Power Hardware-in-the-Loop Setup for Power System Stability Analyses

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ABSTRACT

Most ongoing activities in the field of network stability support are made by pure simulation studies. In order to accelerate progresses and lower costs of design during development phases, new methods for verifying ideas and inventions have to be developed.

The authors propose to utilize a Power Hardware-in-the-Loop test bench for large-scale power system stability analysis. The advantage of this approach is that e.g. new controls implemented for power electronic coupled generation can be directly studied concerning their impact on large-scale power system stability. This approach is shown for two different study cases; both featuring high penetration of power electronics interfaced distributed generation units in the electrical networks.

INTRODUCTION

According to the Task Force set up jointly by the CIGRE Study Committee 38 and the IEEE Power System Dynamic Performance Committee, the definition of the power system stability is the following: *“Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.”* [1]. Considering this, power system stability is an essential study in the planning and operation of an efficient, economic, reliable and secure electric power system. Integration of new Smart Grid technologies, especially with use of renewable energy resources (RES), leads to new aspects for power system stabilities.

Through the massive integration of energy generation from RES and decentralization of power production, classical definition of stability needs to be reconsidered.

Power flow change between transmission and distribution system leads to global investigations with combined power system levels [2]. Supporting power system operations accumulated distributed energy resources (DER) and control strategies needs to be harmonized to replace conventional power plants.

Most ongoing activities to form new approaches in the field of network stability support are made by pure simulation studies. In order to accelerate progresses and lower costs of design during development phases, new methods for verifying ideas and inventions have to be developed.

Based on the classical definition of power system stability [1] taking rotor angle, frequency and voltage stability into account, large-scale power system simulations are required for realistic scenario studies. In following steps of development, Power Hardware-in-the-Loop (PHIL) technologies can be used for extensive power system component testing as well as analyze and verify the contribution of DER in large-scale power systems. This approach allows coming closer-to-reality and it may be better suited to demonstrate and proof new approaches as compared to pure simulation based work.

The authors propose a PHIL test bench used for power system stability analysis. This work presents the approach of scaling a small power Hardware-under-Test (HUT) for representing a full wind park with its dynamic behaviors connected to a scientific respected transmission network simulation of the IEEE 9-Bus system [3].

Different experiments were carried out to study interfaces between the virtual simulation and physical HUT in case of bidirectional influence focusing realistic scenarios. Building equivalent models in a simulated or physical domain needs to be verified to their meaningful advancements. Power system characteristics (like voltage, power and impedance level) have to be adapted, converted and reviewed. This increases the effort and troubles of interface algorithms which are dealing with the test bench’s accuracy and security aspects.

Therefore two experiments will be depicted to prove new controller innovations in case of frequency and voltage stability. Firstly a developed power electrical inertia controller using df/dt control was implemented on a real inverter and tested by different influence level to the IEEE 9-Bus benchmark system. Secondly several implemented active power recovery rates after voltage fault where investigated by use of the benchmark system and physical inverters. In both cases the physical system represented a wind park equivalent, which replaces rotating power generation. It could be shown, how RES can change stability in power system and furthermore how they can even improve it.

DESIGN OF A POWER HARDWARE-IN-THE-LOOP TEST BENCH

Advantages and Issues of Hardware-in-the-Loop Technologies

Since Hardware-in-the-Loop (HIL) tools increased over the last decade [4, 5] in the field of power system investigations for protection, controller and power electronic technologies, the entire setup has to be validated and optimized to match future requirements [6]. HIL provides not only a way to create close-to-reality phenomena for realistic lab-test procedures to investigate entire HUT functionalities. Moreover integrating HUT in multifarious power system simulations enable performance studies of HUT for various power system situations, thus avoiding, at least partially, extensive field tests [7].

However, combining several systems, computer simulations and hardware devices, may lead to inaccuracy and hardware damaging [8, 9]. Therefore several points have to be considered to run realistic and save experiments:

- Real-time capability
- Resonance and error damping
- Emergency circuit system
- Accurate bidirectional coupling

Lots of researches for stable and accurate interfaces are under development to ensure safe and realistic behaviors of HIL procedures [10, 11].

Conception of Multi-Terminal Hardware-in-the-Loop Test Benches

Schematic Design of Power Hardware-in-the-Loop Systems

In the classical sense, a HIL system consists of a physical component which is bidirectionally connected to a real-time computer simulation. In sense of PHIL an additional power adaption is required to convert low-level signals from the virtual simulated system (VSS) to power signals for the physical power system (PPS).

Figure 1 depicts the schematic setup of a PHIL test bench, including real-time power system simulation, additional protection guard and part of the interface algorithm in the VSS and moreover a power amplifier which handles up to three HUT separately in the PPS.

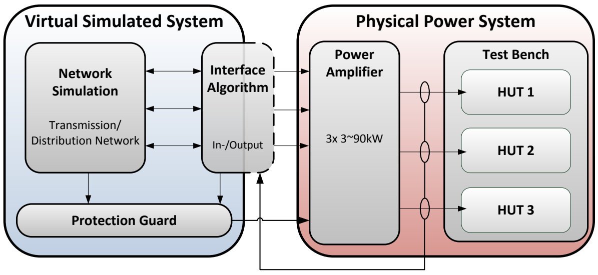

Figure 1 Scheme of a multi-terminal HIL setup

Advanced Test Bench at Fraunhofer IWES SysTec

A flexible PHIL test infrastructure was built-up at the laboratory of Fraunhofer IWES SysTec to perform the following:

- Component testing with more realistic scenarios
- Network simulations including physical black-box or prototype devices
- Component independency testing in embedded network simulation
- Protection relays testing
- Extensions to physical LV or MV test networks

LARGE-SCALE POWER SYSTEM STUDIES USING HARDWARE-IN-THE-LOOP

Demand of Global Power System Studies

Future change of the European power system coming from enormous integration of renewable resources in each voltage level [12], extension and optimization of the power cable grid, energy market renovations and increase of active consumers/prosumers requires holistic power system studies. Large-scale testing of new innovations and developments in the real power system infrastructure won’t be sufficient, because of intensive costs and perilous operations.

To envisage testing procedures of new innovation devices under safe and realistic conditions, HIL turns up to combine the necessity of prospective power system requirements and innovative development of power system controls.

Scaling of Hardware-in-the-Loop Components

Keeping reality as majority key, connecting large-scale power system studies to HUT scaling of either simulation and/or hardware is required and has to be wisely respected. State-of-the-Art operations of HIL setups nowadays only use direct power system level, by means of power flow and voltage level, merging between the simulated to the physical connection point. But on the one hand increasing the effect of physical components and on the other hand making interconnection system feasible for test device conditions, power and/or voltages have to be adapted in a realistic and validated manner.

This paper presents exemplary investigations of large-scale power system simulations for realistic transmission system phenomena generation connected to a previously developed wind park controller implemented on a power electronic converter. Since the converter won’t be able to fully represent holistic wind park conditions an adaptions of missing characteristics where implemented in addition (see study cases).

This adaption enables investigations of the developed wind park controller in terms of realistic power system instability behaviors generated by the simulated system.

EXEMPLARY INVESTIGATIONS OF STABILITY PHENOMENA

Power System Studies using the IEEE 9-Bus System

Creating realistic power system scenarios in case of frequency and short-term voltages stability phenomena the scientific respective IEEE 9-Bus System [3, 13] was implemented on a real-time computer. To fulfill European conditions the original data of the 9-Bus System where modified and validated for representing 50 Hz power system conditions in terms of frequency and short-term voltage scenarios. Furthermore additional generator controllers for G2 and G3 were added to make the simulation closer-to-reality.

For short-term voltage stability studies part of the load models of the original 9-Bus System were replaced by dynamic loads.

Figure 2 presents the single line diagram of the IEEE 9-Bus System. The HUT was connected to Bus B1 to replace partly or in total the power injection of the conventional power generator G1.

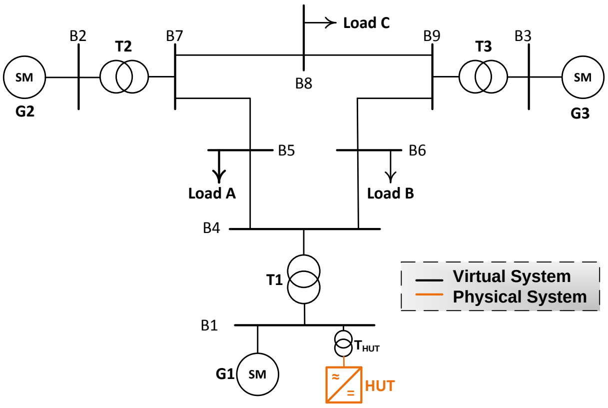

Figure 2 Scheme of the implemented 9-Bus System connected to a HUT (orange)

Software Implementation of Realistic Wind Park Conditions

As pervious mentioned, for connection a HUT to a large-scale power system simulation, an adaption of operation parameters is required.

As in reality a wind park transformer was implemented to transform voltage to the high voltage level of the power system. Additional impedances were modeled to generate a realistic connection between the wind park and transformer. Furthermore, to investigate the impact of the wind park controller to the power system, the measured power of the HUT was scaled to different power levels. This provides several prospective scenarios.

Study Case 1 – Short-Term Voltage Stability with varying Active Power Recovery Rates

Grid Codes demand specific conditions for energy suppling units to support power systems behaviors. According to the German Grid Codes in case of power injection after a voltage disturbance event, a gradient of the recovered active power after voltage drops requires at least 10% of the nominal power per second [14]. DER are capable to provide even faster gradients of the power recovering.

First study case investigates power system support of different active power recovery gradients after short term voltage dips (Low-Voltage-Ride-Through events - LVRT). The wind park power was adapted to replace the entire power of Generator G1.

Short-circuits (SC) with different clearing times T_C were generated on Bus B8 leading to a line surge over the power system, which creates a voltage drop at Bus B1 of approx. 40% of the nominal voltage. Empiric pre-studies investigated the limit of stable network conditions during SC events with T_C = 85 ms. Increasing T_C and weakening the power system by removing G1 can lead to instable system conditions (see Table 1).

Five replications were made for each of the following three test cases:

1. Reference case (without HUT)
2. Fast recovery rate (as fast as the HUT can act)
3. Slow recovery rate (according to [14])

Table 1 Overview of LVRT study case (x marks experiments which led to instable conditions)

Tc= 86ms	Test 1	Test 2	Test 3	Test 4	Test 5	Stability
(1)	✔	✔	✔	✔	✔	100%
(2)	✖	✖	✖	✖	✖	0%
(3)	✖	✖	✖	✖	✖	0%
Tc= 85ms	Test 1	Test 2	Test 3	Test 4	Test 5	Stability
(1)	✔	✔	✔	✔	✔	100%
(2)	✔	✔	✔	✔	✔	100%
(3)	✖	✖	✔	✔	✖	40%

Following results were drawn from Test 5 at T_C = 85 ms (Table 1 red marked column)

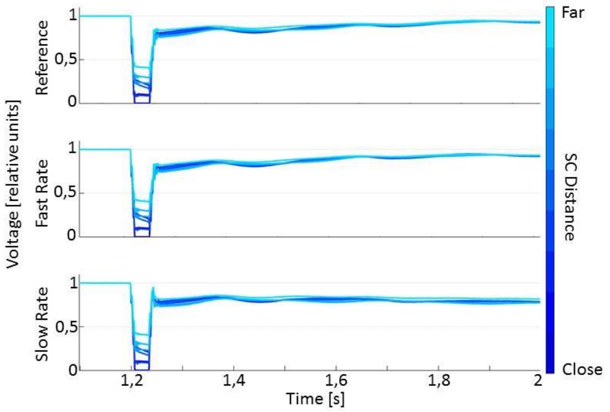

Figure 3 Bus voltages of Test Case 2, Test 5 (T_C=85ms). Darker colors depict closer distance to the short circuit event.

Table 1 depicts that 60% of the experiments with an active power recovery rate according to [14] leads the power system to instable conditions. This was mentioned as the internal protection guard detected overfrequency and harmonic distortion thresholds. Furthermore, test case 3 in Figure 3 shows an additional voltage drop that occurs after the LVRT (after 1.25 seconds), which led the power system to instability.

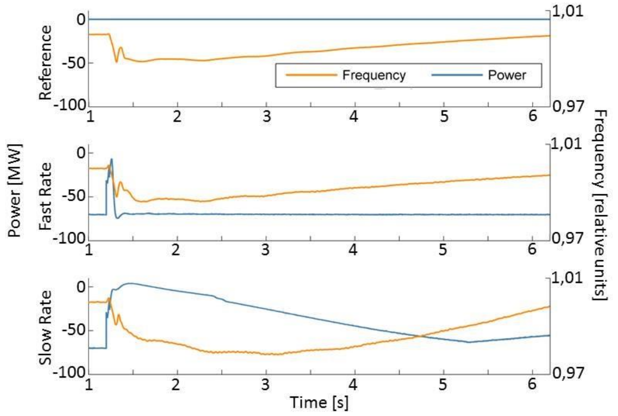

Figure 4 Injected power of the HUT (blue) and frequency (orange).

Figure 4 shows the development of the HUT injecting active power (blue line) after the LVRT disturbance. Middle diagram depicts how fast the HUT can injected power after a voltage disturbance compared to power injecting according to [14] (lower diagram).

Study Case 2 – Frequency Stability with Active Inertia Emulation

Prospective rise of DER integrated power supply requires additional contribution of ancillary services from renewable energy suppling units. To investigate influences of a developed power electronic inertia controller for wind parks, a load imbalance was generated in the 9-Bus System simulation. Therefore a load shedding event at Bus B5 of 25% of the load power was simulated, leading to frequency oscillations in the simulated model. The injecting power of the HUT was adapted to several power levels to replace the Generator G1 by [0; 10; 20; 30] % of its suppling power.

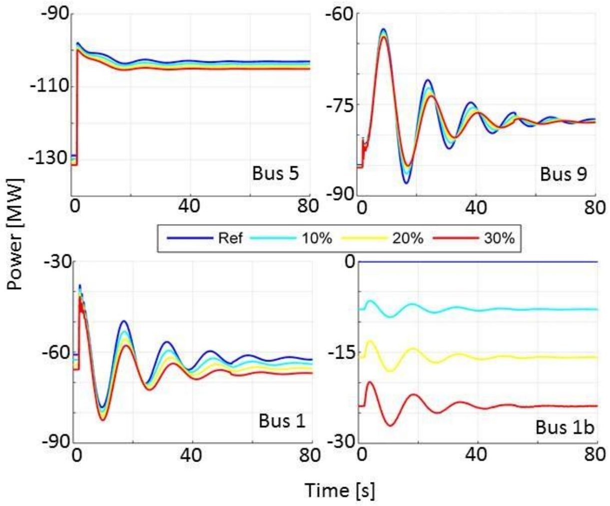

Figure 5 Power at different busses for each test case.

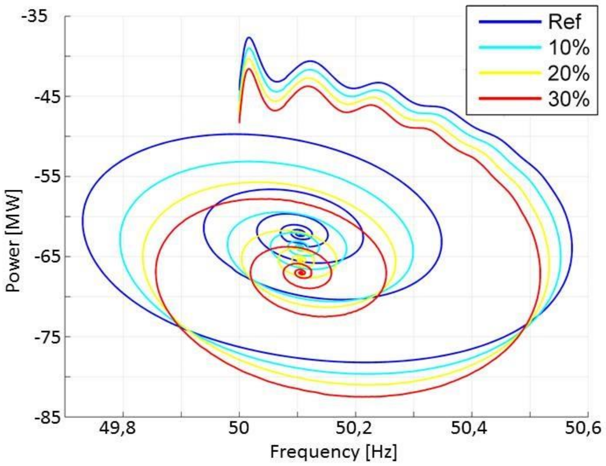

Figure 6 Power over frequency curves for each test case.

According to load shedding, power is oscillating in the power system, which leads to frequency oscillation as seen in Figure 5 for several busses. Furthermore the power injection from the HUT is labeled as Bus 1b, where power supply varied according to the implemented df/dt controller of the HUT.

Figure 6 compares the impact of different power level: A higher power level of the HUT leads to a reduction of the magnitude of the frequency oscillation in the system. Furthermore the steady state operation could be reached faster.

CONCLUSION

Prospective requirements of forthcoming power system operations need to be investigated during development phases of power system component innovations.

Power Hardware-in-the-Loop experiments were performed to proof methods for integrating HUT in large-scale power system simulations, which establish extensive and realistic functionality tests for power system developments and open prospects of field test like studies in a controllable laboratory environment.

The executed and presented study cases in this paper confirm that large-scale power system stability studies involving power electronic coupled generation can be performed in a PHIL test bench in order to verify new concepts at an early development phase.

Nevertheless merging large-scale power system simulations with single DER needs carefully adaptions on both sides. Therefore conditions have to be adapted in realistic manner to provide valid statement and realistic scenario investigations.

In the end it could be shown that a PHIL test bench can be used for holistic stability studies and power system component testing under controllable field test characteristics.

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