POWER HARDWARE-IN-THE-LOOP SIMULATIONS FOR DISTRIBUTED GENERATION

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ABSTRACT

This contribution discusses the wide range of applications, the technical obstacles that have to be overcome and gives some hints how to set up a PHIL simulation focusing on robust stability and accuracy. Two important interface algorithms for a PHIL simulation are discussed and compared. A further possible improvement for the simulation system is described and an example in the field of Distributed Generation is given, in which the elaborated methods have been applied successfully.

INTRODUCTION

The integration of distributed energy systems in distribution networks demands for powerful simulation methods in order to determine both system and component behavior. Prior to the installation the operation of an active network should be simulated in order to ensure safe operation of single components as well as their efficient integration into a whole distribution network. Power Hardware-in-the-Loop (PHIL) simulation is a promising simulation technology, which is capable of simulating electric energy systems including active distribution networks. Alongside with the great progress of real time systems, Hardware-in-the-Loop (HIL) simulations have been used more and more in power systems. However, HIL simulations are mainly limited to the design of controllers, which is called Controller Hardware-in-the-Loop (CHIL) simulation as there is a lack of power amplification and thereby the output power is limited to some Watts.

Introducing a power amplifier, which provides or absorbs real power, to a HIL simulation increases the typical power range up to Kilowatts or even Megawatts. Therefore devices or subgrids can be connected to a real time computing system that simulates a distribution grid and other devices attached to the simulated grid.

The basic setup of a PHIL simulation is depicted in Fig. 1. Despite the big potential of PHIL the introduction of the power interface cannot be seen as ideal. Introducing a real power interface into a system will inherently introduce errors such as e.g. noise, nonlinearities. These errors are caused by various aspects such as a non-ideal transfer function, limited bandwidth, etc. and thereby introduce serious challenges even to the basic development of a PHIL simulation.

The biggest advantage of PHIL can be seen for the application of (sub)systems, or single components, which cannot be modeled appropriately, or which do not have a determined model available, which does not satisfy ones needs in terms of modeling characteristics (depth, accuracy, ect.). The main idea of PHIL simulations for Distributed Generation (DG) is to simulate the large well known part of an active distribution network in software and to integrate critical parts (difficult to model or unknown models) as real hardware into the simulation system. This opens a very wide range of possible applications as for example rapid prototyping and modeling, enhanced fields of component tests and analyzing the impact of distributed energy resources on any specific distribution network. Thus, this setup empowers a wide range of usecases and studies on active distribution grids.

This contribution is structured in the following way: Firstly an introduction is given to the most interesting PHIL interfaces and is followed by a short discussion on their applicability for simulations in the field of DG. It is continued by a technical chapter on PHIL interface algorithms from a stability point of view. In the end, the presented methods are applied to an example in practical with a grid-connected photovoltaic inverter as the dedicated hardware under test (HuT).

PHIL-INTERFACE TOPOLOGIES

There exist different methods – so called interface topologies – to couple a real time computing system with the hardware under test.

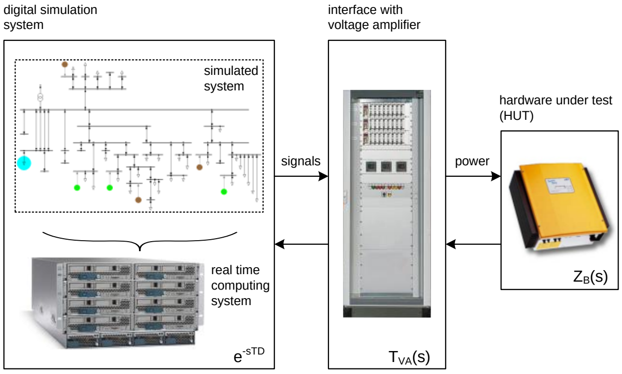

Fig. 1: Overview of a PHIL simulation

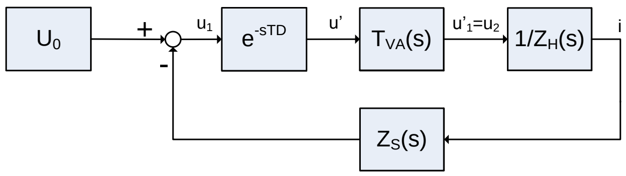

Fig. 2: Signal flow diagram of a PHIL simulation (system theoretic point of view)

In general, it can be stated that even though the real application is stable the appropriate PHIL experiment does not necessarily have to be stable. Basically, this is the result of the fact that the power amplification is not ideal in reality.

The interface of a PHIL simulation is the interconnection between the real hardware and the software simulation. Typically, this is implemented using a power amplifier for the software to hardware link and some measurement devices for the hardware to software connection. The following explanation assumes that the real time simulation is performed discretely, as it is common practice and that the ITM interface (explanation follows) is adopted.

If at any time t_k an error ε is introduced to the voltage amplification of the hardware voltage u_2, the resulting error of the hardware current i out of Fig. 2 is given as it follows

$$\Delta u_H(t_k) = \varepsilon \text{ and } i = {}^{u_2}/_{Z_H} \rightarrow \Delta i(t_k) = {}^{Z_S}/_{Z_H}.$$

Remembering that the real time simulation can be assumed to be discrete, the result at the next time step will be that the previous error is amplified by the factor of $-(Z_S/Z_H)$. As a consequence it can be stated that instability occurs having $Z_S/Z_H>1$, which results in reaching the hardware limits of the HuT or of the power amplification.

It becomes very obvious that the sample time of the real time simulation system is a key element for the stability of the simulation.

Ren [1] published a fundamental paper describing PHIL interface algorithms. The Interface Algorithms of highest interest are the Ideal Transformer Method (ITM) and the Damping Impedance Method (DIM).

The Ideal Transformer Method (ITM)

The ITM (Fig. 3) is a very conventional and straight forward method in implementing a PHIL simulation. Depending on the signal amplification it can be categorized as a voltage or current type ITM. This paper will focus on the voltage type ITM.

Assuming an ideal voltage type power interface the only error introduced to the system is caused by the time delay T_D.

The open loop transfer function of the ITM interface can be derived as follows

$$-Fo(s) = e^{-sT_D} T_{VA}(s) \frac{Z_S(s)}{Z_H(s)}.$$

With Z_S equivalent to the total impedance of the simulated system and Z_H equivalent to the total impedance of the HuT it can be stated that the stability of a PHIL simulation using an ITM Interface is strongly dependent on the ratio of Z_S/Z_H. It can be concluded that, if the voltage amplification is ideal ($T_{VA}(s)=1$), $Z_S/Z_H<1$ can be stated to be necessary for achieving stability.

The Damping Impedance Method (DIM)

The Damping Impedance Method is a combination of the ITM and the Partial Circuit Duplication method (PCD) modified by inserting a damping impedance Z* (Fig. 4). The PCD will not be described in this paper but can be found in [1]. The consistency can be checked by considering the following fact: When Z* is zero, the voltage u* equals u and the DIM becomes the PCD method; when Z* is infinite, the current flowing in the simulated systems equals to i_1, and the DIM becomes the ITM.

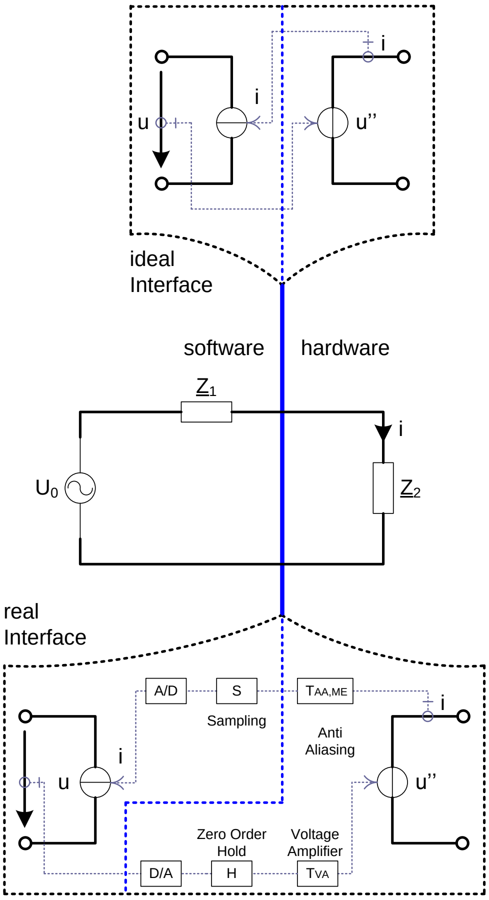

Fig. 3: Schematic overview of the ITM interface

The open loop transfer function of the DIM can be derived from the control loop depiction (Fig. 5) to

$$-F_O(s) = e^{-sT_D}T_{VA}(s)\frac{Z_S(Z_H - Z^*)}{(Z_H + Z_{SH})(Z_S + Z_{SH} + Z^*)}.$$

It can be observed out of the open loop transfer function of the DIM that if Z* equals to Z_H the magnitude of $-F_O$ becomes 0, which implies stability on principle. Ren concluded that the DIM provides both high stability and good accuracy as long as the damping impedance Z* is close to the actual impedance of the HuT, thus recommending this interface method for most PHIL applications.

INTERFACE ALGORITHM DISCUSSION

Despite the fact that the ITM interface algorithm has not as good stability properties as the DIM interface algorithm, it still provides essential benefits as for example a very high accuracy. The major drawback of the DIM interface algorithm is the fact that its performance strongly depends on the damping impedance Z*. Hence, the characteristics of the PHIL interface are only as good as ones knowledge is given about the real HuT, since this directly influences the value of the damping impedance and thereby the performance of the interface [2]. One of the starting points for the usage of PHIL simulations for DG is illustrated in the implementation of components, which are difficult to be modeled or for which no model exists. Therefore if the interface algorithm requires good knowledge of the HuT, the use of PHIL is reduced drastically.

The ITM interface algorithm does not necessitate any knowledge about the HuT and thereby is applicable to every PHIL simulation despite the knowledge about the HuT. The main attributes of the ITM interface algorithm are given in the poor stability properties, but excellent accuracy characteristics.

STABILIZING A PHIL SIMULATION USING THE ITM WITH A FEEDBACK FILTER

The major downside of the ITM interface is that the stability strongly depends on the ratio between the simulated impedance Z_S and the impedance of the HuT Z_H. This becomes very obvious using the very basic example of a voltage divider. Taking a look at the open loop transfer function of the ITM interface it can be stated that apart from the term Z_S/Z_H there is no further damping part, as e^{-sT_D}encircles the origin in the Nyquist stability plot and T_{VA} represents the transfer function of the voltage amplification. As a result it is very obvious that an additional damping factor has to be introduced (Fig. 6) – the feedback filter ($T_F(s)$).

With this introduced feedback filter the open loop transfer function derives to

$$-F_O(s) = e^{-sT_D}T_{VA}(s)T_F(s)\frac{Z_S(s)}{Z_H(s)}.$$

The feedback filter frequency has to be calculated in dependency of Z_S and Z_H. For its calculation it has to be taken into account that T_D is the total time delay introduced and thus double the time step of the real time computation system. One might now say that there is no improvement over the DIM method as knowledge of the HuT is required to calculate the cut off frequency of the feedback filter. This is only partly true as the feedback filter generates an upper bound limiting case. That means that as long as the impedance of the HuT Z_H is smaller than the amount assumed for the calculation, the PHIL experiment will be stable, which results in a massive increase of applicability for PHIL simulations.

The major downside of the feedback filter is that it heavily affects the accuracy of the simulation. The smaller the stability margin (the shortest distance from the Nyquist point to the function of the open loop transfer function in the Nyquist plot) is, the higher the accuracy is becoming and vice versa. This means that the closer the cut-off frequency of the feedback filter is set to the limiting frequency, the higher the accuracy of the PHIL experiment gets for increasing power ratings.

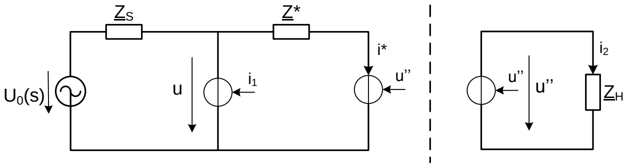

Fig. 4: Schematic overview of the DIM interface algorithm

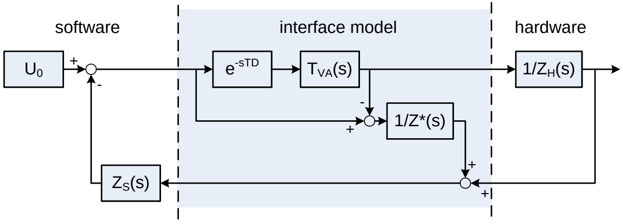

Fig. 5: Control loop of the DIM interface algorithm

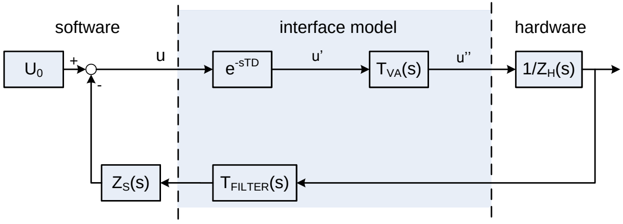

Fig. 6: Control loop of a ITM interface with a feedback filter

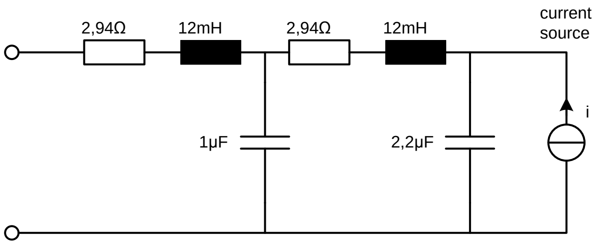

Fig. 7: Simplified model of a photovoltaic inverter

The massive benefit compared to the DIM Method is that stability can be reached at all times, while the reduced accuracy is a direct consequence of the PHIL simulation setting, which can be worked at.

APPLYING THESE METHODS TO A GRID-CONNECTED PV INVERTER

Most published papers discuss a PHIL application having HuT in use with a large inductive part (e.g. Motor Drives [3]). It can be stated that a large inductance in the Hut does help to achieve stability when using an ITM Interface. A brief explanation to this would be that the frequency behaviour of an inductor can be seen as a dampening effect. A more detailed explanation would exceed the scope of this paper but can be found in [4].

DG components such as a photovoltaic inverter do not always offer an inductive behaviour, hence the system design of the HuT does not support the stability of the simulation.

Photovoltaic arrays are producing direct current in dependency of the solar irradiation. Distribution networks typically use alternating current. The inverter transforms the direct current of the photovoltaic array into alternating power which can be connected to the grid. This conversion is typically done using bridge circuits followed by smoothing filters to obtain a sinusoidal shape. Due to power quality standards the output of the photovoltaic inverter has to pass specific quality measurements, which are usually done inside of the device. The connection to the grid is realized using switchable relais and an AC output filter.

Experiments show that the modeling of the whole inverter system is not necessary for stability determinations. The order of the model can be massively simplified and it can be seen as an (ideal) AC current source, which is connected to the grid via the output filter as shown in Fig. 7. It becomes very obvious that the design of the HuT itself does not help to achieve stability in such an above described way.

Hereby, the distribution network is modeled in a very simple way, as the experiment has a feasibility character consisting of a voltage source, a linear load, a nonlinear load as well as some distributed parameter lines. The feedback filter frequency can be based upon the exact knowledge of the simulated grid and a brief information about the HuT.

The used PHIL interface is the ITM interface including a dedicated feedback filter. The power amplification is implemented as a linear voltage amplifier type and therefore the feedback to the real time system is given as a current measurement.

For this specific PHIL experiment all-out stability could be achieved for all operation modi: standby-mode (HuT connected to the grid); operating-mode (HuT injected nominal power to the grid); transient mode (switching events, transients).

CONCLUSION AND OUTLOOK

PHIL simulations are a very promising simulation tool for the huge field of DG network analysis. The most promising interface topologies are the ITM / DIM method, which both have their benefits combined with the specific, previous knowledge in hand. While the DIM method heavily relies on detailed knowledge of the connected hardware to feature its benefits of high stability, the ‘pure’ ITM interface brings along critical stability behaviour together with highly reachable accuracy. Introducing a feedback filter to the ITM interface changes the whole system characteristics in such a way that stability of the PHIL simulation can be achieved, while the simulation accuracy has to be trimmed to a sufficient high level.

PHIL simulations provide massive benefits for state-of-the-art and future challenges in distributed networks, because whole subsystems or single components (grey or black boxes) can be integrated into a simulation environment, which is delivering real-time results of the behaviour of hardware components connected to an arbitrary grid.

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