Interface and Stability Issues for SISO and MIMO Power Hardware in the Loop Simulation of Distribution Networks with Photovoltaic Generation

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Abstract- The Power Hardware-in-the-Loop (PHIL) simulation can be used to determine the dynamic behaviour of renewable energy sources feeding into a grid before deployment. This article shows the necessary prerequisites for achieving stability of the simulation. It enlarges the range of SISO interfaces and introduces the MIMO PHIL simulation and the associated interfaces. A use case is shown with two photovoltaic inverters feeding into a low voltage distribution grid. In a lot of applications stability of the simulation can be judged beforehand by use of analytic concepts and a pure software simulation. This opens the way for a broad range of application for Power Hardware-in-the-Loop simulation studying the interaction component-grid-component.

Keywords- Photovoltaic Inverters, Power Hardware-in-the-Loop Simulation, Stability, MIMO Systems, Renewable Power Generation.

1. Introduction

The Power Hardware-in-the-Loop (PHIL) simulation, as an efficient tool for testing and modelling electrical components or even micro grids in real time, is becoming more and more popular. The use of PHIL should reduce both time and costs allowing experiments not otherwise viable. As opposed to Controller Hardware in the Loop (CHIL), where the simulated part is the environment or plant and the real existing part is the controller hardware, with PHIL part of the plant or system also exists in hardware, which leads to interesting configurations but creates new problems at the same time.

A classic example is a power network, which is partly simulated and partly existing as real hardware, which is attached via a so called Power Interface (PI) to the simulation system (real time computing system). The PI in between software and hardware has to convert the low voltage / low power output signals from the real time computing system into high-power signals and vice versa. This conversion clearly cannot be done ideally; inherent non-ideality affects stability, accuracy, noise behaviour, and other aspects of the configuration. The fact that PHIL allows part of the power hardware to be implemented enables power components, which are difficult to be modelled, to be attached via the power interface directly to the real time computing system, thus guaranteeing better overall results.

At any times, a PHIL simulation must be stable and should exhibit a certain amount of accuracy; both of these issues must be addressed when setting up a PHIL experiment. This contribution approaches the analytical background of determination of stability for linear Power Hardware in the Loop enhancing the literature [1,2]. Results for stability of PHIL simulations are given. The dual interface algorithms are introduced and the describing interface equations for MIMO PHIL are given.

Basic methods used within this contribution are a quasi continuous approach (continuous time domain analysis) for modelling the hybrid PHIL system, the SISO and MIMO Nyquist criteria for determination of stability of a linear system and special results from circuit theory for describing the MIMO PHIL interface. This approach is justified by its ease of implementation and possibility for automation. Additionally, the stability margin can also be determined. The quasi continuous approach has also been adopted by other authors [1,2,3,4]; its consistency with measurements from real system has been shown [2,5].

The article is organized in the following way: Chapter 2 gives a just short overview of a basic PHIL simulation configuration. Chapter 3 deals with all necessary information for stability determination for SISO PHIL simulations, whereas chapter 4 generalizes these results in the MIMO domain. In chapter 5 the theoretical results are applied to a low voltage electrical network with two feeding in photovoltaic inverters. Chapter 6 states the conclusion for the article and gives recommendations for future work.

2. Basic Power Hardware in the Loop Configuration

Figure 1 shows a typical PHIL configuration. A real time computing system is connected via a power interface (it contains usually a linear or switched-mode voltage or current amplifier or a PSM generator which is especially suited in the case of three phase systems [6]) to the real hardware component, the Hardware under Test (HuT) (e.g. a photovoltaic inverter). The HuT can produce or consume energy, consequently the power amplifier must be capable of providing or absorbing power, which all has to be adjusted to the appropriate scale of application.

There are different methods existing, which are denominated as Interface Algorithms (IA), how the coupling between real computing system and HuT is carried out.

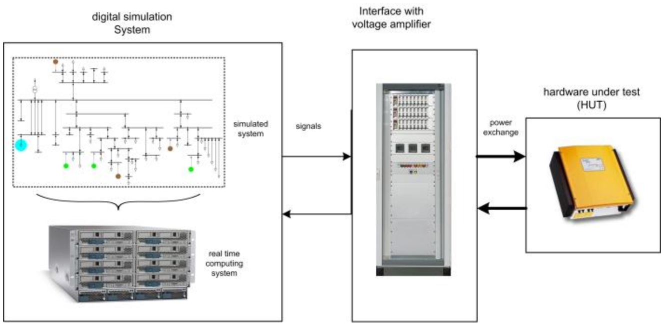

Fig. 1. Typical PHIL configuration (SISO)

3. Stability Determination for SISO PHIL Simulations

In order to introduce this topic, a very simple PHIL setup consisting of a voltage divider circuit and two complex impedances ZA, ZB is depicted in Fig.2. The impedance ZB should not be simulated but realized as real hardware. A lot of applications can be reduced to this simple canonical circuit.

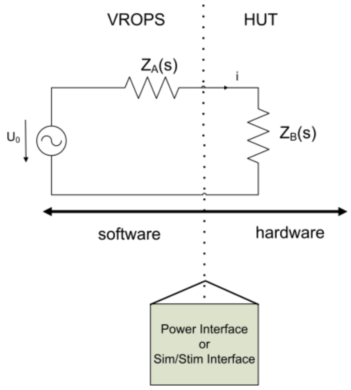

Fig. 2. Basic circuit for introducing the idea of the PHIL simulation

As far as the denotation is concerned, the nomenclature introduced by Ayasun [7,8] is used. In this case, the voltage source in series with the internal impedance ZA represents the simulated part and is called as the virtual rest of power system (VROPS). The interface in between the VROPS and the HuT is named as the Simulation/Stimulation interface (Sim/Stim) or simply the power interface (PI). The circuit topology of the PI is called the Interfacing Algorithm (IA). A thorough description of some of the most common IAs can be found in [2] and [3]. The most basic IA is the Ideal Transformer Model (ITM) method. It has two occurrences, the voltage type and the current type ITM IA.

In Fig.3 (top) the PHIL setup for the discussed circuit with the voltage type ITM IA is shown. The software side consists of a current controlled current source, which is driven by the measured current captured on the hardware side. On the hardware side there is a controlled voltage source (linear voltage amplifier), which is actuated by the output voltage computed on the software side. In Fig.3 (right side) the corresponding signal flow diagram is shown.

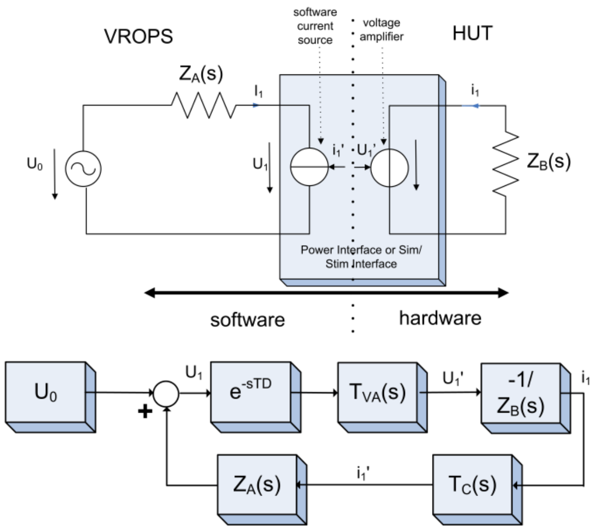

Fig. 3. Basic PHIL setup with PI and ITM IA and the corresponding signal flow diagram

From a system theoretic point of view this PHIL setup can be described as a SISO control loop. The dynamic behaviour of the current measurement scope and the voltage amplifier is considered by the introduction of appropriate transfer functions TC(s) and TVA(s) respectively. As far as the modelling of the discrete behaviour of the real time computing system concerns, as opposed to [7,8] a pseudo continuous approach is taken as in [1,2,3,4,5,9]. The behaviour of the digital simulator is modelled by an additional time delay (e-sTD), which is set to twice of the size of the sampling time TS of the real time computing system (TD=2TS).

Quantization effects are not considered. In order to discuss stability properties of this setup, the open loop transfer function of the whole control loop is of interest and is given as:

$$F_O(s) = -\frac{Z_A(s)}{Z_B(s)} e^{-sT_D} T_{VA}(s) T_C(s). \quad (1)$$

The open loop transfer functions for the most common interface algorithms are summarized in Tab.1. Please note that the dual interface demand a power amplifier that acts as a current source (current type) (I1'), where as the interfaces on the left side of the table require a voltage amplifier (voltage type) (U1').

The determination of the stability in the case of linear SISO PHIL simulation amounts to the task of finding the open loop transfer function of the complete PHIL setup. Then the Nyquist criteria (confer [10]) can be applied to determine both system stability and the corresponding stability radius.

Within this contribution the focus is now set to three IAs [1,2]: the already mentioned ITM IA, the Partial Circuit Duplication (PCD) IA and the Damping Impedance Method (DIM) IA. The PCD IA voltage type is characterized by considering the impedance ZAB that exists on the software as well as on the hardware side of the simulation. In both domains (software and hardware) there are voltage controlled voltage sources driven by the voltages captured at the terminals of the HuT and at the left input of the PI respectively.

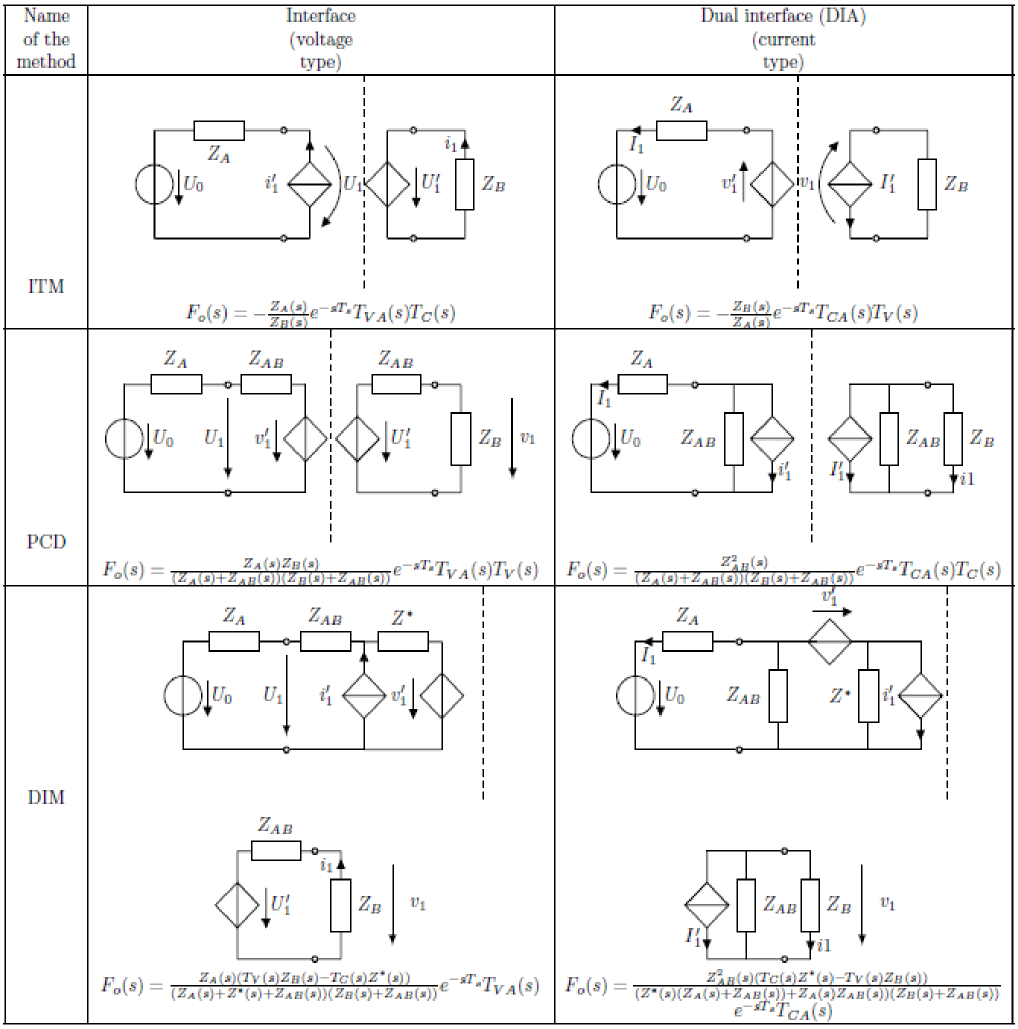

Fig. 4. Interface types (ITM: Ideal Transformer Model, PCD: Partial Circuit Duplication, DIM: Damping Impedance Method) and associated open loop transfer functions of the SISO PHIL simulation. The voltage type interfaces (left side) have been introduced in [2]. The dashed line separate the software implementation of the PHIL simulation from the hardware implemented parts. TV(s), TC(s) are the transfer functions of the voltage and current measurement devices, TVA(s), TCA(s) the transfer function of the voltage and current amplifier in the high power range, TD is the characteristic time delay due to the computing delay of the simulation configuration.

The DIM IA is characterized by the insertion of an additional impedance Z* on the software side only, which is called damping impedance. Both, voltage and current signals, are measured at the clamps of the HuT. They are fed back to drive a voltage controlled voltage source and a current controlled current source respectively on the software side of the PHIL simulation. The damping impedance method achieves an optimal result referring to stability as well as to accuracy, if the value of the damping impedance is equal to the one of the HuT impedance. In practical applications this assumption is not very realistic, since it cannot be assumed that the pre-knowledge of the characteristics of the device under test is given in detail. This imperfection reduces especially the stability margin and the achieved accuracy considerably

Figure 4 summarizes the stability results for the aforementioned voltage and current type IAs. In the second column of Fig.4 the system topology and its related open transfer function for the basic circuit for the different IAs are given, while the third column shows the equivalent results for the dual interface algorithm (DIA). The DIA (also called current type) is obtained by building the dual circuit.

Implementing the DIA asks for a current amplifier (I1') as required power amplification. As can be seen in Tab.1, the open loop transfer function of the DIA and the IA differ from each other in a significant way (implementation and range of applications). Generally spoken, the DIA is better suited if the HuT is connected in series with other elements (e.g. FACTS), while the "non" dual interface features more applicative system behaviour, if the HuT is connected as a shunt (e.g. generators, loads) [3].

4. Stability determination for MIMO PHIL simulations

Until now a PHIL setup has been discussed that allows only one single hardware component be connected via the PI to the simulated system. The main application for such a setup (SISO PHIL) is to improve the modelling and identification of single components. The flexibility offered by the software driven part of the PHIL-simulation can be used in an advantageous way to carry out sophisticated identification procedures obtaining useful models of the component (HuT). Once the model has been identified and created, further simulations based on this model can be run without any need to attach real hardware. Such ongoing system control investigations are heavily depending on the quality of this gained model and it does not matter from a system theoretic point of view, if the simulations are executed offline or in real-time.

If multiple components are attached to a common infrastructure (for example an electrical network), which

- are difficult to model
- are particularly chosen for investigations on interaction of integrated subsystems
- and the common infrastructure cannot be rebuilt in real hardware due to its systematic complexity and physical properties

A MIMO PHIL approach seems to be the right choice for simulation. A MIMO PHIL simulation consists of multiple interfaces between the real time computing system and the HuT as shown in Fig.5.

In order to highlight this situation a very simple impedance network is shown in Fig. 6., which could reflect an electric energy system with a power source, a distribution line and two devices (impedances, generators or loads) attached at the different location of the distribution line.

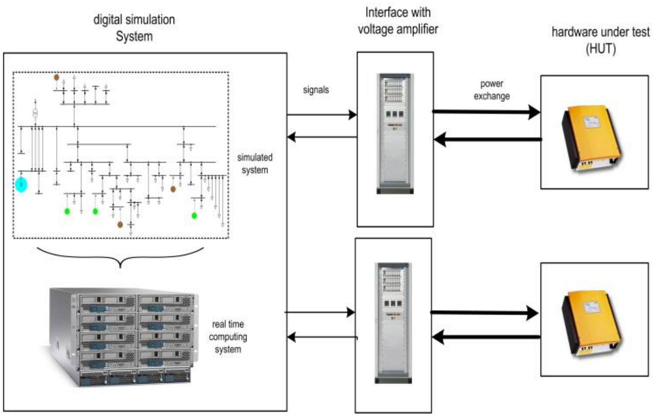

Fig. 5. A MIMO PHIL configuration

The two impedances of this network should be realized as real hardware components (HuT 1 and HuT 2) and the rest of it as VROPS.

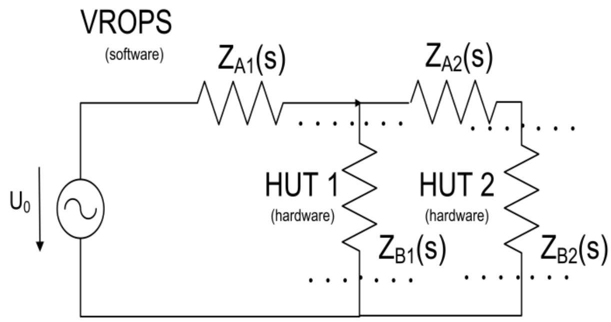

Fig. 6. Impedance network as an example for MIMO PHIL

From a system theoretic point of this setup is similar to a MIMO control loop. By using the ITM IA the signal flow diagram of the resulting PHIL simulation system looks as depicted in Fig. 7.

The generalization of the stability determination to the MIMO PHIL case consists in the fact that the open loop behaviour in the MIMO case is no longer described by an open loop transfer function FO but by an open loop transfer matrix FO.

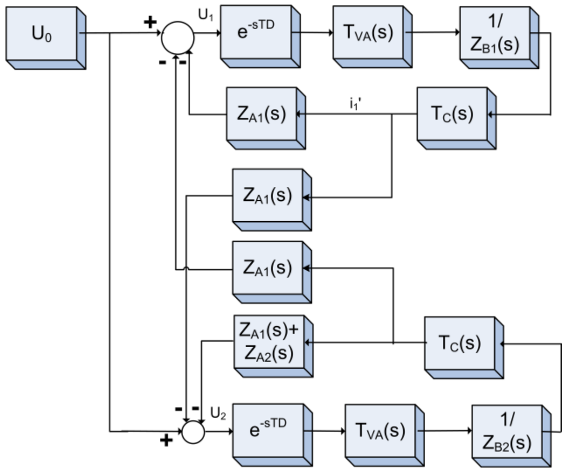

Fig. 7. Signal flow diagramm of the MIMO PHIL example in Fig. 6

The Nyquist criteria can be generalized to MIMO systems [11]. In this case the encirclements of the curve of the function W(jw) regarding the Nyquist point (-1,0) must be evaluated. The function W(jw) is given by

$$W(jw) = -1 + \det(\mathbf{I} + \mathbf{F}_O(jw)), \qquad (2)$$

where **I** is defined as the unit matrix of appropriate dimension

In Fig.9 the topology of the MIMO systems for the three different IAs (the topology is shown for two "real" hardware components but the results apply also for higher order systems) and the open loop transfer matrix functions are given. These are just generalizations of the SISO results given in Tab.1. Please note that all matrices apart from the describing matrix of the electrical networks are diagonal matrices, due to the fact that the two HuTs are coupled via the network.

5. Low voltage grid with Photovoltaic Inverter feeding example

5.1. Setup Description

The theoretical results developed in secion 2, 3 and 4 are now applied to pre-estimate the stability properties of a realistic PHIL simulation scenario. A low voltage grid is simulated in software and two photovoltaic inverters are coupled via PIs to the software simulation system (Fig.8). Such constellation could be used to study interaction phenomenon in between the two inverters coupled via the grid.

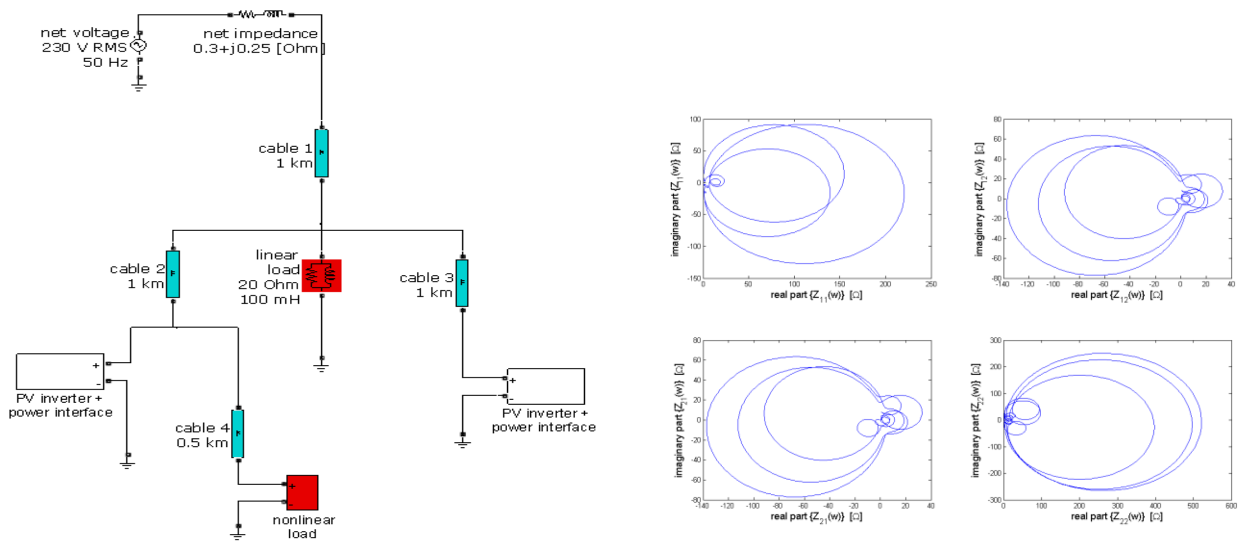

Fig. 8. Distribution network with two PV inverters feeding in considered in the case study (left), Locus plot of the entries of the impedance matrix of the network (right)

The network consists of cables (Type AY50: R'=0.641 Ω/km, X'=0.083 Ω /km, C'=0.8 µF/km), a linear load and a nonlinear load. The introduced nonlinear load consists of a rectifying bridge feeding a linear load. In order to make it highly nonlinear the threshold voltage of the diodes of the rectifier has been set to a high value. Therefore, the nonlinear load injects higher harmonic currents into the network and can be considered as a load like a cluster of computers. The network is simulated both without and with the nonlinear load attached. The stability criteria, discussed up to now, have been determined for linear systems only. The following procedural steps are advised: establish stability for the whole PHIL simulation system without considering the nonlinear load, check if the system runs still stably when the nonlinear load is attached by use of a simulated (computed) PHIL simulation. If not, try to enlarge the stability radius (or margin) of the linear system in order to account for the nonlinear element.

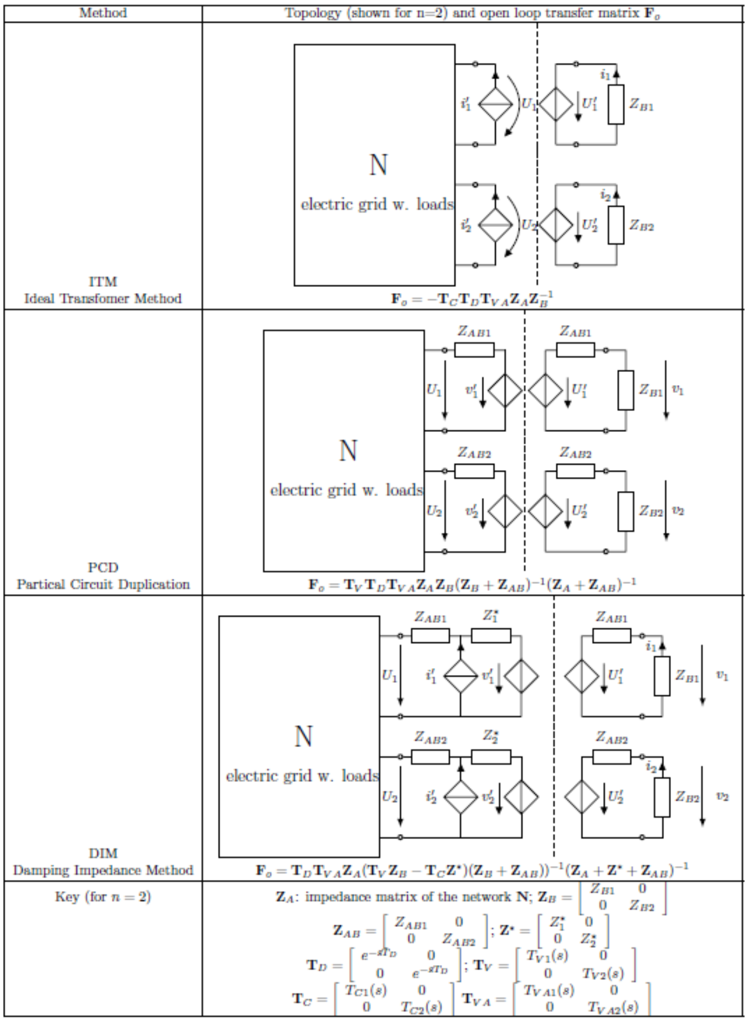

Fig. 9. Interface algorithms for MIMO PHIL and associated open loop transfer matrix. Exemplary the 2-dimensional case is given, but the results apply also for higher dimension.

For the stability determination of the linear part of the simulation, models of the photovoltaic inverters and the energy generation is necessary [12]. This is not straightforward and a demanding task generally since for example the PV inverter topology can be quite complex as in [13]. Modelling the PV generation part has been approached in [14]. A very simple model like in [15,16,17] has been used: Both photovoltaic inverter systems are modelled as an AC current source connected to an output filter of 4th order as shown in Fig. 10 (R=2.94 Ohm, L=12mH, C1=1µF, C2=2.2µF). It is the experience of the authors that the output filter plays an important role in determining stability of the whole PHIL simulation: Photovoltaic inverters commonly monitor both grid voltage and frequency at the point of coupling (U2) before starting to feed into the connected power network [18]. During monitoring time the output filter may be already attached to the network depending on the PV inverter device. If during this monitoring period the PHIL simulation becomes unstable, the PHIL simulation has to be stopped in order to avoid damage to the infrastructure (PI and PV inverter). Therefore, a necessary requirement for the PHIL simulation in this particular case is given in obtaining stability of the simulated network together with the PI and the output filter of the PV inverter.

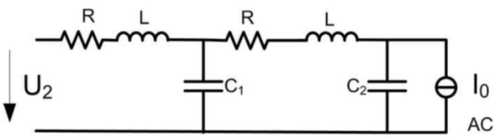

Fig. 10. Modelling of the PV inverter for stability determination purpose

Basically, there is no known state-of-the-art general analysis technique for a PHIL simulation including nonlinear elements existing to determine stability and accuracy [19]. It is suggested to approximate the existing system with a linear system as well as possible and to judge the influence of the nonlinearities by a so called simulated PHIL simulation. This is a pure software simulation, which includes the introduction of the HuT and the IA the simulation model together with the deficiencies of the PI (delays, bandwidth limitation, dynamic behaviour of the power amplifier and the measurement probe, …). Within this contribution stability is determined analytically, omitting the nonlinear load. Having chosen the proper stable interface for the intended test the nonlinear load is reconsidered and the system stability is determined by a simulated (computed) PHIL simulation.

From a system theoretic point of view the linear network in Fig.8 (left) with the attached linear load can be compactly described by an impedance matrix ZA of the size 2*2. The entries of the impedance matrix of the linear part of the network are depicted in Fig.8 (right side). Since the network is reciprocal, Z12 and Z21 are equal.

The network has been prepared for PHIL simulation by choosing appropriate IAs. In the following two cases are compared: the ITM and the PCD IA method. It is assumed that the step size of the real time computing system is around T_S=25 µs leading to a total delay (T_D=2TS) of 50 µs. The PI is described by the transfer functions of the voltage amplifiers $T_{VA1(s)}$,$T_{VA2(s)}$ and the transfer functions of the current and voltage probes $T_{C1(s)}$,$T_{C2(s)}$,$T_{V1(s)}$,$T_{V2(s)}$ respectively. These transfer functions are defined as follows (identified from real equipment):

$$T_{VA1}(s) = T_{VA2}(s) = e^{-s*4.2[\mu s]} * \\ * \frac{1}{1+s*0.8[\mu s]+s^2*2.913*10^{-13}[s]}, \qquad (3)$$
$$T_{V1}(s) = T_{V2}(s) = \frac{1}{1+s*8[\mu s]},$$
$$T_{C1}(s) = T_{C2}(s) = \frac{1}{1+s*8[\mu s]}.$$

As can be seen from (3) the used power (voltage) amplifier is highly dynamic with a time delay of 4.2 µs and some almost negligible PT2 behavior. So the power amplifier should not really be the bottleneck of this setup. It must be said that the used power amplifier has a fully linear design. As opposed to switched mode amplifier it is very fast but dissipates a lot of energy. It is not practically feasible to have linear amplifiers with power ratings of more than 50 kW per phase, but the power ratings of the used power amplification are more than sufficient for this case study.

5.2. *Results and Discussion*

The application of the stability criteria according to chapter 4 leads to the following results:

The PHIL simulation of the configuration with the ITM interface does not run stably without any countermeasure (Fig.11 top). As countermeasure, an inductance on the hardware side has been inserted in series for both PVs (Fig. 11 bottom). Unfortunately, this chosen inductance has to be a high value in order to guarantee stability. This influences negatively the accuracy of the simulation. The Nyquist plot of the function W(jw) is shown in the case of no additional hardware inductance (unstable) and in the case of an additional hardware inductance of 1.5mH (stable) in Fig.11.

In the case of PCD IA the most important parameter is the value of the common resistor; the PHIL simulation of the configuration runs stably when the common resistor is greater than 0.5 Ohm. Figure 12 shows the Nyquist plot of the function W(jw) in this case.

The stability criterion has been derived for the linear case and a very rough model of the PV inverter has been used. To test these stability estimates a PHIL simulation has been carried out with real photovoltaic inverters attached.

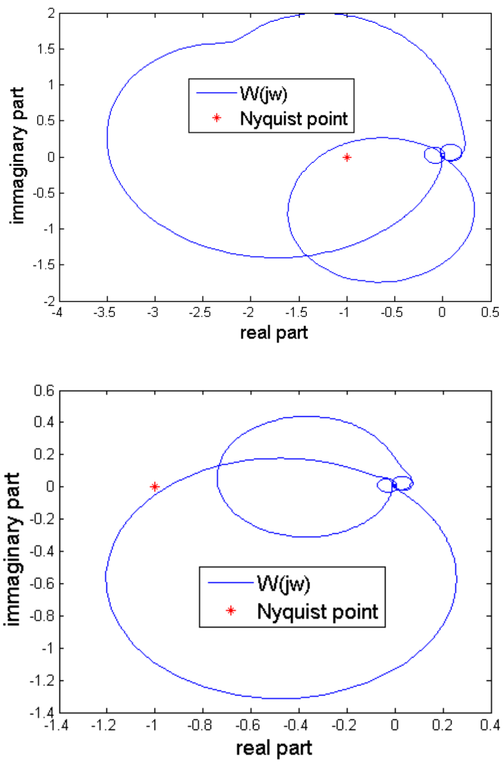

Fig. 11. Nyquist plot for ITM IA without and with additional hardware inductance

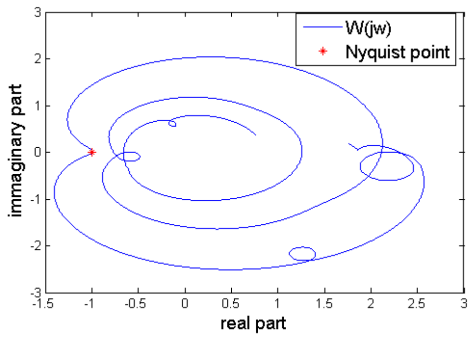

Fig. 12. Nyquist plot for PCD interface (common resistor R=0.5Ohm)

The experiment has been carried out with the ITM interface and additional hardware inductance of 1,5mH at each PI. The nonlinear software element (nonlinear load) is activated (attached to the network) after a certain while. In Figure 13 the voltage over PV inverter 2 obtained by PHIL experiment is shown. It can be seen that the simulation runs stably and that the nonlinear load (activated after t=0.75sec) influences slightly the wave form of the sine voltage.

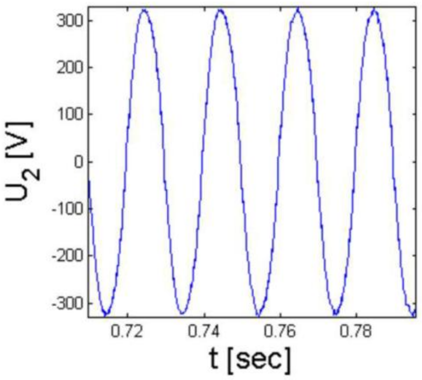

Fig. 13. Voltage U2 with and without attached nonlinear load (ITM IA)

6. Conclusion

Within this contribution the necessary analytic background determining the stability properties of PHIL configurations with the most commonly used interface algorithms has been introduced. The Nyquist criterion has been chosen as the stability criterion and the necessary open loop transfer functions in the case of SISO PHIL configurations or function matrices for MIMO PHIL configurations have been determined. The background elaborated in this article gives the PHIL simulation engineer a powerful tool at hand. In principle, this kind of analysis is restricted to linear systems, but a possible modus operandi is suggested: Nonlinearities should be linearized or omitted in a first step, and the obtained linear system can be analyzed in detail with the use of the results indicated in this article as far as stability is concerned. Consequently an interface algorithm with the right parameterization that guarantees stability and a certain stability margin in order to account for the neglected nonlinearities has to be set. What follows is a simulated PHIL simulation, when nonlinearities are reintroduced and the chosen interface algorithm gets adopted in its parameterization due to the introduced nonlinear components. If the simulated PHIL simulation does not achieve stability more conservative measures have to be considered, which have to be recalculated in an iterative process.

Even if this method does not succeed for all practical cases it represents a satisfactory approach for a lot of systems. The determination of the system stability of a PHIL simulation beforehand has one intrinsic drawback. A sufficiently well-known model of the HuT must be available in advance, which is not always guaranteed. Therefore the search for an adaptive self stabilizing interface algorithm for PHIL simulation together with multi rate simulation approaches like in [17] may be a rewarding research topic.

Acknowledgements

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