Power hardware-in-the-loop setup for stability studies of grid-connected power converters

Power Hardware-in-the-Loop Setup for Stability Studies of Grid-Connected Power Converters

Track number: 8

Abstract-**Interaction of grid-connected inverter and power grid can be analyzed through their impedances. The impedances can be used to evaluate stability at the point of common coupling and to define how the system reacts to harmonic distortion. Because the grid conditions vary over time, online measurements and analysis are most desired for guaranteeing system stability. To simplify the study of the interaction between the grid and the inverter a power hardware-in-the-loop method can be used. The power grid is simulated on a real-time digital system simulator (RTDS) and emulated using voltage amplifier. However, the method causes issues with accuracy and stability of the test bench. Instability can be hazardous as large overcurrents and voltages may appear. A compromise has to be made between these two attributes. The reliability of the test bench is evaluated by calculation, simulation and finally by tests with the hardware.**

I. Introduction

The power grid and power generation is going through a paradigm change in the near future as more distributed generation is connected to the grid. Virtually all of these power sources such as photovoltaic power plants and wind farms are connected to the power grid by power electronics. The increased use of the active devices causes significant effects in the grid dynamics [1]. Large-scale instability problems have occurred in real systems due to impedance-based interaction between multiple inverters and grid [2-3]. As the grid conditions vary significantly, different scenarios have to considered and tested to guarantee the stability of the inverters.

The effect of grid impedance at the point of common coupling (PCC) has been under research. In many studies the impedance has been assumed to be ideally inductive. Actual grid impedance is time varying and has also capacitive characteristics. To be able to study the effects of these characteristics more complex models are required to present the effects at the PCC.

Dynamics of the power grid have become more complex as the active components in the power grid are becoming more common and the direction of power flow may change due to distributed energy resource. Therefore a method is needed to study the interaction of power grid and the inverter in time-varying grid conditions. Power hardware-in-the-loop (PHIL) setup allows running tests with a real device connected to a realistic grid instead of pure software environment [4]. The method is commonly used in the auto industry and lately to study the dynamics of grid-connected power converters.

PHIL test bench consists of the hardware under test, interface, and the simulation. Power grid interface is made with either voltage amplifier or frequency converter. Bandwidth of the grid emulation on the hardware side depends on the interface and the use frequency converter limits the bandwidth to a few hundred Hertz [5-6]. In this paper a linear voltage amplifier is used for the grid side emulation to allow studying the impedance-interactions over a wide range of frequencies.

Power hardware-in-the-loop testing is used when a realistic simulation model is hard or impossible to make and pure hardware test is not reasonable due to cost or complexity. Accuracy of PHIL testing has been under study in [7] as usually there is no possibility to compare the real system to the one made for PHIL-testing. A method to evaluate the accuracy has been studied in [8]. This allows simulations, PHIL-experiments and knowledge of the laboratory equipment to be used as basis for the accuracy and stability analysis of the real system.

The PHIL system requires thorough testing on its stability as the method is prone to instability. The instability is caused by error in the amplification and the A/D and D/A conversions [7]. The simulation is discrete time and as such causes delay into the control loop of the system. Furthermore the amplifier may cause switching noise and has finite response time. The effects caused by interface algorithms and the actual interface have been studied in [7, 9]. Fast nature of the phenomena present in the power electronic device limits choices for the interface algorithm.

II. Modeling of Grid Impedance

Impedance-based interaction between grid-connected converter and the grid impedance may cause increase in harmonic content or even instability [10]. Thus, the grid impedance is an important design parameter for grid-connected converters. However, grid impedance is often modeled as a plain series inductor or a series connection of resistance and inductor with inductance of a few mH. Thorough measurements on real grid impedances are rare, but the acquired results show very different impedance patterns compared to impedance of an inductor [11-13]. Particularly series and parallel resonances cause drastic changes in grid conditions, which may not be included in simple grid models. In addition, often grid impedance experiences strong time-variation during day, as the load profile of the grid changes.

The grid impedance is always related to a certain PCC, and is affected by characteristics of upstream grid, nearby

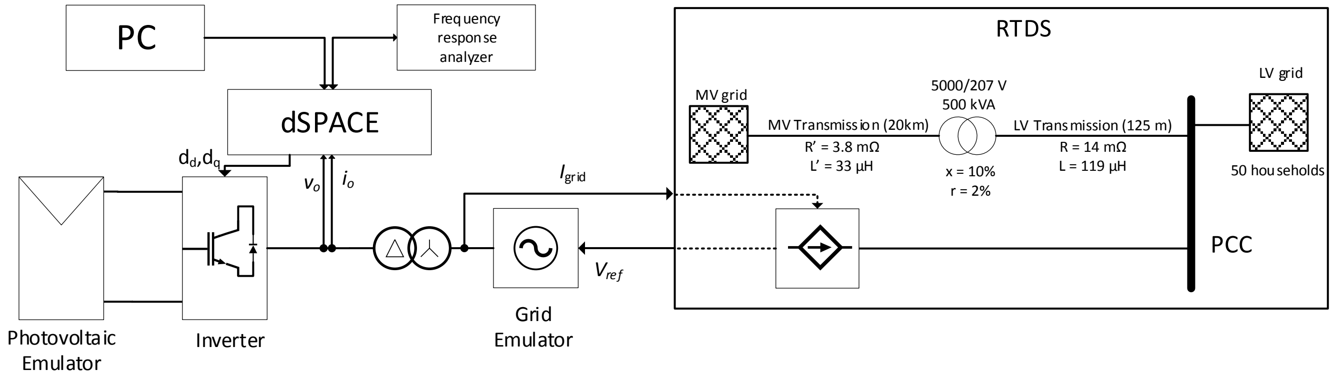

Fig. 1 Layout of the test bench

distributed generation and loads in the grid. Upstream grid is usually mostly inductive due to inductance from transmission lines and transformers. However, grid-connected filters and current control of converters or loads in distribution grid cause capacitive element to grid impedance. Parallel connected capacitances are cumulative and thus the resulting equivalent capacitance may reach significant value. According to [14] a typical household has equivalent capacitance of $0.6 - 6\ \mu$F, and consequently the resulting total capacitance may shift the resonant frequency as low as 250 Hz, which corresponds to the 5^{th} harmonic.

In this paper, a PHIL setup with RTDS-based grid impedance emulation is presented. Thus, the Hardware under test can be connected to complex and versatile grid conditions instead of inductance and stiff voltage source. Moreover, such a setup would allow studying novel concepts such as virtual inertia in weak grids. A pure inductance will fail in this matter since it does not deteriorate the robustness of the grid frequency. The model used in this paper consists of an upstream medium-voltage grid and a group of 50 households. The households are depicted as a lumped parallel RLC load, where value of the equivalent resistance is approximated from the total actual power consumption and capacitance based on 6 µF per household. PCC is located within the low-voltage distribution grid.

III. Hardware under Test

The laboratory has equipment for testing a grid-connected inverter. The test bench is capable of emulating a PV-generator connected to the power grid through an inverter up to 20 kW. The current PHIL test bench allows fast modifications to the inverter control algorithms without having to build a new prototype.

Fig. 1 shows the layout of the test bench. It consists of PV-emulator to reproduce the output of a solar panel, inverter, a 3-phase grid emulator and a Real Time Digital Power System (RTDS) –simulator. The inverter is controlled by a dSPACE real-time simulator. Formerly the grid emulator was used as a stiff voltage source which had fixed voltage and frequency parameters and the grid interaction was modeled by connecting inductors between the grid emulator and the inverter. In this paper the grid emulator is connected to the RTDS for realistic grid side emulation. Current measurements are used as input for the RTDS to simulate the response of power grid.

Components found in the laboratory will not limit the model when the grid emulator is connected to the RTDS-simulator. In addition, emulating the grid impedance allows fast changes to be made to the power grid layout and consequently the operating point of the grid can be changed while the system is online. For example, system can emulate tripping a part of the grid in order to change the power flow in the grid. However, the coupling of the test bench to a real-time simulator causes delay to the grid emulation which can be detrimental to accuracy and stability of the test setup. The system may become unstable even if the tested system would be stable on its own [15]. The instability is caused by errors in the voltage amplification.

Fig. 2 shows the control diagram of the RTDS-PHIL test bench. The stability of the system can be evaluated through the knowledge of the laboratory equipment and the characteristics of the interface algorithm used. For accuracy of the experiments the best suited interface algorithms for testing power electronics are either ideal transformer method (ITM) for its simplicity or damping impedance method (DIM) for its stability [8]. DIM requires matching of the damping impedance in the simulation with the impedance of the hardware under test [16], which is complicated due to active nature of the inverter. In this paper ITM has been chosen as the interface algorithm because of its simplicity and sufficient stability for the phenomena under test. DIM is a possible future improvement for the final paper.

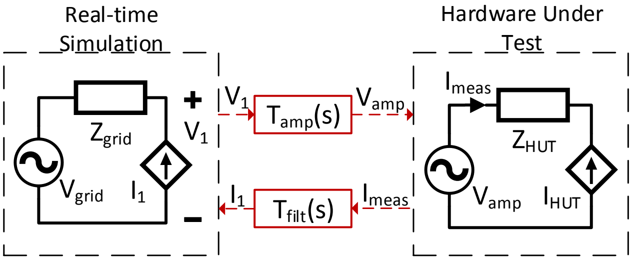

Fig. 2. Control diagram of the PHIL grid emulation with ITM interface algorithm

Delay of the simulation and the conversions between analog and digital signals cause error to the grid emulator output and the error is amplified in the simulation if the impedance ratios between simulated and hardware parts of the system are not considered. When using voltage type ITM the impedance of the simulation may never be higher than the actual impedance of the hardware side [8]. Otherwise the simulation causes a positive feedback loop for the amplification error and the system becomes unstable.

IV. System Stability

Stability of the system can be evaluated by approximating the transfer functions of the interface algorithm and the real-time simulation. The loop of the simulation can be approximated by

$$G = e^{-s\Delta T_d} \frac{Z_s}{Z_{DUT}} T_{amp} T_{filt} \qquad (1)$$

where e^$(-s\Delta T_d)$ is the delay caused by the sampling frequency of the grid simulation, Z_s is the simulated impedance, Z_{DUT} is the hardware impedance, T_{amp} is the voltage amplifier transfer transfer function and T_{filt} is the current measurement low-pass filter.

The voltage amplifier has low-pass filter behavior and as such has finite bandwidth and time delay [15]. The amplifier transfer function is approximated as first-order transfer function

$$T_{amp} = \frac{1}{1 + \frac{s}{2 * pi * f_{bw}}} \qquad (2)$$

where f_{bw} is the bandwidth of the grid emulator which is 30 kHz. The current measurements fed into the grid model are filtered by a first order lowpass-filter

$$T_{filt} = \frac{1}{1 + \frac{s}{2 * pi * f_{co}}} \qquad (3)$$

where f_{co} is the cutoff frequency of the filter. The approximation of the system transfer function was tested by comparing a simulated impedance and a measured impedance from PHIL-test bench. Venable frequency response analyzer was used to measure the impedance from the inverter.

Fig. 3 shows the verification of the transfer function by comparing the calculated impedance to the actual measured impedance. The test was done with an LCL-filter and isolation transformer connected between the inverter and the grid emulator. Combined resistance and inductance of these were 0.4 Ω and 0.9 mH. The simulated part of the impedance was 0.01 Ω and 1.2 mH. The cutoff frequency of the low-pass filter was set 1.6 kHz. The measured impedance corresponds to the value of the approximated impedance. Thus, evaluation of the stability can be done based on this approximation. Stability analysis is carried out when the inverter is offline as the LCL-filter and isolation transformer alone have lower impedance than combined with the inverter impedance.

Figs. 4-5 show the PHIL-grid emulation in stable and unstable operation. When the impedance is increased from 1.5 mH to 1.7 mH the emulation is no longer able to attenuate the error caused by the voltage amplifier. Attaining stability for the system has three different options. The most straight forward option is to increase hardware impedance i.e. in this setup LCL-filter grid side inductor has lower inductance than commonly used in commercial devices. Second option is to choose another interface algorithm such as the DIM. Third option is to tune the low-pass filter so that the magnitude of the

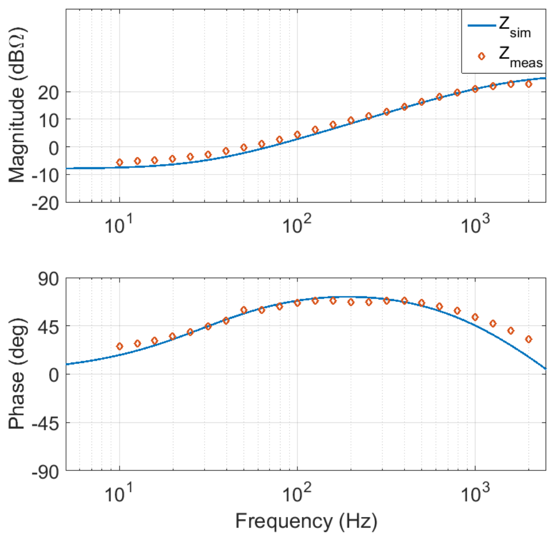

Fig. 3. Measured impedance from the PHIL-test bench (red) and the impedance simulated with the transfer function approximation G (blue).

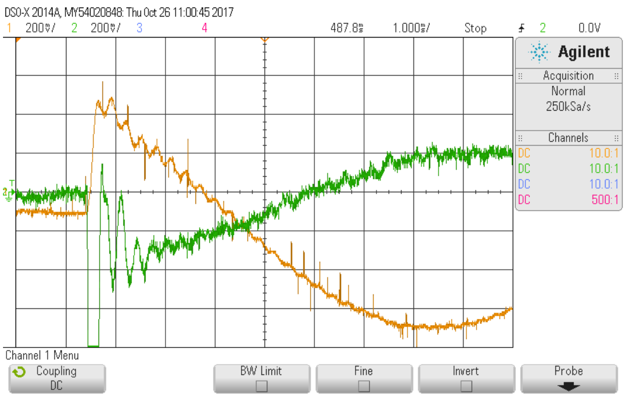

Fig. 4. Voltage (orange) and current (green) when turning on the grid emulation in a stable case. 1.5 mH simulated inductance

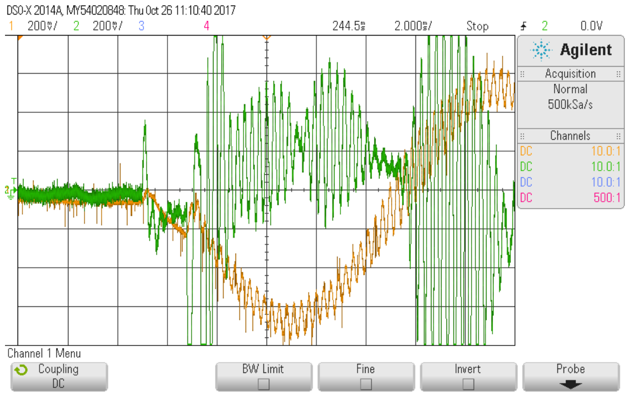

Fig. 5. Voltage (orange) and current (green) when turning on the grid emulation in unstable case. 1.7 mH simulated inductance

simulated impedance is always lower than the limit for stability without affecting the phase in the tested frequency range. This can be achieved with the first-order filter or more sophisticated filters such as Butterworth or FIR-filter. The case in Fig. 5 is stable when the lowpass-filter cutoff frequency is lowered from 1.6 kHz to 1.45 kHz.

A Simulink model of the test bench was made to test system stability without having to turn on the actual testing equipment. The model simulates the power stage of the inverter, inverter control functions, interface algorithm and the grid model.

V. Test Scenario

The system is tested in a scenario where the PCC is located within a low-voltage distribution system consisting of group of households and capacitive loads. The system is shown in Fig. 1. The grid is modeled with low power flow i.e. at nighttime. Therefore the equivalent resistance is relatively high. The low-voltage system is supplied from the medium-voltage upstream grid. Resonance between capacitive low-voltage-branch and inductive medium-voltage branch can be seen in the grid impedance at the PCC.

Fig. 6 presents the impedance measurements done with the inverter connected to the grid. The current measurement low-pass filter cutoff frequency is set to 13.2 kHz, which starts to affect the phase at approximately 1.3 kHz. The series and parallel resonance in the grid model can be seen in the impedance measurements performed on the hardware side. The impedance accurately follows the calculated results. Some difference is observed only at the resonant frequency. The measured impedance shows another resonant frequency slightly below the frequency predicted by the calculated value.

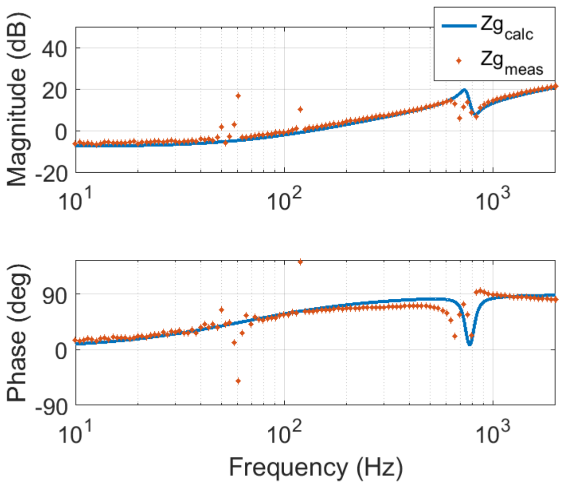

Fig. 6. Measured (red) and calculated (blue) impedances at the hardware side when a resonant frequency in impedance is modeled at 800 Hz

VI. Conclusion

PHIL grid emulation gives a powerful tool for analyzing the power grid – inverter interaction. The grid emulator is capable of producing an accurate grid impedance and the impedance measured from the hardware side follows reasonably well the calculated frequency response. Performing experiments with the setup requires analysis of the accuracy and stability of the test bench as PHIL as an experiment method is prone to instability. Analysis of the equipment used in the laboratory allows predicting the reliability of the experiment.

In this paper, a power grid with a resonant spike in its impedance was modeled. The hardware-side impedance measurement shows that the test setup is capable of producing accurate resonance at high frequency range. However, there is another resonant frequency in the measured impedance at slightly lower frequency than the predicted point. This will be studied in the final paper on whether the effect is caused by hardware, error in the numerical analysis or limitations of the grid emulation.

The final version of the paper will include the accuracy analysis of the test setup in both time and frequency domain. Limits of the test setup will be discussed and demonstrated. ITM and DIM interfaces will be compared and studied whether or not the DIM is required for stability improvement. Simulink model of the test bench used for stability analysis of RTDS-PHIL will be presented. The model used will be improved by formulating a second-order transfer function for the grid emulator. The developed RTDS-PHIL setup will provide a useful tool for studying stability of grid-connected converters in changing grid conditions.

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