deployment of new versions.

Any issues found during the validation stage are quickly fed back into the development stage

2. 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.

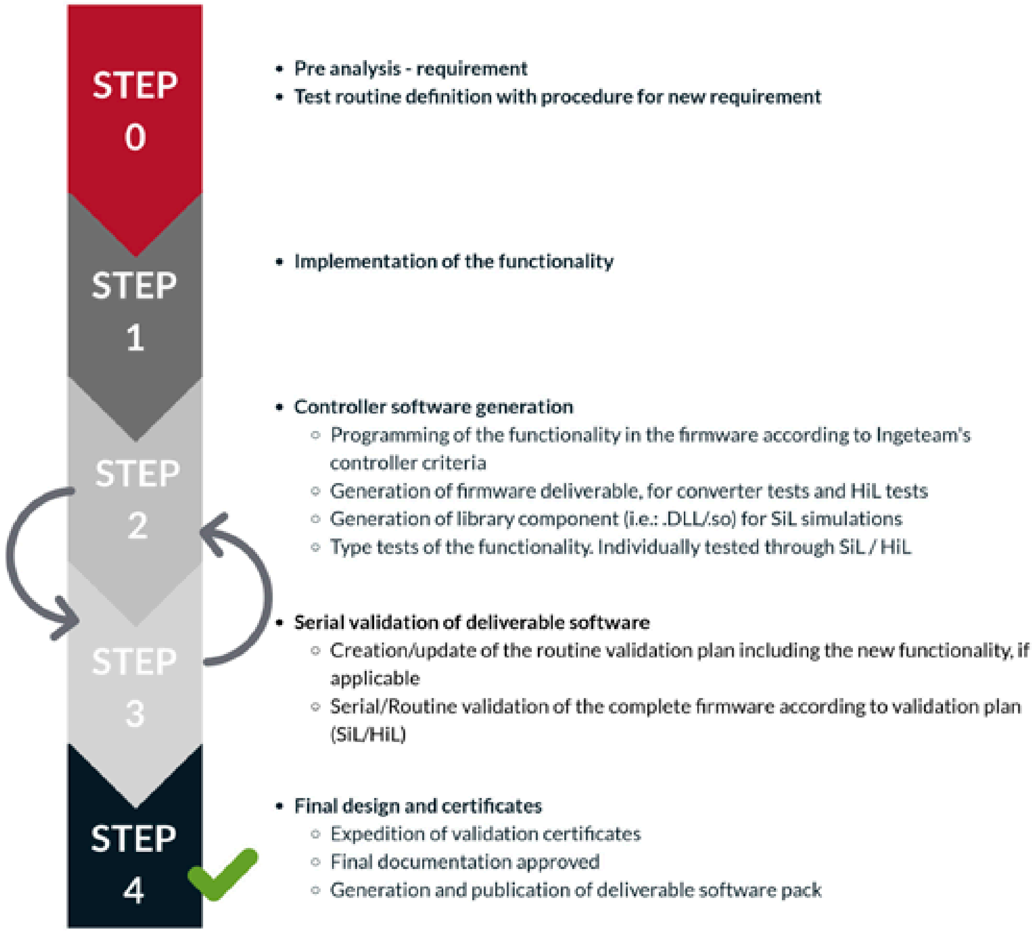


Fig. 1 Figure. 1. Validation procedure, from request to release

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

The present white paper 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.

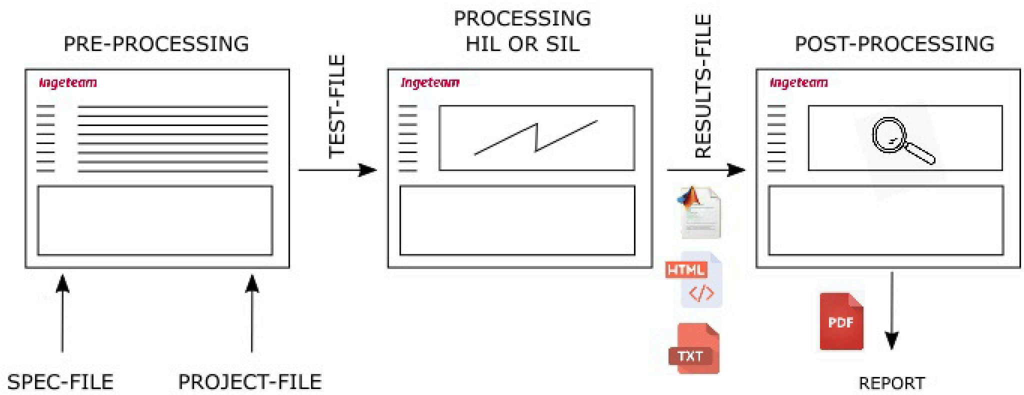


Fig. 2 Test automation tool steps

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.

#	CATEGORY	#	REQUIREMENT TO VALIDATE	#SUB	SUB-REQUIREMENT TO VALIDATE	TEST DEFINITION	ACCEPTANCE CRITERIA	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 61000-3	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 (°C), temperatura inicio derating (°C), pendiente derating (kW/°C)	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 (°C), temperatura inicio derating (°C), pendiente derating (kW/°C)	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 DEBE DISMINUIR ANTE UNA SUBIDA DE FRECUENCIA ENTRE 50.2 Y 51.5 Hz	HIL

Fig. 3 Overview, test categories and target system

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.

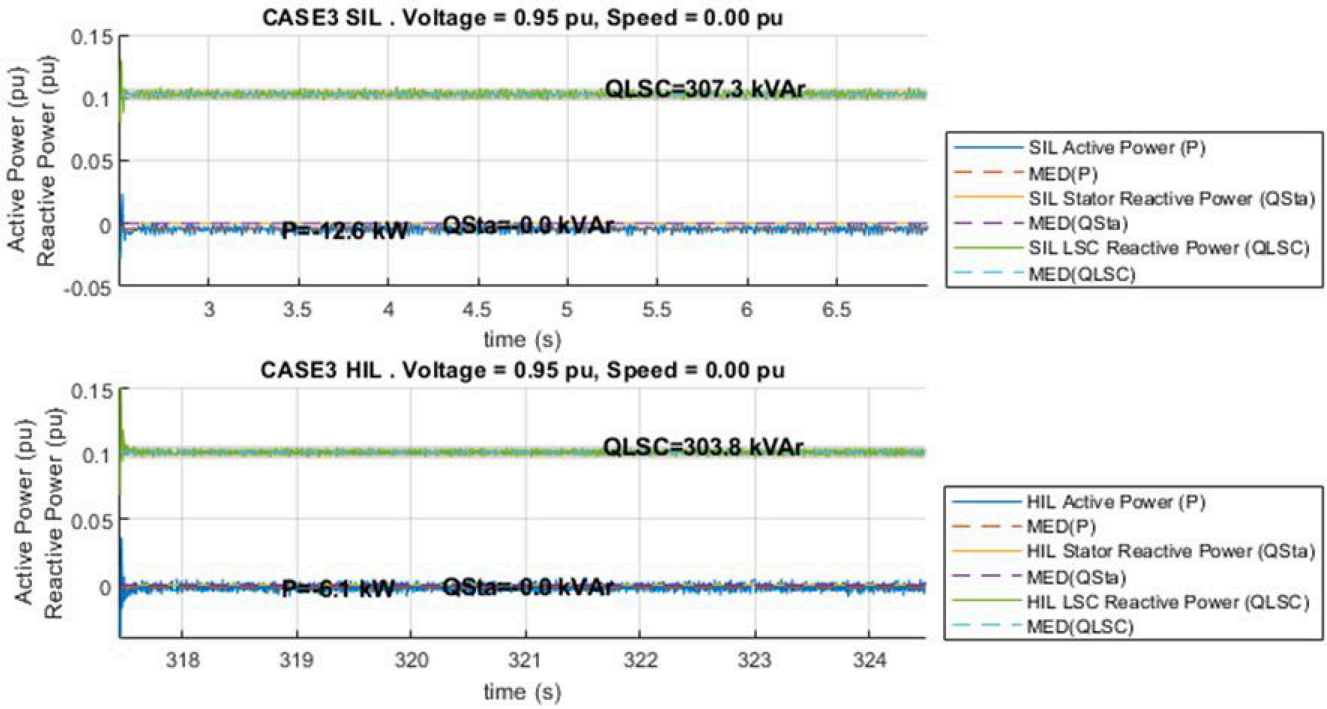


Fig. 4 Post-processing of results for the same test case, executed both in HiL and SiL systems

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

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.

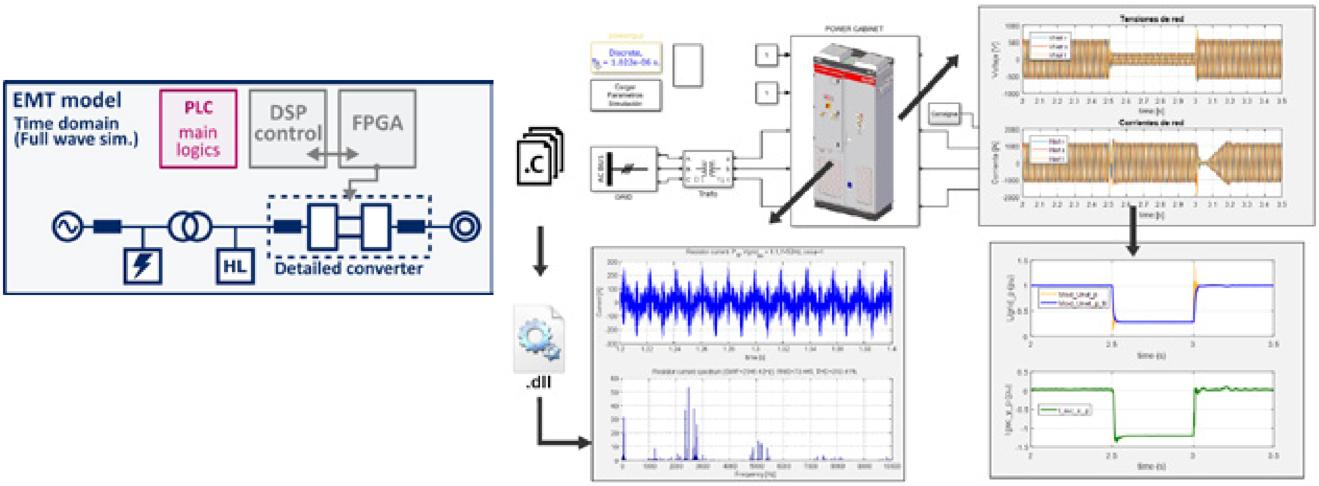


Fig. 5 SiL EMT model overview

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)
· 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:

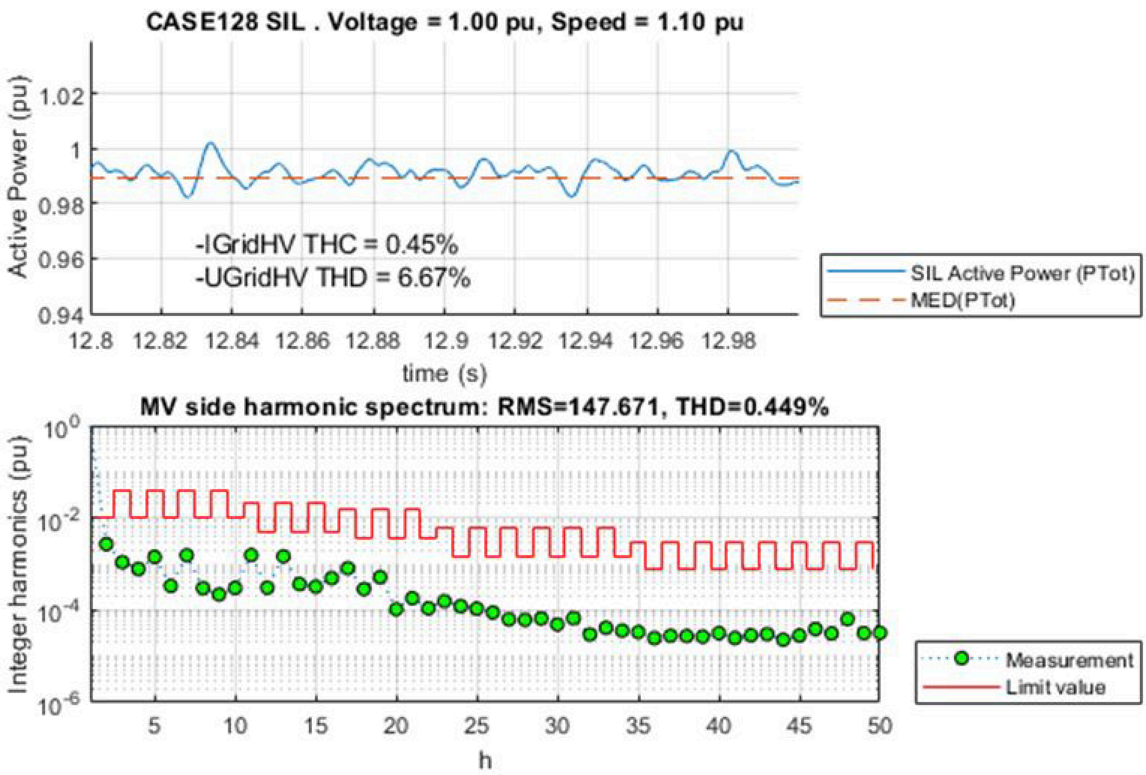


Fig. 6 Harmonics compliance SiL test case, based on IEEE requirements

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.

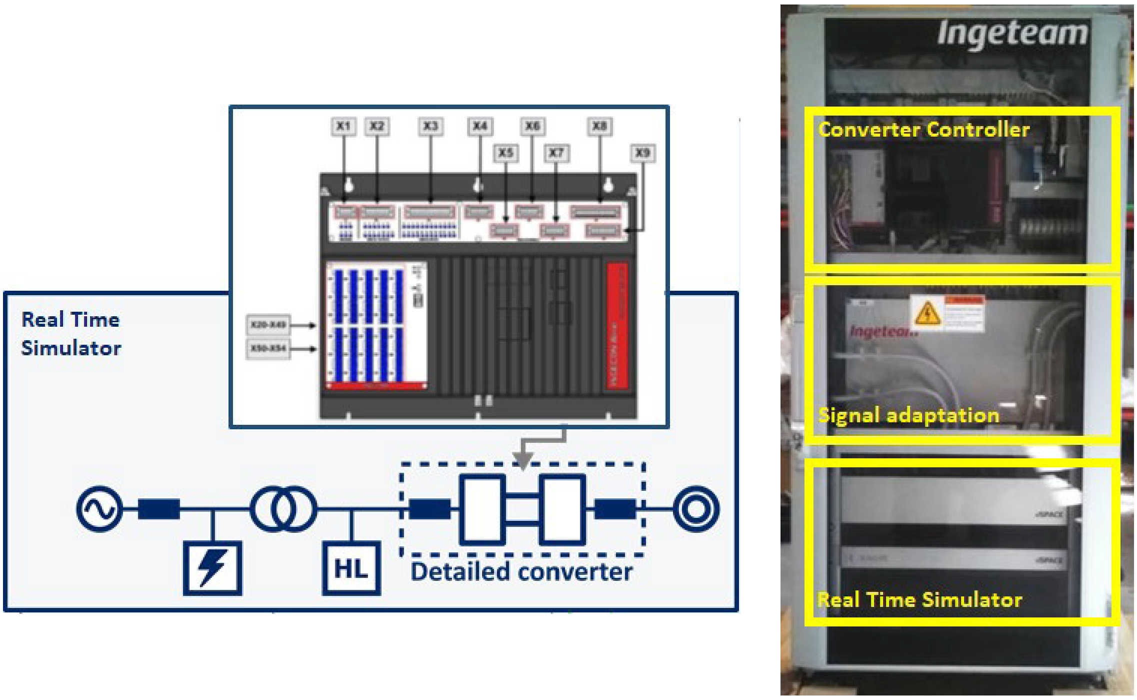


Fig. 7 HiL system overview

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.

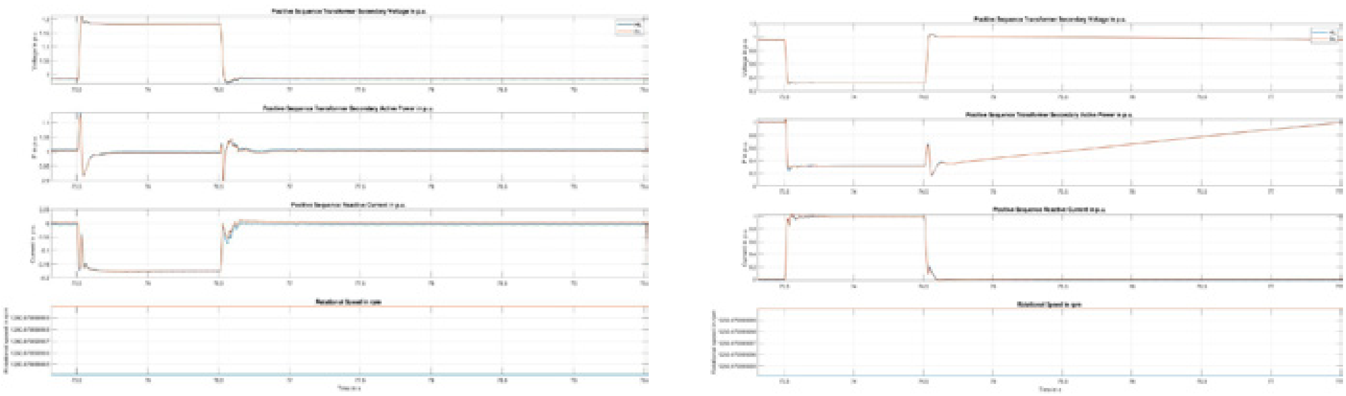


Fig. 8 Ingeteam's dynamic response under SIL & HIL simulation for a three phase 120% overvoltage (left) and 30% undervoltage (right) cases

3. 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.

4. Author

Eduardo Sanz
Technical Services Product Manager

contact:
wind.energy@ingeteam.com