Application of a Testing Chain Methodology for Improving Power Converter Controllers

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***Abstract*—The practice of testing power system equipment like converters usually involves simulation, laboratory and field testing in that sequence. Such an approach lacks smooth transition and wide coverage of new services which are being introduced by the smart grid concept. A systematic approach to sequentially test various functionalities may lead to reduced costs and speed-up the process from concept to implementation. Testing chain is such an approach where specific capabilities of pure simulation, hardware-in-the-loop, laboratory and field testing are leveraged sequentially to cover wide aspects of the system under investigation. In this study, a test case is exemplary realized aiming to demonstrate the potential of a multi-site testing chain with varied testbeds for generating systematic improvements on the performance of power converter control functions.**

I. Introduction

A core element of smart grids concept is the ubiquity of communication technologies in power system targeting increased monitoring and control functions [1], [2]. This is driven by the increasing necessity of real-time control and flexibility in the power system to cope with the integration of intermittent and distributed forms of energy resources. Another dimension of complexity in the traditional power system is the raising demand for integrating different forms of energy vectors (electricity, heating, cooling, etc.) driven by environmental and economic factors [3]. These developments entail the basic requirement of having a multi-domain and holistic approach to study and test different conditions and solutions in smart grids and corresponding components [4].

One testing approach proposed in the literature to facilitate the process from concept development to real implementations is the Testing Chain Method. The method is initially introduced in [5] aiming to increase the realistic behavior of a test system step-by-step. In [6], advance approaches are incorporated and proof-of-concept validations of the testing chain method are presented. The method has been applied since then in some studies such as [7]. In [7] smart grid testing chain is defined as a sequence of steps that need to be followed in order to validate effectively a control algorithm of a smart grid. It is applied in [7] to investigate different control strategies for battery-less PV-DDG (Photostatic Diesel-Driven Generator) system. In [7], the method is identified as an efficient way to validate smart grid controllers safely in the laboratory environment. According to [6], the benefits of testing chain method include systematic analysis during all stages of development, early detection of issues in the development process and savings in time and cost.

As an example, this testing chain method is applied in this study to a test case of converter controller development. The method therefore is applied in more complex setting where not only specific capabilities of test approaches such as pure simulation, Controller Hardware-in-the-Loop (CHIL) and Power Hardware-in-the-Loop (PHIL), it also leverages the capabilities of smart grids laboratory infrastructures distributed in three different countries in Europe.

The contribution of this paper mainly lies in its attempt to highlight the benefits and challenges experienced during the applications of the testing chain approach in geographically distributed research laboratories for the selected test case of converter controller development. This paper discusses also specific solutions such as holistic test description method applied to address challenges associated with application of the method involving experts from different regions. Also, future improvements for the refinement of the testing method are analyzed.

The paper is organized as follows: Section II presents the test chain methodology while Section III describes the test implemented in this study together with the used converter controller. In Section IV experiment setups of pure simulation, CHIL and PHIL are presented with the respective test results. Finally, Section V discusses main findings and observations from the implementation of the tests while Section VI provides the concluding remarks.

II. Overview of the Testing Chain Methodology

Testing in the context of smart grids is extremely complex due to the multi-layer structure of the overall infrastructure [4]. In addition, smart grid testing involves the integration with hardware devices, making use of modeling and simulations highly relevant to discovering integration issues at scale [8], [9]. The testing chain is a series of experiments (from pure

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simulation to actual field-testing) used to develop a new component reducing the risk of failure or to validate a component with an holistic approach cost effectively. As the testing chain approach involve multiple implementation of experiments, large extent of coordination is required in the planning as well as execution. The following points are identified to be important factors in the test design and planning process:

- Formulating common Key Performance Indicators (KPI) consistent throughout the test chain
- Devising simplified and understandable method for describing test plans and data formats of test results
- Splitting the test system based on objectives (i.e., validating test results in different test setups and testing specific characteristics tailored to the specific capabilities of the test implementation method)

The testing chain approach can investigate the whole range of functions and hardware in the test system resulting in a cost efficient validation. In general, the following testing methods can be involved in the test chain [6], [10], [11]: *(i)* pure simulation, for demonstration of concepts; *(ii)* Software-in-the-Loop (SIL), where the simulation of the Object under Investigation (OuI) and the rest of the system are executed on the same computer; *(iii)* CHIL, where OuI is on a separate computer/controller with realistic interface to Rest-of-System (RoS)-simulation; and *(iv)* PHIL where OuI is interfacing a testing chain power unit and connected to RoS-simulation.

In this study, the test chain methodology is applied using pure simulation, CHIL and PHIL sequentially as it is illustrated in Figure 1. The first stage of the chain is pure simulation followed by CHIL and the third stage is PHIL. The OuI stays the same throughout the chain while the parts represented by physical components increase. Independent simulation studies are conducted in research infrastructures located in Spain and German while CHIL in Austria and PHIL in Norway.

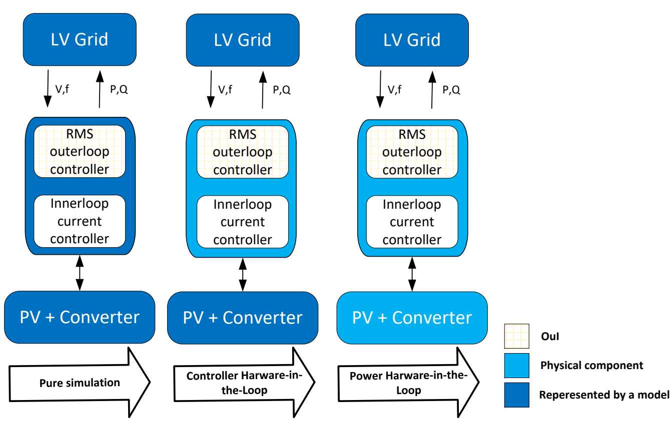

Fig. 1. The System under Test.

The testing chain implementation, as it is illustrated in Figure 2, involves two rounds of tests where the first round aims to characterize the controller and propose improvements while the second round aims to validate the improvements. The information exchange among the implementations of the testing chain include:

- *Step 1:* Run simulation and prepare load profiles for consequent tests
- *Step 2:* Run CHIL and PHIL tests and communicate the results with recommendation for improvement of converter controller
- *Step 3:* Re-run simulation and propose improvements after which CHIL and PHIL validate the improvements

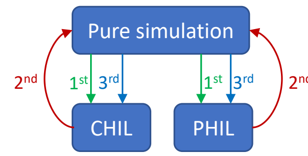

Fig. 2. Overview of the testing chain implementation strategy.

Simulation implementation serves best the detail design of the controller and the Hardware-in-the-Loop (HIL) approaches are utilized for validation purposes. Description of the individual validation approaches and their specific capabilities are documented in [4]. The individual implementations of the testing chain in this study are selected for specific purposes based on their respective capabilities. The contributions of the simulation, the CHIL and the PHIL in the testing chain are described in Table I. The test case for which the testing chain methodology is applied for is described in detail in Section III.

TABLE I
PURPOSES OF THE IMPLEMENTATIONS IN THE CHAIN.

Implementation	Goal
Simulation	Characterize converter controller model in simulated environment. Controller model tuning to match the responses observed in the other three tests.
CHIL	Characterize converter controller hardware in simulated environment. Controller tested under highly dynamic and transient power system phenomena under real-time constraints. Stability of controller under grid frequency and voltage disturbances induced by the variability attribute (i.e., variable load).
PHIL	Characterize stability of converter controller hardware in closed loop full power setting. Testing stability of controller under harmonic disturbances in the system.

III. TEST CASE DESCRIPTION AND IMPLEMENTATION

In this work the testing chain approach has been applied for improving the performances of a power converter controller. In particular, the power converter under investigation is designed for Photovoltaic (PV) applications. The system used to test the converter controller includes: *(i)* distribution system (grid), *(ii)* converter controller under investigation, as well as *(iii)* PV and power converter. The specific test system used for the tuning of the converter controller includes the inverter's belonging to a PV power plant connected to a grid. The selected Low Voltage (LV) test grid, considered as relevant enough for testing the converter controller, is based on the CIGRE LV network modified with Distributed Energy Resource (DER) that can be found in [12]. Over this grid, slight modifications

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have been done. Therefore, the test grid eventually considered is a version of the modified CIGRE LV benchmark where the flywheel has been substituted by a battery, the wind turbine has not been included and the fuel cell and microturbine have been replaced by PV systems, as can be seen in Figure 3.

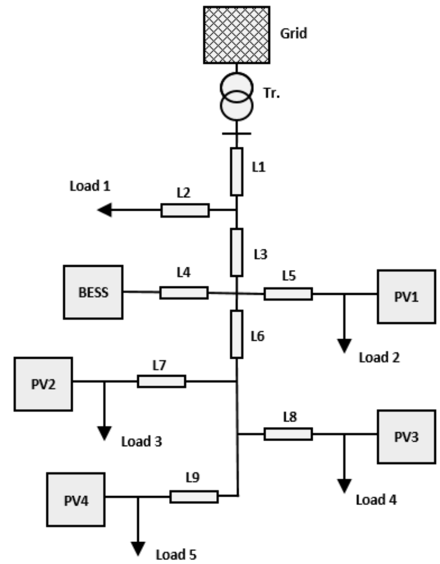

Fig. 3. Modified CIGRE LV distribution grid model (adopted from [13]).

All the static parameters concerning the grid (line impedance's, transformer parameters, rated powers of the sources) are public available from the original design of the CIGRE LV benchmark published in [13]. For the initialization of the tests and the establishment of the steady-state conditions, several active and reactive power patterns have been created for the sources, the battery and the loads. These patterns have a full-day duration with a resolution of 1 sample per second and are adapted from real measurements taken from PV installations and consumers (and only need to be scaled in some cases when integrated in the grid). Even the response of the converter will be tested in short periods (to evaluate the transient response), these patterns are necessary and useful to harmonize the simulations and the experiments in case the controller needs to be tested in different operating points.

A development and validation plan with a standard approach would include a simulation for tuning the inverter and, then, an experiment with a real power converter connected to grid simulator. However, this kind of approach implies high risk of failure since the behavior of real components is different from their models. Hence, this approach could lead to waste of time and money. On the other hand, with the testing chain approach, the implementation plan expected two pure simulation experiments, one CHIL experiment and finally one PHIL experiment. In the first simulation experiment the converter controller has been characterized and some improvements to the outer loop have been proposed. Then a series of experiments (another one simulation, one CHIL and a PHIL) have been performed in order to compare the original converter controller and the one with the improvements (see Figure 1). The full description of the test case using the ERIGrid Holistic Test Description (HTD) method [14] is provided via [15].

A. Power Converter and Controller Characteristics

A topic that is becoming a challenge in the context of smart grid is the development and testing of converter controllers [16], [17]. Since the number of power converters connected to the power system is rapidly increasing due to the spread of renewable energy resources, the interaction between the different controllers becomes very relevant. If it is not properly controlled it could lead to undesirable conditions of the power system [18]. For this reason the developing phase of a converter controller needs to take into account the real behavior of the power system to which the converter under investigation is connected. Considering a simple equivalent model of a power system is no longer sufficient since it neglects how the system behavior is affected by the converter. This means that simulation environments used to develop the converter controller become more complex, involving different type of components. In principle, the model should include all the electrical components, as well as their controllers, connected to the power system [19]. Moreover, in order to evaluate the real behavior of the OuI and how it behaves in the field, the testing procedure has to include also advanced testing methods more similar to a testing field than a simple simulation. These methods are the CHIL and the PHIL techniques [20], [21].

For the developed algorithm the outer loop of the converter controller is essentially and hence, it does not take into account the modulation (inner loop). The inputs of the Root-Mean-Square (RMS) controller are the components of the voltage on the dq-axes (V_d and V_q) and the active and reactive power setpoint (P and Q). The controller is composed of two subfunctions where the first evaluates the components of the current on the dq-axis (I_d and I_q) while the second one controls that the module of the current does not exceed the maximum current of the converter. The corresponding formulations are presented in Figure 4.

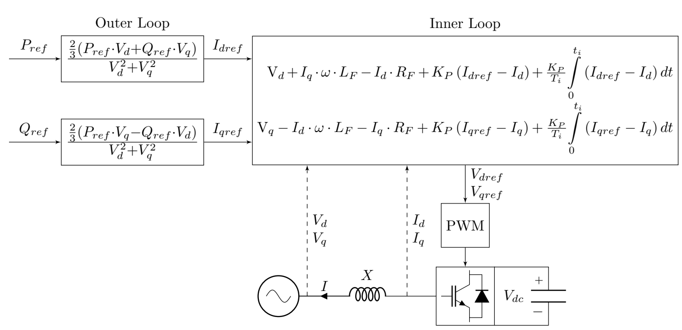

Fig. 4. Overview of the converter controller inner and outer loop.

The characterization of the controller has been done by defining several target metrics to be evaluated in different simulation tests. It has been done by means of simulation by analyzing the behavior when testing the controller in stand-alone mode or interacting with neighboring controllers. However, in order to verify the operation of the controller

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without the interference of other devices, the System under Test (SuT) selected has been the CIGRE LV benchmark model modified with DERs previously described where one of the inverter's belonging to a PV installation host the controller and the other installations are modeled as variable PQ profiles with no dynamics.

In the test chain the target metrics selected are summarized below in the Table II. The selected KPIs in this study are not very thorough as their definitions vary also in the reviewed literature. They shall be considered as partial indicators of the performance of the controller and further exhaustive converter controller KPIs shall be applied in future activities. After the evaluation of these metrics in the first-round test, improvements for a better tuning of key parameters in the inner and the outer control loops have been proposed to be validated in the second-round test.

TABLE II
TARGET METRICS FOR CHARACTERIZING THE CONVERTER CONTROLLER.

KPIs	Description
Settling Time (ST)	Time elapsed (s) from the application of an instantaneous step input to the time at which the amplifier output has entered and remained within an error band of 5%.
Overshoot (%)	$OS(\%) = \frac{V_{peak} - V_{ss}}{V_{ss}} \cdot 100$
Peak Time (T_p)	Time at which the peak value occurs (s)
Damping Factor (Θ)	$\Theta = \frac{-ln\left(\frac{OS}{100}\right)}{\sqrt{\pi^2 + ln^2\left(\frac{OS}{100}\right)}}$

B. Converter Controller Parameter Improvements

1) Inner Control Loop: A parametric analysis has been carried out to evaluate the impact of the Proportional–Integral–Derivative (PID) constants in the system response when facing a step in the solar power generated. In any case, a wide range of K_p and K_i values have been tested to find the better trade-off between the settling time and the overshoot. The PID response for the different K_p values are simulated where the default values for the constants were K_p=1 and K_i=1 and those values were used for the original controller. The final set of parameters selected for the K_p and K_i values of the PID were K_p=2 and K_i=50. Comparative evaluation of the converter performance for the original and modified Kp and K_i constants will be shown in Section IV-A.

2) Outer Control Loop: The outer control loop potential improvements are linked to the adjustment of the measurement filters in the I_d and I_q, and that results in the adjustment of the damping ratios (D). The damping ratio is a parameter linked to the quality of the filter in the way a higher damping ratio involves a higher quality. The parametric analysis over the damping ration of the I_d and I_q filters show that a reduction of D from 1 to 0.85 reduces the delay of 11 ms while with a lowest value of D, there is not an improvement in the response time and the filter exhibits an oscillating response. Due to this result, the recommendation of the D value for the improved Id filter is 0.85. For the I_q filter the most suitable value for the D parameter of the I_q filter is 0.5, that reduces the response delay of 10 ms. The comparison between the original and the improved converter controller according to the target metrics defined in Table II that will be shown in Section IV-A also include the changed parameters in the damping factors of the I_d and I_q filters, that were originally set to D=1.

IV. Experimental Results

A. Comparative Simulations of the Controller Operation

The goal of this test is to characterize the effect of one PV controller, i.e., PV1, on the voltage at the connection point to the grid (see Figure 3). To isolate the performance of PV1, all other loads and DERs were modeled as 3-phase dynamic loads, with constant input corresponding to 50% of their aggregate nominal value. The power factor of all DERs and loads are considered as unity and 0.85 respectively. The simulations are conducted in MATLAB/SimPowerSystems tool.

A series of step load profiles for Load 2 is used to test the controller response. The simulations have a resolution of 0.1 ms with a 2 s interval for the system to stabilize in-between each step change. The droop controller characteristics from [22] were used to determine the step load profiles. Using this, different active and reactive powers of Load 2 were determined so as to activate the controller in different control sectors (shown in Figure 5). The behavior of the controller was analyzed at the nominal frequency range (i.e., below 50.3 Hz), while covering the full range of operational voltage. Hence, the selected cases are the sectors C1 to C5. An iterative simulation process was done varying the active and reactive powers of Load 2. A case without the controller was also implemented by replacing it with 3-phase dynamic load, similar to the other PVs. This is used to compare the grid's behavior with and without the controller. Table III shows the values of Load 2 designed to active the controller in the selected regions. A positive value indicates power consumption while a negative value indicated power generation. It has to be noted that the cases C1-C3 that indicate power consumption are used in the further HIL tests. Negative power in C4 and C5 represent power generation or injection. The controller characterization is done using the target metrics from Table II.

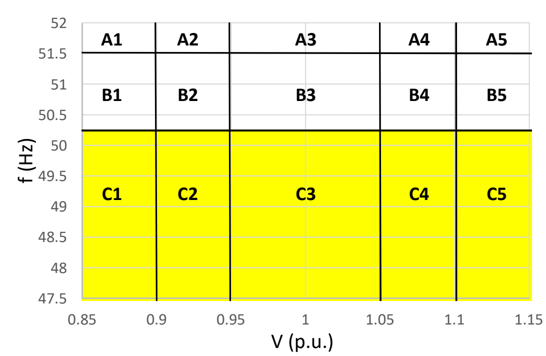

Fig. 5. Sectors for controller evaluation.

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TABLE III
LOAD 2 VALUES FOR SELECTED CASES.

Case	S (kVA)	P (kW)	Q (kVAR)
C1	62	52.7	32.7
C2	43	36.6	22.7
C3	15	12.8	7.9
C4	-25	-21.3	-13.2
C5	-55	-46.8	-29

In order to characterize the converter controller, simulations are conducted for the selected cases. The first step was to verify the expected behavior of the controller in relation to the power input of PV1 as well as considering the droop characteristics. This helped to troubleshoot errors in the controller parameters. Two different values of maximum PV1 input corresponding to nominal power (30 kW) and 50% of nominal power (15 kW) were used. The next step was to characterize the converter controller using the chosen KPIs (see Table II). Based on the controller improvements suggested in Section III-B, a second characterization was also performed. This was done by suitably modifying the inner current loop gains and damping ratio from the RMS outer loop controller. The resulting KPIs for the original as well as the improved controller (mainly faster response time) for the selected cases are summarized in Table IV. Note that the simulations were done using only one controller (i.e., at PV1) as the scope was to characterize the performance of only one controller. Introducing controllers at other PVs may bring-in cross-coupling effects which may potentially yield different results. The results from the simulation tests is then used as a benchmark for the CHIL and PHIL tests.

TABLE IV
COMP. OF ORIGINAL & IMPROVED CONTROLLERS FOR CASES C1 TO C5.

Case	Original Controller				Improved Controller			
	ST [s]	OS [%]	T_p [s]	Θ	ST [s]	OS [%]	T_p [s]	Θ
C1	0.8697	1.01	0.028	0.826	1.1316	1.55	0.02	0.799
C2	0.2319	0.25	0.033	0.886	0.1069	2.5	0.031	0.886
C3	0.0001	0.17	0.02	0.897	0.0001	0.01	0.045	0.947
C4	0.0295	0.29	0.020	0.881	0.0534	0.11	0.045	0.908
C5	0.2783	1.3	0.02	0.81	0.0483	0.005	2	0.863

B. Controller Hardware-In-the-Loop Results

While for pure simulations one only needs access to a computer and specialized software, for CHIL tests access to specialized hardware, namely real-time simulators and properly interfaced digital control cards, is also required. Figure 6 shows the setup used for performing the CHIL tests as part of the testing chain approach. While several real-time simulators targeting electrical energy systems are available on the market [20], for this test, due to equipment availability, the PLECS-RT Box is used.

The residential feeder of the CIGRE LV benchmark grid, used also in the previous section, was emulated in real-time using the PLECS RT-Box. Since the computing power of this device is relatively limited, the model of the network had to be simplified in order to fit into the computing constraints. To this end, cable models were reduced to simple RL impedance's, i.e., mutual coupling between phases was not considered. Using this simplification, we were able to run the model with a time step T_s=50 μs.

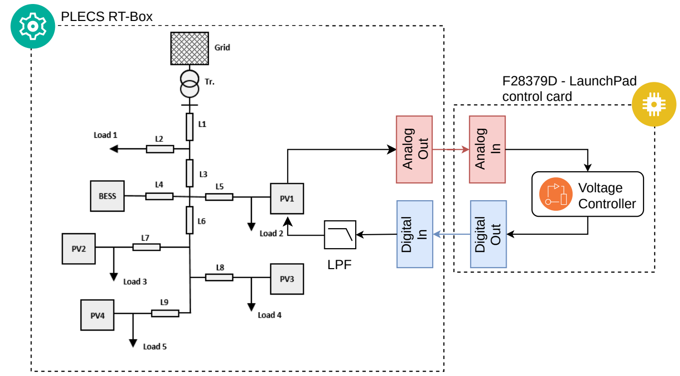

Fig. 6. CHIL test setup consisting of a PLECS-RT Box and a Texas Instruments C2000 F28379D LaunchPad control card.

Meanwhile, the PV converter controller was implemented as C code and deployed to the F28379D LaunchPad control card. As the name suggests, during CHIL tests it is the controller that it is being validated. Therefore, the controller implementation as well as the control card hardware need to be as close as possible to the ones used in the final prototype.

The inputs and outputs of the control card were connected to the ones of the real-time simulator via a RT LaunchPad interface board. Voltage and current measurements are provided to the control card by the simulator via analog channels. Meanwhile, voltage references are sent to the real-time simulator via the digital outputs of the control card. The voltage reference is sent as a Pulse Width Modulation (PWM) signal modulated at 10 kHz. On the side of the simulator the PWM signal had to be filtered in order to obtain its running average value. To this extent filters have been added after the PWM-capture blocks, as can be seen in Figure 6. One has to note that these filters are introduced inside the control loops and, consequently, they will have an effect on the response of the controllers. However, in a real-world scenario the power electronics inverter with its output filter will have a similar effect on the control loop as the introduced filter.

The control card interfaces at the PV1 photovoltaic generator. In terms of tests performed, both sets of controller parameters which were discussed in the previous sections were tested. In each of the two cases active power steps were applied to the converter and the results can be observed in Figure 7 and Figure 8. For both scenarios the following signals were recorded and are depicted in the plots: measured active power and the reference power signal, both represented plotted in [p.u.]; the voltage of the 3 phases alongside the dq-axis components, all displayed in volts. Additionally, for the d-axis voltage the $\pm$2% region around the steady state voltage, i.e., the settling region, is displayed with red dotted lines. All the KPIs, i.e., settling time (ST), overshoot (OS), peak time (T_p), and damping ratio (Θ) were computed for both scenarios

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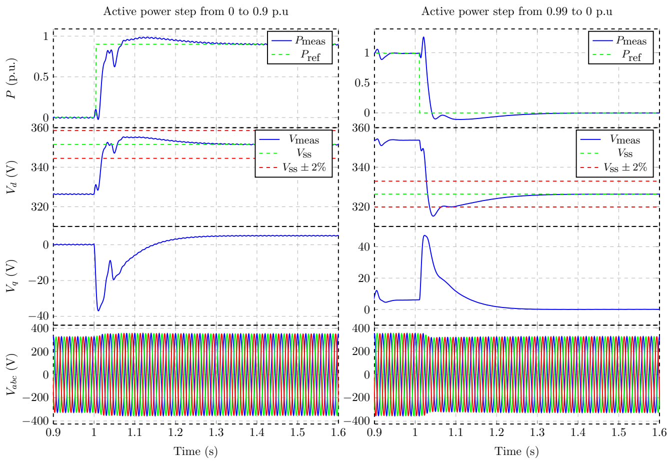

Fig. 7. CHIL results: Response of original controller to active power steps. From top to bottom: active power in [p.u.], d-axis component of the voltage, q-axis component of the voltage, 3 phase voltage.

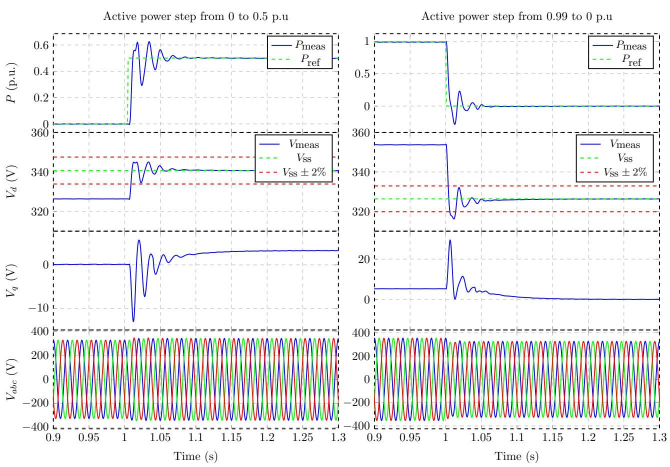

Fig. 8. CHIL results: Response of improved controller to active power steps. From top to bottom: active power in [p.u.], d-axis component of the voltage, q-axis component of the voltage, 3 phase voltage.

TABLE V
KPIs of CHIL experiments.

Controller	Scenario	ST [s]	OS [%]	T_p [s]	Θ
Original	$P_{\text{ref}} = 0 \rightarrow 0.9$ p.u	0.02	0.73	0.1	0.843
Original	$P_{\text{ref}} = 0 \rightarrow 0.5$ p.u	0.02	0.73	0.1	0.843
Original	$P_{\text{ref}} = 0.99 \rightarrow 0$ p.u	0.06	3.37	0.04	0.734
Improved	$P_{\text{ref}} = 0 \rightarrow 0.9$ p.u	n.a	n.a	n.a	n.a
Improved	$P_{\text{ref}} = 0 \rightarrow 0.5$ p.u	0.01	1.23	0.01	0.814
Improved	$P_{\text{ref}} = 0.99 \rightarrow 0$ p.u	0.01	3.09	0.01	0.742

and displayed in Table V.

As can be seen from the results present in Figure 7, Figure 8, and Table V, the improved controller reduced the settling time of the system, however the phase margin of the control loop has been considerably reduced, thus resulting in larger overshoots and an overall more oscillatory behavior. This made impossible to execute scenarios that involved large power injection steps, e.g., a change in the power reference from 0 to 0.9, as they rendered the system unstable.

As mentioned before, the additional filters which were added to the voltage control signals in order to interface the real control card with the simulator most definitely have a negative impact on the control loop. However, this would also be expected from a real-world scenario, as the power electronics inverter together with its output filter will have a similar effect on the control loop. Therefore, we expect the second version of the controller to behave also in reality worse (in terms of oscillatory response) than the first version of the controller. This observation is also backed up by the results obtained by the PHIL implementation in the following section.

C. Power Hardware-In-the-Loop Results

The PHIL test essentially aimed to characterize the stability of converter controller hardware in closed loop full power setting. Unlike to CHIL, the input and output signals can be typical power systems levels. Consequently, the error (i.e, time delay and distortion) introduced by the power interface may cause instability in the test setup making such implementations challenging. The PHIL implementation in this study aims to contribute to the characterization of the outerloop RMS converter controller by leveraging the specific capabilities of the implementation method. Specifically by studying the step response for active power output, the PHIL implementation validates the response of the converter hardware operating with the RMS converter controller.

In the PHIL test the MATLAB/Simulink model of the same modified CIGRE LV benchmark grid used in the previous implementations is used. To implement the test, OPAL-RT real-time simulator is used with 200 kW high-bandwidth power converter as power interface to a 60 kW converter hardware. The PHIL experiment setup is illustrated in Figure 9. For complete understanding of the system it is recommended to read through the layouts provided at test case level, for example Figure 1. AC side of a 60 kW two-level converter is interfaced through Egston grid emulator to the CIGRE LV

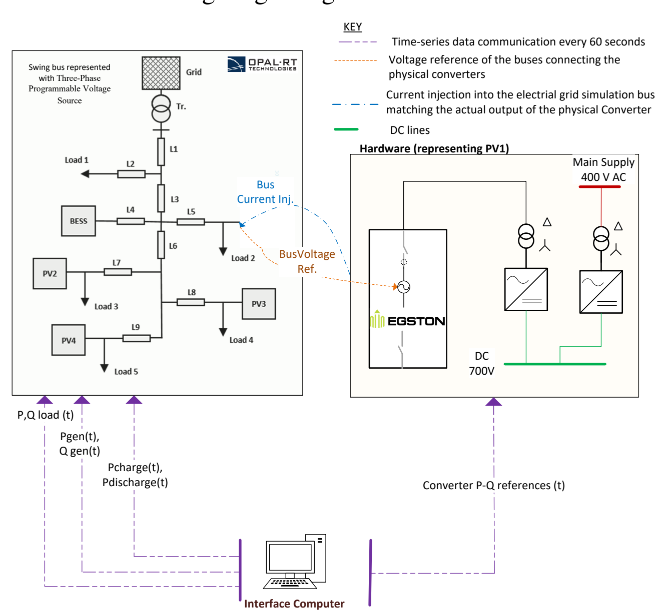

Fig. 9. PHIL experiment setup.

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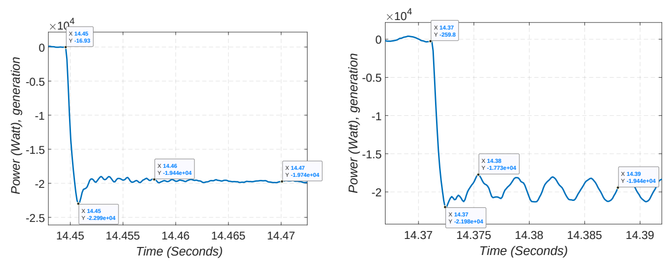
model simulated in OPAL-RT. The DC side of the converter is connected to 700 C DC bus supplied through the two buses of the six legged Egston grid emulator.

The PHIL test mainly was active power step response of the 60 kW voltage source converter. There has been two rounds of test in the test chain. After performing one round test a second round test is performed with improved filter damping ratio of the converter controller. In addition, specific to the PHIL setup, there has been a test with 5th harmonics disturbance of the reference voltage sent to the power interface connecting the 60 kW converter. Hence, the following four experiments are conducted using the test setup:

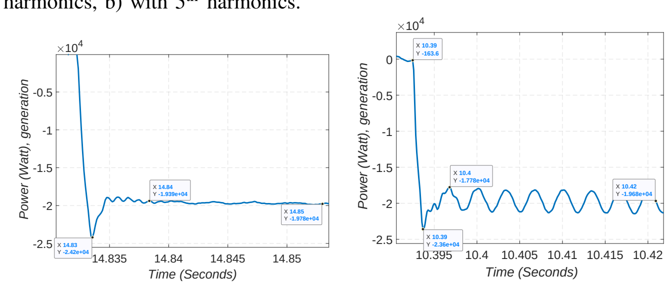
- *Round-1:* Step-up and step-down of PV output (filter damping ratio $D(I_d)$=$D(I_q)$=1)
  - Without 5th harmonics 14 V disturbance in the AC voltage reference
  - With 5th harmonics 14 V disturbance in the AC voltage reference
- *Round-2:* Step-up and step-down of PV output (filter damping ratio $D(I_d)$= 0.85, $D(I_q)$=0.5)
  - Without 5th harmonics 14 V disturbance in the AC voltage reference
  - With 5th harmonics 14 V disturbance in the AC voltage reference

The step response of the converter controller is characterized by recording the voltage level at the common coupling point and the active power output of the converter. As one can see in Figure 10 and Figure 11, the improvements on the



(a) ST=0.0084 s, OS=16.5115, T_p=0.0012 s, Θ=0.4974 (b) ST=NaN, OS=13.0833, T_p=0.0012 s, Θ=0.5434

Fig. 10. Converter active power response to step-up of PV active power output with controller filter damping ratio $D(I_d) = D(I_q)$=1; a) without 5th harmonics, b) with 5th harmonics.



(a) ST=0.0062 s, OS=22.3635, T_p=0.0014 s, Θ=0.4303 (b) ST=NaN, OS=19.8903, T_p=0.0011 s, Θ=0.4572

Fig. 11. Converter active power response to step-up of PV active power output with controller filter damping ratio $D(I_d)$=0.85, $D(I_q)$=0.5; a) without 5th harmonics, b) with 5th harmonics.

damping ratio of the I_d and I_q filter of the RMS converter controller resulted in reduced settling-time in the active power step response of the PV converter. However, the experiment results show that this improvement will be at the expense of the level of the overshoot.

V. Discussions and Recommendations

In this study, pure simulations, one CHIL and one PHIL tests with two rounds of experiments were implemented. The first round conducts the test for the agreed test network and profiles and the second round repeats the tests after the improvements on the converter controller are applied based on the analysis of the results from the first-round tests. Table VI presents summary of the results of the experiments for the original controller parameters. Although the improvements and changes with the adjustment of controller setting is documented in the different implementations, the results are not directly comparable. Hence, in this section the three main observations from the testing activities are discussed.

TABLE VI
Coupling point voltage response KPIs for stepping up output of PV connected through the converter for the implementations.

Test Type	Action	ST [s]	OS [%]	T_p [s]	Θ
Simulation	Step-up PV output with 1 p.u.	0.35	4.34	0.22	0.7
CHIL	Active power step from 0 to 0.9 p.u.	0.02	0.73	0.1	0.843
PHIL	PV output step-up from 0 to 20 kW. Without 5_{th} harmonics	0.0102	0.25	0.02	0.8856
	PV output step up from 0 to 20 kW. With 5th harmonics	0.0104	0.254	0.02	0.8851

A. Advantages of Pure Simulation Experiments

The execution of pure simulations within the testing chain methodology allowed multiple facilities to perform experiments in parallel. In this way, each facility was able to conduct tests from different perspectives and share the results. This proved to be an useful procedure to detect errors and to suggest improvements in multiple areas. Simulations proved to be cost effective because it allowed the execution of a large number of experiments within a short time, correcting and optimizing parameters without risks of damaging any physical equipment's. This include the detection of operational ranges of the model. As a result, the characterization of the controller through pure simulations improved the controller to be used in further testing chain steps. Moreover, as seen the case C4 and C5 in Section IV-A, pure simulations also allow for the conducting tests which are beyond the capabilities of the available hardware.

B. Need for Tool Standardization

One of the challenges that we encountered while trying to apply the testing chain approach was the lack of engineering support as well as incompatibilities between tools when advancing from one step in the chain to the following. For

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example, in order to perform the pure simulations the different models were prepared using MATLAB/Simulink. Meanwhile, for the CHIL experiments the system had to be completely remodeled using PLECS because there are no import-export functionalities for models developed using different tools. This process, besides being time-consuming is also very error prone as at every step of the testing chain an engineer has to interact with the model in order to make it compatible with the tools that are being used. Therefore, we consider that, in order for the proposed approach to gain traction in the power system testing and validation field, a standardization of the different tools involved in the process would be required.

C. Need for Methods for Tracking Setup Changes

There was a challenge to quantitatively compare results of the implementations due to significant differences in the experimental setups. Also, maintaining all variability attributes similar in the tests prove to be challenging. Hence, there is still a method required to objectively compare test results keeping the impact of test setup variability in check.

VI. Conclusions

The testing chain approach is better fitting to validate the different aspects of a test case utilizing the specific capabilities of different testing methods. The approach requires more coordinated planning than the processes of simply validating the results of one implementation with another. In this study, the testing chain method is successfully applied for the improvement of power converter controller. Some of the challenges experienced in the testing process are highlighted and discussed. One of the challenges is the model incompatibility among the different implementations along the chain. This challenge partly can be alleviated by thorough planning and also through standardization of models and tools [4], [19].

In addition, when testing chain approaches are used, there should be clear interpretations of the implications of variations introduced by the specific nature of implementations. Result interpretations shall be carried out carefully mapping the results to the right variability attributes considered. The improvements achieved in the converter controller in this study need more refinement in future works as more priority was dedicated to the evaluation of the testing chain method. Pure HW test can also be included in the chain to test the response of the converter hardware towards wide range of control signals from the controller in open loop setup. The inclusion of pure HW setup may contribute to the improvement of controller as well as to the improvement of component models in other setups such as CHIL.

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