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

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Abstract: In Power-Hardware-In-the-Loop (PHIL) setups, the device under test (DUT) 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 comprehensive theoretical framework for the analysis of the two aspects of a PHIL system with different 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.

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

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 turbines are in-field tests, certification is a long and costly, non-predictable process due to the dependence on external influences, like wind speed. If the tests are done on system 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 of the behaviour of a wind turbine for different grid 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 PHIL setup, depicted in Fig. 1, the wind turbine as device under test (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/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, 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 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 non-idealities of the power amplifier. These non-idealities, e.g. delays, sensing errors, non-linearity, prevent the power amplifier from providing a high-precision 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 PHIL simulations. Several IAs are investigated and compared in [Hatakeyama et al.], [Ren et al.]. A comprehensive modelling framework is therefore needed to provide guidelines addressing the effect of IAs on the stability and accuracy requirements for a PHIL experiment. Previously 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 passive DUT. In this paper, the theoretical model is refined by taking into account all the main dynamics of the software/hardware interface. These dynamics include 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 case of an active DUT, implying opposed power flow direction with respect to the model in [Hatakeyama et al.]. Moreover, it presents how this theoretical framework can be used on a PHIL test bench for wind turbine nacelles.

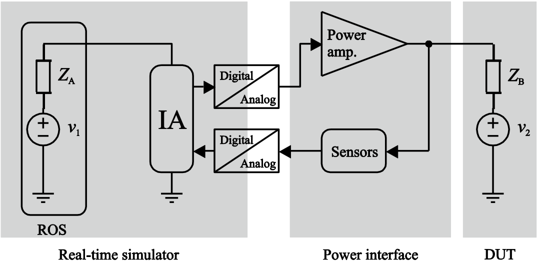

Fig. 1. Block diagram of a PHIL system [Hatakeyama et al.].

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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 real-time simulator to the power amplifier. At the same time, current $i_{B,PHIL}$ and voltage $v_{B,PHIL}$ 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 real-time simulator for the ROS, a 6 MVA power amplifier, and a research wind turbine as DUT.

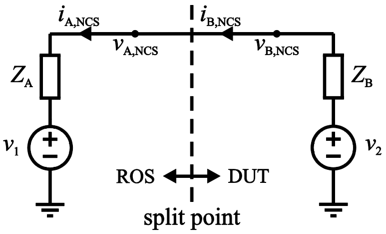

Fig. 2. NCS representative of the wind turbine with its grid-connected converter and the power grid [Hatakeyama et al.].

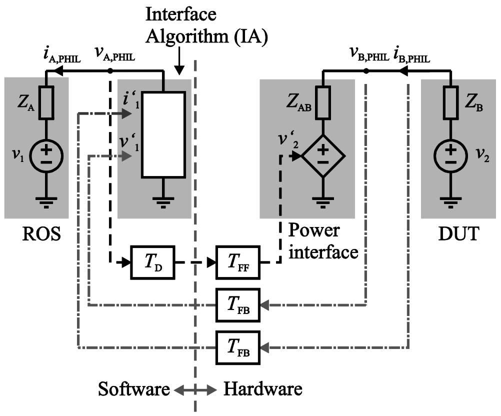

Fig. 3. PHIL system of the NCS shown in Fig. 2.

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 $v_{A,ITM}$ from the real-time simulator and provides power to the DUT. Simultaneously, the sensor measures the current $i_{B,ITM}$ through the DUT and feeds it back to the ideal current source connected to the ROS in the real-time 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.

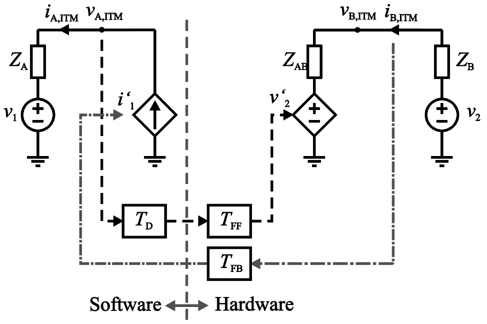

Fig. 4. PHIL system with ITM IA [Hatakeyama et al.].

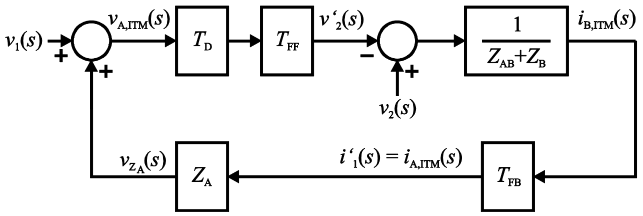

Fig. 5. Equivalent block diagram of the PHIL system with ITM IA [Hatakeyama et al.].

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