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Key Stability Issues in a Power Hardware-In-the-Loop Experiment: Let's Make it Converge

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***Abstract*—Real Time Simulation is a powerful tool to study the dynamics of power systems, in particular when combined with Power Hardware-In-the-Loop. However, obtaining a stable test setup for Power Hardware-In-the-Loop is not trivial, as system stability is influenced by several factors. In this paper the stability of a Power Hardware-In-the-Loop test setup is studied. The focus is on evaluating the hardware used and the interaction of the tested hardware in the virtual environment. The methodology used to analyze the stability of the test setup, including the measurement of the dynamic response of the system and the evaluation of the hardware components, is presented. The results of the study demonstrate the effectiveness of the proposed method in achieving a stable test setup for Power Hardware-In-the-Loop simulations. The findings of this research can be used to improve the reliability of Power Hardware-In-the-Loop simulations for power systems and provide a better understanding of the behavior of the tested hardware in a virtual environment. Furthermore, the paper highlights the importance of evaluating the hardware components' responses (in particular that of the power amplifier) and their interactions in Power Hardware-In-the-Loop simulations in order to achieve a stable test setup.**

***Index Terms*—PHIL, HIL, stability, filter, electric vehicle chargers, EV**

I. INTRODUCTION

Real Time Simulation is a powerful tool to study the dynamics of power systems. In fact, it allows two interesting possibilities: remote co-simulation, as described in [1], and Hardware in the Loop (HIL) or Power Hardware-In-the-Loop (PHIL), whose potentials are described in [2]. In both cases two separate systems are coupled for an ”integrated” simulation, and in both cases stability issues can arise as exposed in [3] and in [4].

This paper addresses the second possibility, i.e. PHIL, in which the Real Time Simulator (RTS) is coupled with a Hardware Under Test (HUT) through a power amplifier.

Such possibility extends the horizon of simulations, as in a standard simulation environment the non linear models of devices could lack of accuracy because they may not include all the dynamics involved. In HIL and PHIL applications, this problem is overcame by connecting the simulation to the real hardware. Most of the literature regarding HIL addresses its application, but only a limited number of papers targets high power applications in PHIL configuration. In this configuration, the error introduced by the power interface, in terms of delay and distortion, poses some issues regarding the stability of the control loop and the accuracy of the results. Understanding and mitigating these aspects will be mandatory before applying PHIL as a reliable test-bench.

A. Aim of the paper

The aim of the paper is to describe the main aspects that contribute to the system stability in a PHIL simulation. Often some of them are neglected, for example the interaction among multiple hardware or grid parameters in the simulation side, but this aspects concur to the correct system operation. Also the entire transfer function of the power amplifier is often collapsed in a simple delay, while here it will be evaluated as a second order transfer function to allow a better approximation of the phenomenon. Following the proposed steps the simulations should correctly work in any similar configuration.

B. Review of stability

As mentioned before, the first aspect of the PHIL setup that needs to be assessed is the Interface Algorithm (IA), which is responsible for closing the loop of the system. Different IAs could be used in PHIL applications: in [5], five different approaches are described and compared with respect to the system stability. Through simulations it is revealed that some interface algorithms exhibit higher stability and accuracy. In our application the Ideal Transformer Method (ITM), showed in Fig. 1, has been used due to the simple implementation and the high accuracy.

Each of the devices, introduced in the system to couple the hardware with the simulation, is responsible for introducing a delay into the signal communication path. That delay may impact the stability and accuracy of the simulations. Moreover, speaking of the devices, they need to be characterized not only

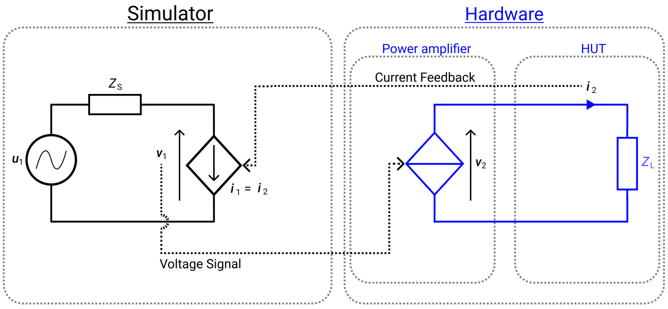

Fig. 1. ITM configuration used in the PHIL simulation.

in terms of delay introduced but also from the point of view of the transfer function. Otherwise, assessing the components as simple delays leads to a not negligible approximation in the control loop. An example is presented in [6], where the transfer functions of three different power supplies are retrieved to be considered in the PHIL control loop. The transfer functions allow the evaluation of the stability behavior of the system with three power amplifier technologies: linear, switching and rotating. Once that the control loop is defined, its stability needs to be evaluated and multiple examples can be found in literature. In [7] a comprehensive small-signal model for a PHIL test-bed to evaluate grid-connected Electric Vehicle Chargers (EVCs) is presented. The paper provides a mathematical framework to analyze the stability and predict the accuracy of both PHIL-based emulators. An experimental platform is used to validate theoretical predictions, and the validated test-bed is used to analyze the performance of a commercial EV charger and its interactions with a weak low-voltage network. Also in [8] the testing of physical equipment in a real-time simulation environment is discussed and the focus is on the role of the power interface (PI). The article compares several HIL test setups, and analyzes their overall stability and accuracy, based on detailed modeling of the interfaces. The stability is verified using the Nyquist stability criterion. A previous work, [9], also presents an analysis based on the Nyquist stability criterion applied to the transfer function of a simplified circuit. The major factors affecting stability, such as impedance ratio, time delay, amplifier characteristics, and low-pass filtering are considered. The results show that even unstable PHIL set-ups can be stabilized.

II. LABORATORY SET-UP

This study was carried out at the G-RTS Lab at the Energy Center of the Politecnico di Torino (PoliTo). The G-RTS Lab is a globally interconnected laboratory for Real-Time simulation, focusing on the role of electricity in the energy transition and the development of new smart and super grids. The lab's activities are integrated into the Energy Center Lab (EC-Lab), which conducts interdisciplinary studies across various energy sectors, including electricity, gas, and heat [10].

The lab features two different Real-Time simulation platforms, with ample computing power and the ability to perform simulations in both the time and phasor domains. Additionally, it is equipped with power amplifiers ranging from 20 to 60 kVA and an array of hardware devices.

The power amplifier used in this study is a three phase linear amplifier with a rated power of $21\,\mathrm{kV\,A}$ ($7\,\mathrm{kV\,A}$ per phase) that has the ability to work in both AC (three-phase) and DC modes. This technology was selected due to its exceptional dynamic performance, making it ideal for operations that require quick response time. Additionally, linear amplifiers have the added benefit of a minimal time delay, which allows for the implementation of a simpler interface topology and fewer instability issues.

In this study the HUT is an electric vehicle connected through a charging station. The car is a Nissan Leaf electric vehicle, equipped with a $62\,\mathrm{kW\,h}$ battery and the DC CHAdeMO charging plug. The charger used in the tests is a three-phase power supply, which allows for maximum charging and discharging powers of $11\,\mathrm{kW}$ and $10\,\mathrm{kW}$ respectively. The exact model of the charging station can not be disclosed for confidentiality reasons.

A scheme of the laboratory setup is visible in [11].

III. STABILITY ISSUES

In order to assure perfect synchronization between the simulated system and the real hardware, the interface between the HUT and the simulation environment should not introduce any delays to the control loop. It should have unity gain and infinite bandwidth. Unfortunately, such an ideal connection between the two systems is not achievable. As a result, PHIL simulations contain errors, possibly leading to accuracy and stability problems in the simulation setup.

Instability issues in PHIL simulations could arise for many different reasons, and in particular from:

- interface algorithm;
- simulation Time-Step;
- power amplifier transfer function and introduced delay;
- resonance of converters connected on the same node.

In this Section the different causes of instability will be analyzed in detail.

A. Interface algorithm and simulation Time-Step

As stated in [12], starting from the error introduced from the power amplifier it is possible to evaluate the IA transfer function. We can assume that the interface is non-linear, so at a generic time t_k, the voltage amplifier produces an error in the v_2 voltage on the HUT:

$$\Delta v_2(t_k) = \varepsilon, \quad v_2 = v_1 + \varepsilon, \quad i_2 = \frac{v_2}{z_L} \tag{1}$$

So, the error on the voltage v_2 causes an error on the current, that can be calculated as in equation (2).

$$\Delta i_2(t_k) = \frac{\Delta v_2(t_k)}{z_L} \quad \Rightarrow \quad \Delta i_2(t_k) = \frac{\varepsilon}{z_L} \tag{2}$$

The current measured on the HUT side is fed back to the simulation side and injected in the circuit with an ideal current generator. From the scheme depicted in Fig. 1 the equation (3) can be written:

$$v_1 = u_1 - z_S \cdot i_1 \tag{3}$$

Ideally, the current i_1 should be equal to i_2 but the error is fed back, and so:

$$i_1 = i_2 + \Delta i_2 \qquad \Rightarrow \qquad i_1 = i_2 + \frac{\varepsilon}{z_L} \tag{4}$$

In (5) we obtain the voltage difference on the simulation side that will be applied to the amplifier input at the time t_{k+1}

$$\Delta v_1(t_{k+1}) = -\varepsilon \cdot \frac{z_S}{z_L} \tag{5}$$

It is shown how the error is amplified by the ratio of the impedances. In order to keep the system stable, it is clear that the ratio between z_S and z_L must be lower than 1. If the simulated grid impedance is higher than the impedance of the HUT, the error is going to increase its amplitude at each time step, up to the hardware limit, triggering the protections.

From the interface algorithm scheme it is possible to derive the equivalent transfer function of the PHIL system and check the step response in the two cases, $z_S > z_L$ and $z_S < z_L$.

The simulation time step is taken into account as a delay T_s, both on the forward and feedback branch, as explained in [13]. Its value should be as low as possible to enhance both stability and accuracy of the simulation. According to some works, as in [14], the value for a mid scale grid model, to reproduce transients faithfully in 50 Hz power systems, is roughly 50 µs.

B. Power amplifier transfer function and introduced delay

As previously mentioned, delays in the loop are mostly caused by the amplifier and by the time step used in the simulation. The time step can be easily identified, but the delay caused by the amplifier depends on the used technology. Different applications may require different amplifier technologies, so the dynamics of the specific device must be considered when selecting the amplifier for PHIL applications. The best conditions occur when there is zero delay from the amplifier and the lowest time step is used in the simulation. However, when dealing with bigger models, the computation time increases, and lower delay from the amplifier means more expensive equipment. As a result, many PHIL setups use switched-mode amplifiers. These amplifiers are non-linear and can be used to feed high power loads, but increasing the power also increases the delay introduced in the simulation loop. Alternative solutions for the amplification stage are examined in [6]. In this paper the linear amplifier was chosen because of its dynamic performance. A key point is in any case the characterization of the hardware in use to have a lower error in the control loop.

In order to assess the performance of the amplifier in the system, its transfer function was determined using measurements of the step response of the real linear power amplifier, as shown in Fig. 2. Initially, the delay between the input voltage and the beginning of the response is measured, and it is found to be $t_{delay} = 4\,\mu s$. Then, various parameters are measured, as the maximum overshoot MP and damping ξ presented in equations (6) and (7):

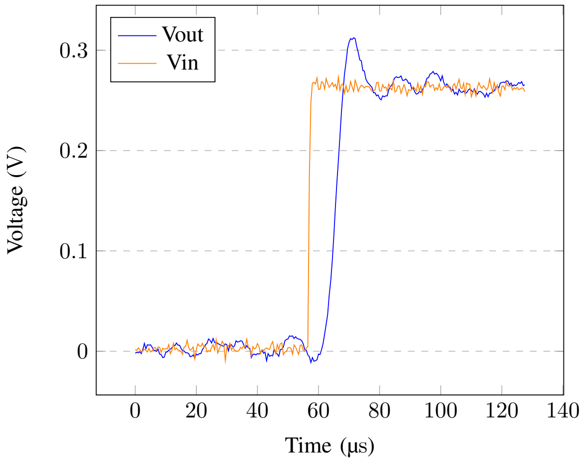

Fig. 2. Linear amplifier step response

$$MP = \frac{y_{peak} - y_{steady-state}}{y_{steady-state}} = 0.1874 \tag{6}$$

$$\xi = \sqrt{\frac{\ln MP^2}{\ln MP^2 + \pi}} = 0.47 \tag{7}$$

Then, from the period between the first two peaks of the response, the natural angular frequency was calculated with equations (8), (9) and (10):

$$T_d = 1.55 \cdot 10^{-5} \Rightarrow f_d = \frac{1}{T_d} = 6.45 \cdot 10^4 \tag{8}$$

$$\omega_d = 2 \cdot \pi \cdot f_d = 4.055 \cdot 10^5 \tag{9}$$

$$\omega_n = \frac{\omega_d}{\sqrt{1-\xi^2}} = 4.595 \cdot 10^5 \tag{10}$$

The transfer function of a second-order system can be represented using damping and natural angular frequency in the following form:

$$G_{ampli} = \frac{y_{steady-state} \cdot \omega_n^2}{s^2 + 2 \cdot \xi \cdot \omega_n + \omega_n^2} \cdot e^{-t_{delay} \cdot s} \tag{11}$$

This transfer function can be finally used in the control loop to verify if some instability issues could affect the simulation. The first step is to verify if the analytical step response follows the original measured one, so in Fig. 3 both the calculated and measured step responses of the linear amplifier are reported. Then, the transfer function has been used in the control loop reported in the Fig. 4.

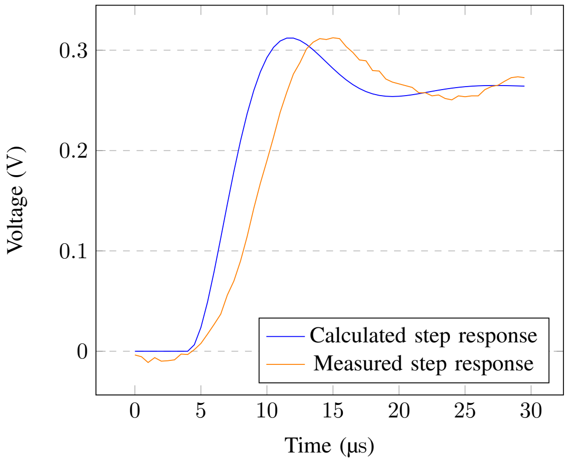

Fig. 3. Step response comparison

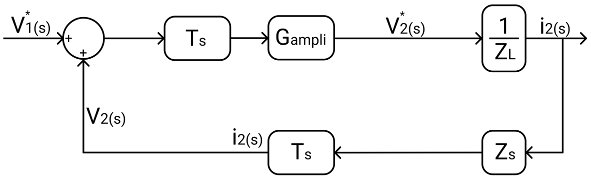

Fig. 4. Control loop with the characterized power amplifier

C. Resonance of converters connected on the same node

The use of EVCs to provide services to the grid is a promising technology for future network needs. However, the widespread implementation of converters may create problems due to the harmonic interaction between them and with the utility grid. In order to build a realistic grid topology for a parking lot in PHIL configuration, several EVCs need to be virtually connected in parallel. In this case, in order to investigate the stability issue as well as to improve the practical application for large-scale EVCs parking lots, the interaction among the EVCs needs to be investigated. The resulting harmonic interaction can cause disturbances in the simulated environment or even hardware protection triggering, penalizing the accuracy or stopping the simulation.

In [15] was showed how multiple converters connected in parallel can suffer from stability issues; then, the Authors assess an impedance model to predict the resonance point, important because the resonance frequency is related to factors such as the output filter, controller, and grid impedance. Furthermore it has been found how the converters need to be specifically designed, for example introducing an inner-loop control strategy.

A similar model, for PV converters connected in parallel, is reported in [16], where some results on harmonic frequencies are similar to the EVCs test case.

In this paper, the topology of the converter and the control strategy are unknown, so the resonance frequency are be found experimentally and possible solutions to the associated stability issues in the simulations are proposed.

IV. RESULTS

For each of the previously described instability sources, the choices made in the test case will be explained, highlighting the key points to assure a stable behavior of the system.

A. Impedance ratio and simulation Time-Step

It has been showed in Section III-A how the error is amplified by the ratio of the impedances. To maintain the system's stability, it is necessary to ensure that the ratio between Z_s and Z_L is less than 1. If the simulated grid impedance is higher than the HUT's one, the error will increase in amplitude until it reaches the hardware limit and triggers the protections. The first operation, then, will be the impedance calculation of the simulated part of the system (the grid topology is described in [11]). The short circuit power of the simulated medium voltage network was known and equal to $A_{cc} = 600\,\mathrm{MV\,A}$, so starting from the open circuit nominal voltage it is possible to derive the grid impedance from:

$$Z_g = \frac{V_n^2}{A_{cc}} = 0.81\,\Omega \tag{12}$$

then active and reactive components are retrieved from:

$$X_g = 0.995 \cdot Z_g = 0.805\,\Omega \quad R_g = 0.1 \cdot X_g = 0.08\,\Omega \tag{13}$$

and summed to the transformer and cables contributions, allowing the calculation of the impedance at the low voltage connection point:

$$X_{geq} = 0.0723 \quad R_{geq} = 0.0371 \tag{14}$$

Also the impedance of the converter is calculated from the measured instantaneous voltages and currents:

$$X_L = 1.743 \quad R_L = 15.79 \tag{15}$$

Similarly as in this paper, in [17] is presented a straightforward stability criterion using the Nyquist curve for PHIL systems. Then both the influence of the time step delay and the impedance ratio are tested. In the test case here reported the time step which allows the system to work properly is equal to 50 µs to have a proper accuracy as stated in [14]. In a canonical distribution grid, the condition on the impedances ratio is usually verified, as in our case. The time step of the simulation, indeed, needs more attention due to the size of the simulated system related to its topology and the computational power available.

B. Improving stability

The first intervention was filtering the feedback current signal as in [18] and in [19]. [9] presents also an analysis based on the Nyquist stability criterion applied to the transfer function of a simplified circuit. The major factors affecting stability, such as impedance ratio, time delay, amplifier characteristics, and low-pass filtering are considered. The results show that even inherently unstable PHIL cases can be stabilized with feedback signal filtering method. However, due to lower loop

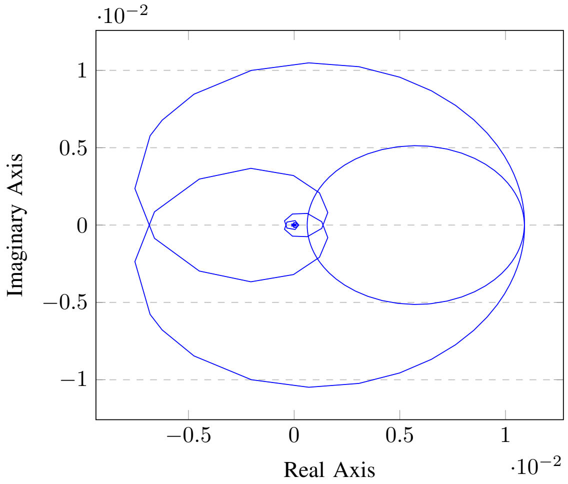

Fig. 5. Nyquist plot for the original test case

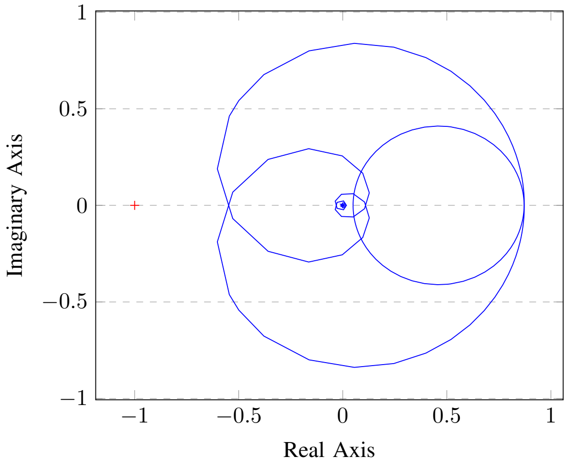

Fig. 6. Nyquist plot for a simulated grid impedance $Z_{geq} = 2.969+5.78j\Omega$

delays, linear converters require less intensive stabilization, which has a positive effect on simulation accuracy. The feedback signal filtering has also the advantage of deleting the unwanted harmonics components, but the cut off frequency of the filter must be properly set in order not to cancel the harmonics order that should be evaluated (in this case till the 40^{th}). In this paper the stability of the system has been improved with a second order Butterworth filter on the feedback currents. It is important to clarify that the filters contribute to the system stability, but if the main stability conditions are not respected the simulation will provide wrong results. The first condition to address in this PHIL configuration is the impedance ratio, which depends on the selected IA. In the exposed case the impedance ratio is respected and the stability of the whole system is guaranteed as showed in Fig. 5.

If different cases are considered, firstly, the impedance relationship needs to be studied. In Fig. 6 the Nyquist plot of the same loop, with an equivalent grid impedance equal to $2.969 + 5.78j\Omega$ is depicted.

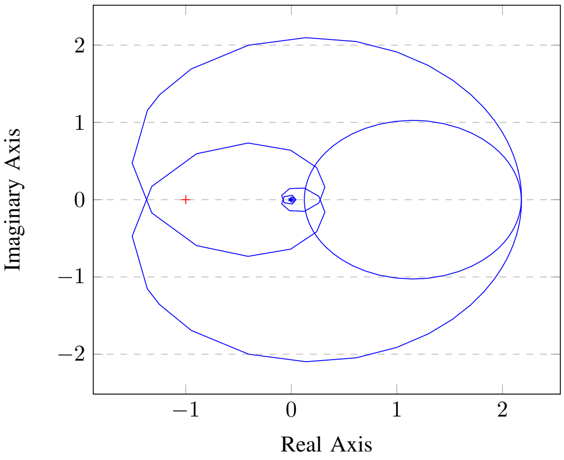

Fig. 7. Nyquist plot for a simulated grid impedance $Z_{geq} = 14.45+7.422j\Omega$ higher than the load one

Viceversa, in Fig. 7 a simulated grid impedance equal to $14.45+7.422j\Omega$ is showed. With these parameters an unstable behavior is evident, despite the feedback current filtering. The values of impedances used are obtained multiplying the base value to emulate alternative simulated conditions.

C. Chargers resonance

The simulation emulates 20 connected virtual chargers in the same parking lot [11]. As mentioned before, despite a stable behavior of the control loop, the insertion of the chargers into the simulation leads to instability issues and protection triggering. This is due to many factors, first of all the control strategy of the converters, then the power amplifier response on the load insertion and, finally, to the resonance phenomenon that appears among the converters when the simulation is running. In Fig. 8 the distorted waveforms are depicted, showing the most dominant parallel resonance frequency between the 17^{th} and 23^{rd} harmonics as in [16]. To keep the system correctly working, another second order Butterworth filter has been introduced before sending the voltages to the power amplifier. Decoupling the real hardware from the network rises up the resonance frequency, leading to stable operation. Attention must be paid to the filter setting in order not to impact the output voltages in terms of magnitude and phase at the fundamental frequency. In the Fig. 9 the same measurement is done with the voltages filter activated.

V. CONCLUSION

The work is focused on how to configure a stable PHIL simulation layout, considering the specific hardware available. In fact, the hardware characterization is fundamental to correctly set up the filters in the model.

The stability study started with the analysis of the delays introduced by the simulation and of the interface algorithm. Secondly, the feedback signals were filtered to enhance the stability. Then, it was possible to implement a simple transfer function to study the system response. Hence the transfer function of the amplifier was calculated and used to see the impact of the amplification stage in the control loop. As a

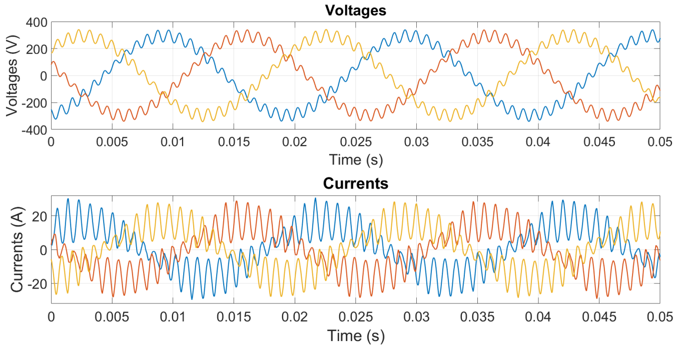

Fig. 8. Resonance among converters

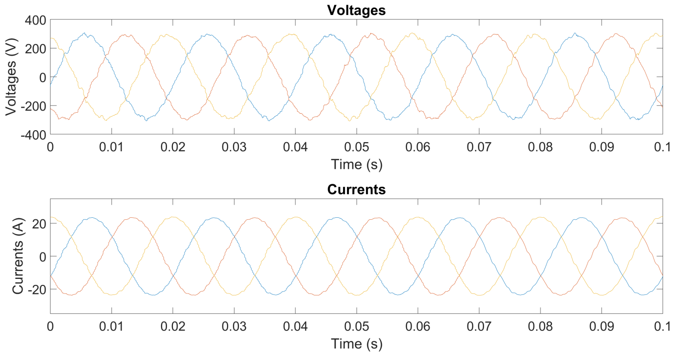

Fig. 9. Converters decoupled with the output voltage filter

result, it was discovered that some of the instability issues on the load insertion were caused by the high overshoot of the amplifier response, so the problem was solved with a low pass filter on the output voltages, that smoothed the response and decoupled the converters from the network, solving also the resonance issues due to the chargers interactions.

In conclusion, it has been observed that the simulation set-up and the characterization of the exploited hardware is extremely important to have consistent results in the PHIL tests and none of these parameters are negligible to assure a stable simulation under different testing conditions.

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