AN APPROACH FOR VALIDATING AND TESTING MICRO GRID AND CELL-BASED CONTROL CONCEPTS

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ABSTRACT

This contribution describes a setup for the combined system and equipment testing of micro grid and smart grid control concepts and components. The key aspects is the use of simple setup compared to typical power hardware-in-the-loop setup. This is achieved by using steady-state load flow calculations and a switched-mode amplifier. This setup was used to test a simple coordinate voltage control for distribution grids utilizing decentralised generation units. The used controllers and infrastructure comply with the German advanced metering infrastructure according to the digitalisation of the Energy Transition Act in July 2016.

INTRODUCTION

The transition towards renewable energy and decentralized power supply leads to several challenges for the grid operation, particularly on the distribution level. To mitigate potential problems in the power grid, such as voltage violations or over loading, Distribution System Operators (DSOs) need to undertake smart operation strategies. An example of smart operation strategies the cellular approach is suggested for example in the C/sells [1] and the ELECTRA IRP [2] projects, which divides the grid into smaller cells. Each grid cell tries to solve its own problems based on its own available flexibility, and communicates with other cells to provide or receive flexibility for solving the problems in the entire power system. Such a smart operation and control strategy requires various infrastructure for Information and Communication Technology (ICT) and also various interfaces between the cells as well as between components in one cell. This contribution focuses on the development of a simulation environment, which combines Power Hardware-in-the-Loop (PHIL) as laboratory simulation with a Software-in-the-Loop (SIL) of a distribution grid as well as for micro grids. This environment is then utilized to test ICT interfaces and component behavior.

METHODOLOGY

Control concepts for micro grids or smart grid cells require the use of ICT combined with control algorithms, which typically have high complexity and thus must be evaluated and analyzed extensively in a laboratory environment [3]. Therefore, field tests are usually carried out for such combination before it can become a procedure for the operation of distribution grids or micro grids. However, performing a pure hardware test with only physical components in laboratories for a certain grid cell can require an extensive budget or be even too complex. Hence, a combination of a software and hardware test environment is proposed in this contribution. This proposed test setup is based on a complete simulation of a grid cell in SIL as well as a detailed hardware test of an Equipment under Test (EUT). Within the SIL test environment, control schemas can be tested and therefor it can be described as a Controller (Hardware)-in-the-Loop (C(H)IL) test. The differences in the scope are depicted in Figure 1.

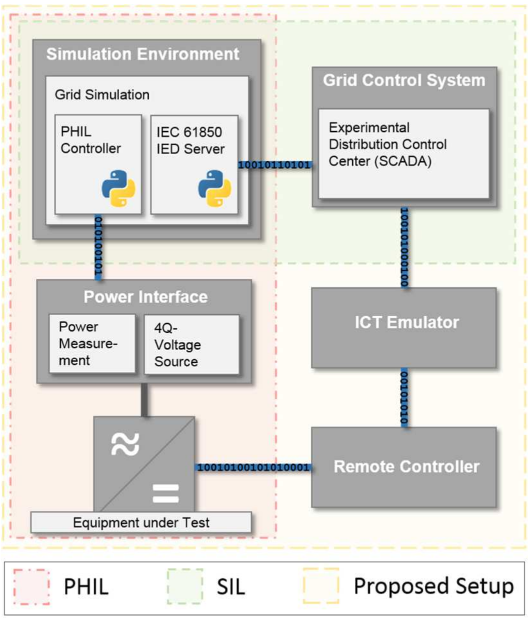

Figure 1: Schematic illustration of the SIL, PHIL and the proposed setup.

The proposed setup is relatively simple compared to a standard PHIL setup which uses a real-time simulation system [4; 5]. The scope of the combined SIL and PHIL is to examine the functionality of a control algorithm implemented by the central entity e.g., a DSO SCADA system to control a decentralized generation unit.

The PHIL part of the proposed setup utilizes the steady-state load flow calculation of the power system analysis tool DIgSILENT PowerFactory and passes the calculated voltage value at a predefined bus bar as a new voltage set point to a power interface, which consists of a switch-mode voltage source and a corresponding measurement device. The steady state simulation approach is in clear contrast to the cycle times of a couple of µs for a transient PHIL simulation setup [5]. This transition can best be described by the expression below (with left part as the instantaneous value of the voltage und $U_{\text{grid}}(t)$ as the steady state / RMS value):

$$\hat{u}_{\text{grid}} * e^{-j\omega t+\varphi_{u_{grid}}} \rightarrow U_{\text{grid}}(t)$$

The suggested und utilized concept is shown in Figure 2. The core element is the power interface which is basically a controllable switched-mode voltage source and a measurement device. The introduced deviation in the voltage typically leads to a reaction in active or reactive power of the EUT due to fast regulating algorithms within the equipment or through slow control algorithms from the superior entity (e.g., DSO SCADA).
The measurement device feeds active and reactive power measurements back in the simulation. Therefore, the transition from transient PHIL setup is best described by the following expression (with instantaneous current and voltage value and derived readings of active and reactive power at the connection point of the EUT):

$$\hat{\imath}_{\text{inv}} * e^{-j\omega t+\varphi_{i_{\text{inv}}}}, \hat{u}_{\text{inv}} * e^{-j\omega t+\varphi_{u_{\text{inv}}}}, \rightarrow P_{\text{inv}}(t) + Q_{\text{inv}}(t)$$

For the proposed setup, cycle times of 400ms are observed in the laboratory. This is mainly restricted by the time necessary to interact with the voltage source over its proprietary interface. The differences between a real-time PHIL using a system like OPAL-RT [6] and the proposed steady state PHIL setup were evaluated as well but are not in the scope of this contribution and will be published in the future.
Regarding the process for examining smart operation strategies with the above described setup, a detailed analysis is carried out and is illustrated in the Smart Grids Architecture Model (SGAM) [7]. The main goal of the system analysis is to decide which effects or control mechanism of the EUT have to be considered. In a second step, the communication infrastructure is analyzed, and the requirements for the communication modeling is specified as well. The resulting setup is discussed in the following section.

IMPLEMENTATION OF PROPOSED SETUP

Laboratory Setup

The basic structure of the test setup is represented in Figure 1 and is detailed as a SGAM function layer diagram in Figure 3, comprising essential hardware and software components for the smart operation strategies, which are investigated in this contribution. As a simulation model, a test grid cell with four low voltage nodes is modelled in PowerFactory. The transition between software simulation and EUT is marked with T in the SGAM diagram.
During the simulation, the actual voltage value and feed-in power flow are recorded by an independent measurement device for further analysis. In the following section, the used EUT and its parametrisation as well as the implemented control infrastructure are described.

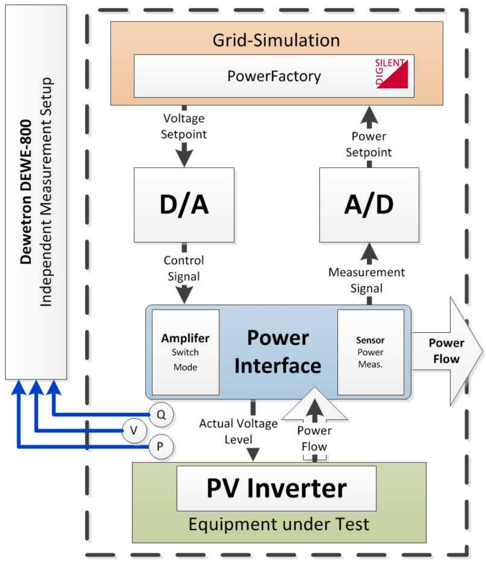

Figure 2: Basic principle for the PHIL part of the proposed setup describing the signal flow.

Power Interface

For the power interface a switch mode amplifier is used as it has advantages compared to Synchronous generators or linear amplifiers. This includes a small size, simple to use and maintain and low losses. On the other hand update of the set point is limited and it introduces together with the cabling of the experiment an inherent impedance. This results in a small voltage deviation. For the measurement device a simple industrial power measurement device is used and readings are collected via Modbus/TCP.

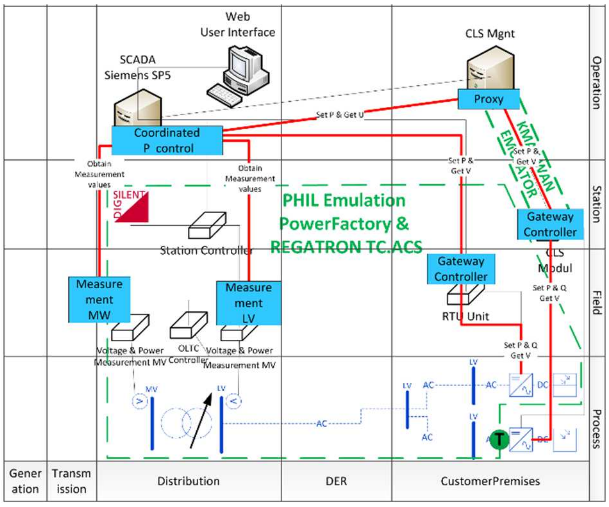

Figure 3: SGAM function layer diagram representing smart operation strategies for decentralized PV-Systems

Equipment under Test

During the test, the performance and response of the EUT, in this case a Fronius PV inverter and a coordinated voltage control, is to be observed. The inverter has a nominal active power of 20kW, while it is set to grid feed-in of 10kW during the test. As another condition a Q(U)-control with the following characteristic for the inverter is adjusted as follows: no reactive power feeding by voltage amplitude between 1.02 and 1.05p.u.; linear increased inductive (capacitive) reactive power feeding by voltage amplitude between 1.05 and 1.08 (respectively 0.99 and 1.02) p.u. until Q_{max} is reached; otherwise constant inductive (capacitive) reactive power feeding with Q_{max}. This is based on the suggestions used by the Austrian DSO Vorarlberg Netze [8].

Control Infrastructure

The control of EUT is executed by a gateway controller named CLS-box (Controllable Local System), which is known as part of the Smart Metering Infrastructure in Germany as described in TR-03109-1 [9]. The real PV-inverter is observed and managed by a CLS-box utilizing SunSpec protocol [10]. At the same time, the CLS-box acts as an IED server (IEC 61850 Intelligent Electronic Device [11]), and sends actual measurements of the PV-inverter via an encrypted channel using the proxy functionality of a CLS Management Server, which complies to the TR-03109 standard in Germany.
The grid information processed by PowerFactory, including real-time values of active power, reactive power, voltage amplitude and tap changer position are collected by a simulated IED server, which runs as a Python script. This information will be transmitted offsite via Virtual Private Network (VPN) to the Experimental Distribution Control Center (EDCC) [12] at Ulm University of Applied Sciences.
Both IED servers communicate with the EDCC through IEC 61850 standard. As a result of interacted hardware measurement and software simulation, an active power set point in percent value with respect to nominal active power of the PV-inverter, will be sent back to the CLS-box and subsequently is forwarded to the PV-inverter.
The voltage control algorithm itself is implemented as a Visual Basic script within the SCADA system (SIEMENS SPECTRUM POWER 5), which is triggered every 10s. It sets the percentage power curtailment rate for the PV-inverter in gradual steps by 10% à 0.05 p.u., triggered when the voltage is bigger than 1.05p.u..

RESULT

The described methodology was used to test and evaluate the setup described in the previous section. The simulated On-load Tab Changer (OLTC) of the grid was actuated to step through the voltage range to trigger the two (Q(U) & P(U)) control regimes. Figure 4 shows the results of the executed experiment as a plot of active respectively reactive power over the voltage at the Point of Common Coupling (PCC) of the inverter. The described steps can be seen in clusters of data points in the diagram. The characteristics for the local Q(U) and the superior P(U) control are represented as lines as well. The green colored area represents the anticipated deviation for the Q(U) control due to output filters and error of the measurements from the inverter as well as from the independent measurement. Nevertheless the measured values for Q(U) control remain close to the desired characteristics.

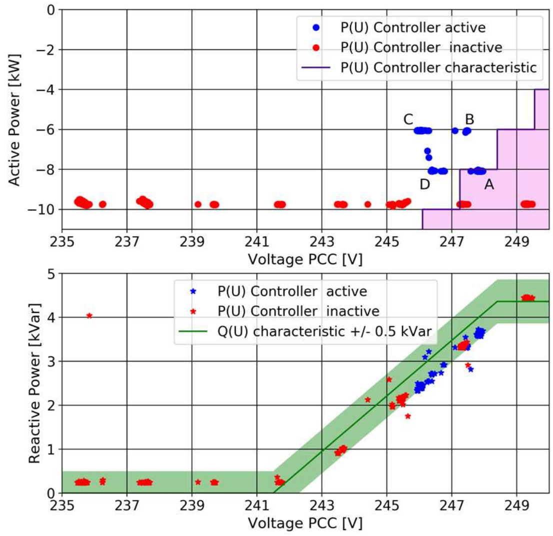

Figure 4: Comparison of the coordinated P(U) control governed by the EDCC and the Q(U) control of the inverter. Control characteristics are represented by the purple respectively green lines.

Regarding the P(U) control governed by the SCADA system: The deactivated P(U) control results in stable operating points at different set points of the simulated voltage regulator of the transformer. The in-feed power of the inverter is not curtailed. With activated P(U) control the purple colored area represents the undesired voltage range. As the control-algorithm is a very basic lookup-table the voltage has to be within this area for at least one transmitted period. In the active power and voltage plot in Figure 4, a few control actions of the control algorithm are depicted. The value pairs form four main clusters, which are inherent to the used setup. The direct causes of the change from one cluster to another are described in the following list:
(**A➔B**) Voltage within the undesired range and curtailment command is transmitted after the executed cycle of the control algorithm. Decrease in feed-in power due to the curtailment command and slightly reduced voltage level due to the inherent properties of the voltage source (please refer to the previous section).
(**B ➔ C**) Due to a new voltage set point for voltage source the voltage readings decrease after a load flow calculation is carried out.
(**C ➔ D**) with the next execution of the tested control algorithm the voltage is in an acceptable range and the curtailment is retracted. Due to the inherent properties of the voltage source the voltage increases slightly.
(**D ➔ A**) with the next carried out load flow calculation the system state returns to **A**.

Analysis showed, that the proposed setup with the simple test algorithm is working. This is visualised in the time-series plot of Figure 5, where the measurements of the independent measurement device and the transmitted readings of the SCADA system are compared. Due to the automatically send commands of the SCADA system, the field gateway is passing the curtailment to the inverter. The inverter is limiting the feed-in to the desired value. This leads to a change in voltage level due to the PHIL setup. As the result of the experiment the postulated oscillating is occurring, nonetheless the control algorithm would not be suitable for a real grid operation. Finding a flawless control algorithm was not the aim of the carried out experiment. When comparing the measurement and the transmitted and archived values of the SCADA system, the discretization is clearly observable.

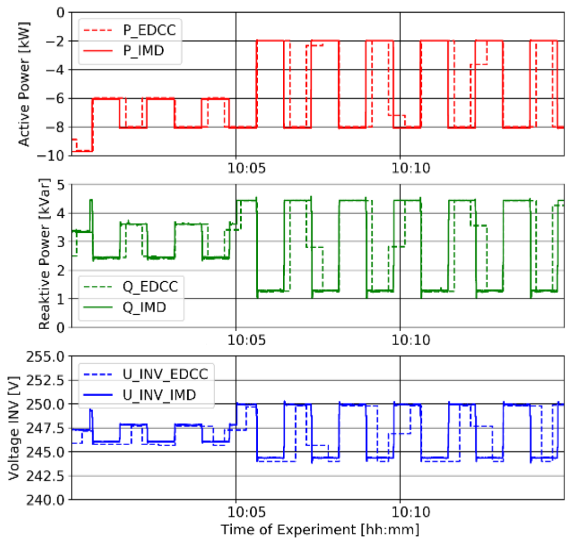

Figure 5: Transmitted Readings (EDCC) and independent measurements (IMD) for a time period with activated P(U) control algorithm.

CONCLUSIONS AND OUTLOOK

As a conclusion, it can be stated that the used SIL/PHIL setup was able to examine the simple P(U)-algorithm, the involved components and subsystems and therefor can substitute a complex and expensive pure physical simulation environment. In addition, the control algorithm, which was developed and implemented to be tested in the proposed setup, worked properly and solved the voltage problems. As side aspect, the used EUT represent a successful laboratory test of the infrastructure following the German concepts of CLS module for the monitoring and control of small decentralized generation units. This includes the use of the IEC 61850 communication protocol, secured data transmission and utilization of the SunSpec protocol.As further task to improve this concept for testing of smart and micro grid control algorithms the following steps are planned for the future: an in-depth comparison between the used setup and classical PHIL setups, a more detailed characterization of the voltage source and development of compensation methods and inclusion of a Wide Area Network Emulator for a more detailed modelling of the communication path.

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