

IFAC PapersOnLine 50-1 (2017) 10977–10984 **Stability and Accuracy Considerations of Power**

Stability and Accuracy Considerations of Power Hardware- in-the-Loop Test Benches for Wind Turbines Stability and Accuracy Considerations of Power Stability and Accuracy Considerations of Power Stability and Accuracy Considerations of Power Hardware- in-the-Loop Test Benches for Wind Turbines Hardware- in-the-Loop Test Benches for Wind Turbines

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Abstract: in Fowel-Haldwale-In-the-Loop (FHIL) setups, the device under test (DOT) is connected to
the rest of the system (ROS) running in a real-time simulator through an Interface Algorithm (IA) and power amplifier, which strongly influences stability and accuracy of the test setup. This paper presents a power amplifier, which shongly influences stability and accuracy of the test setup. This paper presents a
comprehensive theoretical framework for the analysis of the two aspects of a PHIL system with different Complements we incoretical mannework for the analysis of the two aspects of a FITLE system with different IAs, and demonstrates its applicability to the design of PHIL test benches for wind turbines. For the IAS, and demonstrates its applicability to the design of PHIL test benches for wind turbines. For the theoretical modelling derivation, the interaction of two lumped active systems is considered. *[ARiccobono, AHelmedag, ABerthold, RAverous, post_pgs, and post_acs]@eonerc.rwth-aachen.de* This, and demonstrates its applicability to the design of FHIL test benches for which turbines. For the theoretical modelling derivation, the interaction of two lumped active systems is considered. Abstract: In Power-Hardware-In-the-Loop (PHIL) setups, the device under test (DUT) is connected to Interesting its application in demonstrates in the design of PHIL test benches for the philosophers for the state of t

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Keywords: Power Hardware in the Loop; Interface Algorithm; Stability; Accuracy; Test bench for wind Keywords: Power Hardware in the Loop; Interface Algorithm; Stability; Accuracy; Test bench for wind drives. drives. drives.

1. INTRODUCTION 1. INTRODUCTION 1. INTRODUCTION 1. INTRODUCTION 1. INTRODUCTION

Renewable generation systems like wind turbines need to fulfil technical requirements to be allowed to connect to the power grid. The compliance to the requirements is tested in
certification processes. Since most of the tests in case of wind certification processes. Since most of the tests in case of wind turbines are in-field tests, certification is a long and costly, non-predictable process due to the dependence on external non-predictable process due to the dependence on external
influences, like wind speed. If the tests are done on system
lavel test benches, the testing process is faster and therefore level test benches, the testing process is faster and therefore costs can be reduced [Helmedag et al. (2013)]. The Power-Hardware-In-the-Loop (PHIL) setup allows the investigation Hardware-In-the-Loop (PHIL) setup allows the investigation
of the behaviour of a wind turbine for different grid
situations. All the required certification tests can be done. situations. All the required certification tests can be done. situations. All the required certification tests can be done.
Moreover, each grid fault can be simulated without an
influence to the outside real power grid. In a PHII setup influence to the outside real power grid. In a PHIL setup, influence to the outside real power grid. In a PHIL setup,
depicted in Fig. 1, the wind turbine as device under test
(\overline{O} LIT) acts in real, whereas the rest of the system (\overline{P} \overline{O} S) in (DUT) acts in real, whereas the rest of the system (ROS), in (DUT) acts in real, whereas the rest of the system (ROS), in
this case the electrical power system, is implemented in a real
time, simulator. A software/bardware, interface, i.e., an time simulator. A software/hardware interface, i.e. an time simulator. A software/hardware interface, i.e. an interface algorithm (IA) on the simulation side and a power
amplifier (AMP) with its own sensors on the hardware side amplifier (AMP) with its own sensors on the hardware side, allows the virtual exchange of power between the ROS and the DUT. This PHIL setup allows performing highly realistic simulations without the need for physical prototypes of the entire system. Classical advantages of PHIL simulation entire system. Classical advantages of PHIL simulation techniques lay on the reduction of costs, risk, and time. techniques lay on the reduction of costs, risk, and time. Renewable generation systems like wind turbines need to Renewable generation systems like wind turbines need to entire system. Classical advantages of PHIL simulation techniques lay on the reduction of costs, risk, and time. techniques lay on the reduction of costs, risk, and time.

Despites their unquestionable advantages, PHIL simulations present challenges in terms of stability and accuracy mainly
due to pop-idealities of the power applifier. These popdue to non-idealities of the power amplifier. These nonidealities, e.g. delays, sensing errors, non-linearity, prevent the power amplifier from providing a high-precision the power amplifier from providing a high-precision Despites their unquestionable advantages, PHIL simulations Despites their unquestionable advantages, PHIL simulations the power amplifier from providing a high-precision the power amplifier from providing a high-precision the power amplifier from providing a high-precision reference tracking over a wide frequency band. In order to reference tracking over a wide frequency band. In order to
address those challenges, it was recognized that the IA plays
a key role to improve both the stability and the accuracy of a key role to improve both the stability and the accuracy of PHIL simulations. Several IAs are investigated and compared
in Hatakayama, et al. I. [Ren. et al.]. A comprehensive in [Hatakeyama et al.], [Ren et al.]. A comprehensive in [Hatakeyama et al.], [Ren et al.]. A comprehensive
modelling framework is therefore needed to provide
mudelines addressing the effect of LAs on the stability and guidelines addressing the effect of IAs on the stability and accuracy requirements for a PHIL experiment. Previously
presented work [Hatakayama et al.] focused on the theoretical presented work [Hatakeyama et al.] focused on the theoretical modelling for a simple case in which the software/hardware interface was modelled as a pure delay and on the case of a interface was modelled as a pure delay and on the case of a
passive DUT. In this paper, the theoretical model is refined
by taking into account all the main dynamics of the by taking into account all the main dynamics of the software/hardware interface. These dynamics include the
effects of finite handwidth and output impedance of the effects of finite bandwidth and output impedance of the effects of finite bandwidth and output impedance of the
power amplifier, the sensor gain, and the delay of the digital
real time simulator. The paper, furthermore, focuses on the real time simulator. The paper, furthermore, focuses on the case of an active DUT, implying opposed power flow
direction with respect to the model in Hatakayama et al. direction with respect to the model in [Hatakeyama et al.]. Moreover, it presents how this theoretical framework can be more ver, it presents how this inversion mathematic wear can be reference tracking over a wide frequency band. In order to the frequency band of the frequency band. In order t
In order to the frequency band of the frequency band of the frequency band of the frequency of the frequency o reference tracking over a wide frequency band. In order to used on a PHIL test bench for wind turbine nacelles. used on a PHIL test bench for wind turbine nacelles. Moreover, it presents how this theoretical framework can be

Fig. 1. Block diagram of a PHIL system [Hatakeyama et al. 1] al.]. al.]. al.]. al.]. \blacksquare al. Block diagram of a PHIL system \blacksquare al.].

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10.1016/j.ifacol.2017.08.2470 **10.1016/j.ifacol.2017.08.2470 Copyright Copyright Copyright Copyright Copyright Copyright Peterstion of Automatic Copyright Peterstine Copyright On 1016 (i.i.f., c.) 0017 08.0470.**

2. MODELING OF THE POWER HARDWARE IN THE LOOP WITH DIFFERENT INTERFACE ALGORITHMS

In this section, the model of the Power Hardware in the Loop (PHIL) with several Interface Algorithms (IAs) is derived.

The exemplary Naturally Coupled System (NCS) presented in this paper is a voltage divider, shown in Fig. 2, which is the connection of two active systems, i.e. the wind turbine with its grid-connected converter and the power grid. Specifically, v_2 and Z_B model the output characteristics of the grid-connected converter, while v_1 and Z_A model the power grid. The conceptual PHIL implementation is shown in Fig. 3. The NCS is split in two parts, i.e. the ROS and the DUT. In this representation, v_1 and Z_A are part of the ROS, while v_2 and Z_B are part of the DUT. The power amplifier is modelled as an ideal voltage source with the feed forward transfer function T_{FF} , which models the limited bandwidth of the amplifier. The voltage reference $v_{A,PHIL}$ is sent from the realtime simulator to the power amplifier. At the same time, current $i_{\text{B,PHIL}}$ and voltage $v_{\text{B,PHIL}}$ are sensed and fed back to be included in the real-time simulation. The impedance Z_{AB} models the input impedance of the power amplifier acting as a sink of the power generated by the wind turbine. The transfer functions T_D and T_{FB} model the time delay introduced by the real-time simulator and the sensing feedback path, respectively. The experimental setup connects RTDS as realtime simulator for the ROS, a 6 MVA power amplifier, and a research wind turbine as DUT.

Fig. 2. NCS representative of the wind turbine with its gridconnected converter and the power grid [Hatakeyama et al.].

Fig. 3. PHIL system of the NCS shown in Fig. 2.

Ideally, the PHIL system should behave exactly like the NCS if Z_A and Z_B are accurate models of the actual grid impedance and output impedance of the grid-connected converter, respectively. However, the PHIL system may behave rather differently from the NCS mainly because the power interface has a finite bandwidth, delays, and presents errors such as offset, harmonics, nonlinearities, etc. Therefore, the PHIL system may become unstable or being inaccurate with respect to the NCS, which is the reference test case. In the literature, it was presented that the IA plays a key role in the PHIL system to ensure both stability and accuracy. Among the several IAs that have been proposed [Hatakeyama et al.], [Ren et al.], the following subsections present the modelling of the PHIL system with two IAs: the ideal transformer model (ITM) and the damping impedance method (DIM).

2.1 Ideal Transformer Model Interface Algorithm (ITM IA)

The ITM IA is the simplest IA. Fig. 4 shows the PHIL system with ITM IA. In this system, the power amplifier receives reference voltage $v_{A,\text{ITM}}$ from the real-time simulator and provides power to the DUT. Simultaneously, the sensor measures the current $i_{\text{B,ITM}}$ through the DUT and feeds it back to the ideal current source connected to the ROS in the realtime simulator. The feedforward path of this PHIL system contains a time delay $T_D = e^{-sT_d}$, which represents the sampling of the real time digital simulator, and a transfer function T_{FF} , which model the bandwidth of the power amplifier. The only feedback path, instead, contains a transfer function T_{FB} representative of the sensing of the power amplifier. The equivalent block diagram of the PHIL system with ITM IA is shown in Fig. 5 and it is derived by inspection of Fig. 4.

Fig. 4. PHIL system with ITM IA [Hatakeyama et al.].

Fig. 5. Equivalent block diagram of the PHIL system with ITM IA [Hatakeyama et al.].

2.2 Damping Impedance Method Interface Algorithm (DIM IA)

The damping impedance method (DIM) IA is slightly more complicated than the ITM IA. The PHIL system with DIM IA is shown in Fig. 6. In addition to the current-controlled

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