Power Hardware-in-the-Loop Testbed for High Frequency Interdependency Issues of Inverter-Based Generation

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ABSTRACT

The integration of inverter-based prosumers and consumers in the electrical power system depicts an increase of power quality issues. High dynamic interactions among inverter-based power system components and within the power system may generate dynamic oscillations leading to harmonic disturbance.
Up-to-now, no appropriate laboratory-based test system exists to capture these high frequency oscillations in a controllable and realistic testbed. Power Hardware-in-the-Loop-based testbeds offer promising options for performing realistic unit testing and extension for system testing. This paper introduces a concept to overcome current limitations and operational bandwidth limitations of such systems. The proposed concept is based on a fast Hardware-in-the-Loop system, that is capable to capture high frequency oscillation phenomena in a controllable laboratory environment.

INTRODUCTION

Due to climate policy goals for CO2 reduction [1, 2] the accompanied renewable energy integration (see Fig. 1) results in inverter-dominated areas of the European interconnected power system. Especially in closed distribution networks, this trend introduces consequences in terms of dynamic effects (e.g. inter/harmonics, interdependencies between inverters, malfunction of protection/metering) [3, 4].

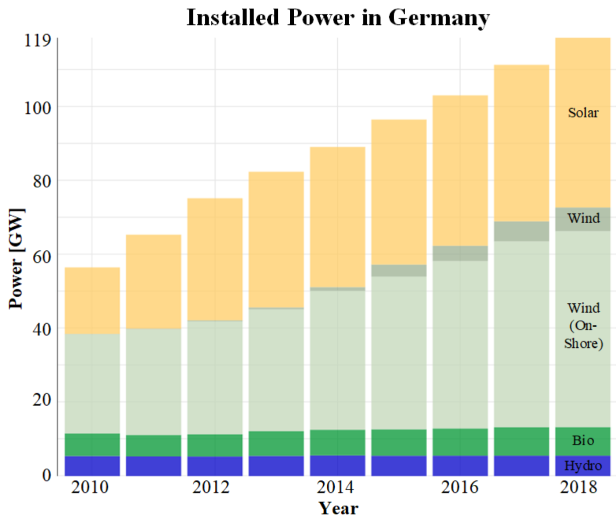

Fig. 1: Development of installed power of renewable energy generation in Germany [5].

Many challenges can be investigated by means of preliminary analyses and simulation, but those methods cannot cover all phenomena that can be expected in physical power systems, due to models assumptions. Furthermore, pure laboratory tests are also limited in representing realistic power system behavior.
Hardware-in-the-Loop (HIL) systems bridge the gap between real-world field tests, laboratory tests and simulation studies [6–8]. However, currently HIL systems are limited in the field of investigations of effects and must be optimized to be prepared for future energy system conditions [9–11].

CHALLENGES OF THE ENERGY SYSTEM

The ongoing transformation of the electrical energy system is leading to new challenges for the power system stability and power quality. Power quality related challenges are also due to high power oscillations between power systems components. Formerly, power systems were mainly facing oscillations between rotating generation [12, 13] and HVDC systems, that typically include low-frequency oscillations with less than 3 Hz between rotating generators and the transmission system caused by internal interdependencies [14]. These sub-synchronous oscillations are well known and have been studied over years [12, 14, 15]. In the current context of the power systems integrating high shares of inverter-based units, super synchronous oscillations (e.g.; harmonic oscillation interaction between multiple converters and the distribution network [16, 17]) can cause malfunction in the secure operation of the electrical grids. Moreover, the integration of big power electronic based power plants (wind and PV park systems [15, 18]) could potentially increase the internal harmonic oscillation level up to several kHz, thus possibly causing failure of the power system and its components.
Generally, the coupling of phase lock loops, the resonance of filter circuits and improper parametrization of the converter controllers can cause high frequency oscillations [14, 15].

Case Studies of Network Failure due to Dynamic Frequency Oscillations

High frequency oscillations can cause power quality related issues like overloading the neutral conductors, overheating of transformers or false tripping of circuit breakers.
With the prospective increase of fast DC charging stations

in the field of electro mobility, the work presented in [19] describes the interdependencies of harmonics between charging stations and PV inverters. Investigations in closed distribution network cells results in a summed up harmonic current of both components independent of the magnitude of their charging currents. This means even at lower power, power electronic units are influencing the power quality, and therefore influence other network components such as meters, protection devices and system and plant protection [20].
[21] describes the interaction between power electronic devices in PV parks. 9 of 11 transformers were destroyed due to harmonic current interaction between the inverters. Furthermore [21] stated that currently power quality standards such as the EN50160 [22] do not take these dynamic oscillations into account.
Other phenomena are particularly evident in locations with high share of inverter-based generation. As a result, in 2014, several shutdowns and smoldering fire occurred at the wind park BARD Offshore 1. According to the TenneT Holding B.V. the shutdown was attributed to current flickers and harmonic. Additional attenuation filters and software adjustments had been retrofitted, to ensure a stable operation of the wind park.

TESTBED FOR HIGH DYNAMIC POWER SYSTEM SCENARIOS

Many problems can be detected and investigated within preliminary analyzes by use of power system and component simulation. Due to the complexity of modeling high dynamic effects, these phenomena are mostly simplified or neglected, but are essential for stable operations. Nowadays field tests ensure the safe operation and are used as system validation; nonetheless, the process of field installation, optimization and retrofitting is a cost and time expensive process. However, since pure laboratory tests are limited in the emulation of realistic power system characteristics and therefore cannot cover all power system to power component interdependency phenomena, new techniques of power system validation are required.
Hardware-in-the-Loop (HIL) systems bridge the gap between field tests and controllable laboratory tests and flexible simulation studies, and is nowadays used widely in the field of power system testing. However, even with the beneficial use of HIL systems, high frequency oscillation phenomena are out of scope due to limited system bandwidth occurring by time delays and harmonic distortion, especially in Power Hardware-in-the-Loop (PHIL) systems [23]. This paper presents the design of an improved PHIL system with the aim for testing high dynamic effects in a laboratory closed-to-field environment.
To analyze and study high dynamic power system effects, [24] descripts the time step size requirements for performing accurate simulation.

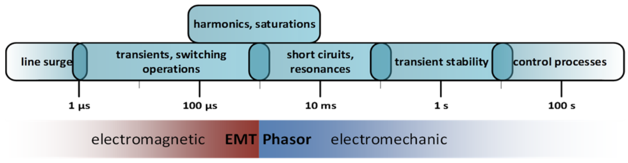

Fig. 2: Simulation step size based on power system phenomena studies according to [24]

As depict in Fig. 2 the step size range of harmonic and transient operation studies is between 10 µs and 1 ms. This means, to perform high dynamic power system studies by use of a PHIL system, the operational frequency of the PHIL system needs to be in the range of at least 10 kHz or above.
The operational range of a PHIL system mainly depends on the impedance ratio between the simulated system Z_S and the hardware system Z_H, as well as the occurring time delay of the round trip loop of the overall system T_D [25].

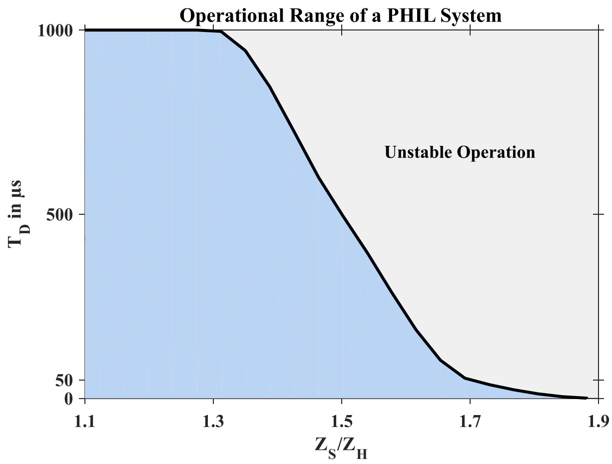

Fig. 3: Measured operational range of a PHIL system composed of a low dynamic power amplifier [25].

When the time delay of a PHIL system will be to large, not only a loss of accuracy of high dynamic effects will occur, but moreover the time delay can lead the system to an unstable state (see Fig. 3). This can result in unusable results and at worst harm laboratory devices [9].
This means, even if the real-time simulation can be executed with a time step sizes in the smaller µs range, this does not mean that the PHIL system will be efficient enough to keep up the same speed. Mainly internal delays and non-ideal dynamic behavior of power amplifiers, measurement probes and especially their connections and interface challenges a stable and accurate PHIL operation.

Design Concept of a Fast Hardware-in-the-Loop Testbed

Today's PHIL systems are custom designed by considering the integration of different components and their interfaces. Due to the use of equipment from different manufactures, high effort in building adequate and stable interfaces is needed. This is limiting potential applications of the overall system, due to time delays, inaccuracies and operational safety aspects of the individual equipment [25,

26].
The development of a PHIL testbed, designed from scratch, based on a real-time simulation system (RTSS), allows the simulative representation of realistic power systems dynamics and the integration of inverter control algorithms, controls a LV line impedance and analyses measurement data. The RTSS is connected to a multi kHz-capable linear amplifier and a switched-mode amplifier. The linear amplifier serves as high dynamic power system emulator generating frequency oscillation power system conditions. The switched-mode amplifier serves as test device for the development of new inverter controls. Due to the higher dynamic capability of the proposed system compared to state of the art PHIL systems, the authors introduce the term "Fast PHIL" (F-HIL) system.
The overall F-HIL system will be able to include several external test devices connected to the power system emulator (e.g. PV-/Wind systems, EV charging-station, rotating generation, CHP, Microgrids, etc.) and a controllable line impedance. Fig. 4 depicts the concept of the F-HIL system.

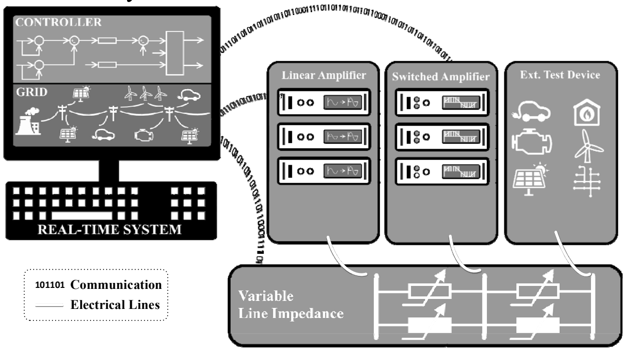

Fig. 4: F-HIL system including inverter-based generation and power system emulator.

1. Real Time Simulation System

The RTSS is executing power system models and controls of generation plants and consumer. For performing high dynamic effects, a high level of details for plants and power systems must be achieved in order to implement various scenarios. The system must therefore be able to calculate the implemented models in real time and communicate via suitable interface with several devices (e.g.; power amplifiers, test devices, etc.).
Since the computation speed of the simulated system, as well as high speed signal in- and outputs are essential for high dynamic oscillation effects, a very high-performance and reliable interface between the RTSS and the power amplifier is required.

2. Power Amplification System

To perform holistic system testing, the proposed F-HIL testbed does not only contain a power system emulation in style of a PHIL system. Moreover, an adaptable (in hardware and software e.g. control algorithms, filter coils, power level and pulsing frequency) switched-mode amplifier gives the representation of inverter-based test devices. For being able to generate high dynamic power system phenomena, a linear amplifier represents test cases executed by the RTSS. This means the RTSS will perform power system simulation transferred by the linear amplifier and inverter control scheme execution transferred by the switched-mode amplifier.

3. Variable Line Impedance

Current PHIL systems are able to represent voltage and frequency behavior of a power system in a realistic way, but are incapable of represents realistic network impedance characteristics. Therefore, a variable line impedance represent the dependencies between network impedances and power oscillation effects, which cannot be neglected in studies of distribution systems with inverter-based integrations.
The network impedance, calculated during the simulation by the RTSS, is transferred and adapted online by the variable line impedance to physically emulate power systems condition in the most realistic manner.

TESTING APPLICATION OF A FAST HARDWARE-IN-THE-LOOP TESTBED

A PHIL system developed from scratch as one testbed and designed for emulating high dynamic power system condition and moreover able to emulate different power electronic units provides a new methodology for holistic unit testing. Furthermore, the system will be capable to interact with additional power systems (e.g.; LV-test networks, Microgrids) and further components (e.g.; charging systems, combined heat and power plants, converter units, rotating machines).
In general, the F-HIL systems advantages can be split in categories:

1. Supporting developments as a test and validation system for:
   - Distributed generators (DG) in realistic power systems;
   - EV charging systems in realistic power systems;
   - DGs in closed distribution systems and islands ;
   - Closed distribution systems (e.g. Microgrids).
2. Supporting developments as a test and validation system for mapping:
   - Bidirectional interaction between power systems and test systems (HIL technique);
   - Realistic power system cases;
   - Variable line inductances cases;
   - High dynamic network oscillations and interaction of several units and systems.
3. Supporting developments of a test system for emulating behaviors of:
   - DG interdependencies in realistic power systems;
   - Active power system components (e.g. charging stations, active consumers / producers);
   - Inverter-based generators interaction with power systems.

CONCLUSION AND OUTLOOK

Due to the ongoing installation of inverter-based power units (e.g. wind and PV parks, EV charging stations, HVDC terminals…), it is expected that the power quality will be impacted by high dynamic oscillations (see Chapter 'Challenges of the Energy System'). This paper addresses the improvement of current testing and validation of the prospective power system conditions by introducing an appropriate PHIL-based testing system.

Up-to-now, PHIL systems were constructed by integrating components that were limited in their operational ranges, especially in terms of capturing high dynamic oscillations, due to internal interface issues (e.g. signal noise, time delays and signal mismatch).

This paper introduces a concept to overcome current limitations and operational bandwidth limitations of such systems. The proposed concept is based on a fast Hardware-in-the-Loop system, that is capable to capture high frequency oscillation phenomena in a controllable laboratory environment.

Further advancement in the construction and implementation of such a system is planned. Furthermore, several models are planned to be generated and clustered within a library/test cases toolbox.

MISCELLANEOUS

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Only the authors are responsible for the content of this publication.

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