InFIS – Integrated Research Infrastructure

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***Abstract*—In this paper we present the current state of the project InFIS – Integrated Research Infrastructure. Specifically we show how a PV Battery Energy Storage System (BESS) can be connected to a grid emulator and a central simulation environment. The grid emulator is a modular multilevel converter consisting of six arms containing four Insulated-gate bipolar transistor (IGBT) submodules each. The grid simulation operates on commercial PHiL hardware simulating the CIGRE distribution grid benchmark network. Communication is established in real-time using the Villas Framework. Results presented show how each component is built and connected to the central simulation system as well as some initial results on system scaling and dimensioning.**

Keywords—Distributed Power Hardware in the Loop (PhiL), Battery Energy Storage System (BESS), grid emulator

I. Abbreviations

Abbreviation	Explanation
2L-VSC	Two level voltage source converter
3L-VSC	Three-level voltage source converter
APOD	alternative phase opposition disposition
BESS	Battery Energy Storage System
CCM	Centre control module
DUT	Device(s) under test
DC	Direct current
DRTS	Digital Real-Time Simulators
GEM	Grid Emulator
IA	Interface algorithm
IGBT	Insulated-gate bipolar transistor
ITM	Ideal transformer model
PHiL	Power hardware-in-the-Loop
LSPWM	Level shift pulse width modulation
LV	Low voltage
MMC	Modular multilevel converter
PCC	Point of common coupling
PD	Phase disposition
POD	Phase opposition disposition
PSPWM	Phase shift PWM
PV	Photovoltaic
PVGIS	PV Geographical Information System[1]
THD	Total harmonic distortion
VSC	Voltage source converter

II. Introduction

Smart home, prosumer, distributed renewable energy sources – all these are terms frequently used to describe technologies to be deployed in the electricity grid in the future. The key element most of these technologies share is that both loads and generators will non-linear and possibly remote-controllable. Examples are

- photovoltaic (PV) installations using inverters which in parts can be controlled by the distribution grid operator,
- Battery Energy Storage Systems (BESS) which increase self-sufficiency of households and provide control reserve to the grid,
- heat pumps replacing the burning of fossil fuels for heating while adapting their consumption to the current generation situation,
- and many more small smart devices, each with its own operating strategy.

As these devices penetrate the grid in ever larger numbers, the behaviour of the system is bound to change. Electric power supply is in a unique position where the safety and reliability is integral for the functioning of society, but testing is limited, especially for the interaction between many devices. Reasons for this are multiple with the most important one being that any large-scale experiment in the real-world system could cause blackouts and therefore large economic losses.

This paper outlines one approach to still make statements about system behaviour. We show how multiple devices can be integrated into a larger simulated environment thus forming an extended power hardware in the loop (PHiL) setup.

III. Literature review

When trying to answer questions about how the power grid will react to a high share of modern, non-linear loads and generators, researchers have used methods such as:

- Computer simulations [2–4],
- Field demonstrators [5, 6], or

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- PHiL testing [7–9].

There are some issues attached to each these approaches. For computer simulations, the problem is mostly that only those effects can be observed which have previously been modelled. A wrong assumption or simplification in the model could cause the researcher to miss important effects. Field demonstrators have the disadvantage that they mostly only observe normal grid conditions as they are connected to the public power grid. Studying the behaviour of equipment in extreme situations, e.g. blackouts, severe power quality issues, is challenging while connected to the public grid. Using a demonstrator in a PHiL on the other hand requires careful design of the software environment. Since the loop around the hardware is essentially a simulation, similar disadvantages can occur as compared to using computer simulations alone.

A current trend is to switch towards a combination of computer simulation and PHiL testing where one or more power devices are either physically or virtually coupled. In this setup, non-critical components may be simulated and key components, which are suspected to have the largest influence on system behaviour, are deployed as hardware. Palmintier, Lundstrom et al. [10] for instance have developed a platform capable of running such a setup. Focussing on electric power trains, Sen, Evans et al. [11] took the idea a step further and enabled the system to operate devices located at remote geographical places by converting the behaviour of each machine into the frequency domain and transmitting that information. The advantage of such an approach is that more real hardware responses can be observed through the connected devices. This allows for the detection of more effects as compared to the previous approaches.

At the RWTH Aachen University, the project InFIS is underway to apply the idea of remote operating devices to the power sector. Particularly, the goal is to observe how a smart home as outlined in the introduction reacts to power quality issues. As a first stage, a BESS will be tested. This paper describes how the system was connected with a special focus on how a BESS can be modified to function in such an environment. A key challenge is that such a system both draws and supplies high powers and measures real power flows.

In literature, several BESS have been tested as PHiL implementations with various components either simulated or present as real hardware. Frequently, new controllers are tested where the battery and grid behaviour is simulated [12–14]. Alternatively, the battery may be hardware and the remainder simulated to observe what effects a control strategy has on battery dynamics [15, 16]. The advantage of these two approaches is that researchers have access to all relevant components of the system and can freely design the BESS. A disadvantage of this approach when trying to study real-world applications is that the setups used are still laboratory setups at the end of the day. Commercial systems may show behaviours that are not present in laboratory setups. To the best of our knowledge, no research has been conducted on how a commercial system reacts to different grid states.

Our contribution to literature therefore is that we use commercial hardware as installed in thousands of homes in combination with a hardware in the loop system with multiple components. This paper shows how the first step, i.e. building a suitable grid emulator for the battery and connecting all battery sensors may be executed.

IV. Methodology and Material

A. System setup

Figure 1 shows a schematic setup of the project in the fully developed stage. The central digital components, namely the electrical grid simulation and the data link, are described in the following subchapters. For the hardware implementations as well as the photovoltaics model treated in this paper, please refer to IV.B to D.

1) Real-time simulation of electrical grids

As one of the key goals of the project is to understand how distribution grids behave with a high share of smart grid devices, a grid simulation lies at the core of the project. The focus of development here lies in the accurate modelling of transients for all devices. All simulation models and the solver of the simulator are suitable for performing the electromagnetic-transient simulations. In the model, each device, real or simulated, is connected to nodes of this grid.

To allow for integration and testing of real physical devices, Digital Real-Time Simulators (DRTS) are required for the simulation of distribution grids. OPAL-RT and RTDS (both commercial DRTS) form the PHIL setup. The communication interface between Grid Emulator (GEM) and DRTS is described in IV.A.2). Interface Algorithms (IA) play an important role in preventing loss of simulation fidelity and stability which the communication interface and the GEM might otherwise cause to deteriorate. A comprehensive overview of IA for PHIL is provided in [17].

Initial analysis of simulation fidelity in this work is based on the simplest IA, which is Ideal Transformer Model (ITM).

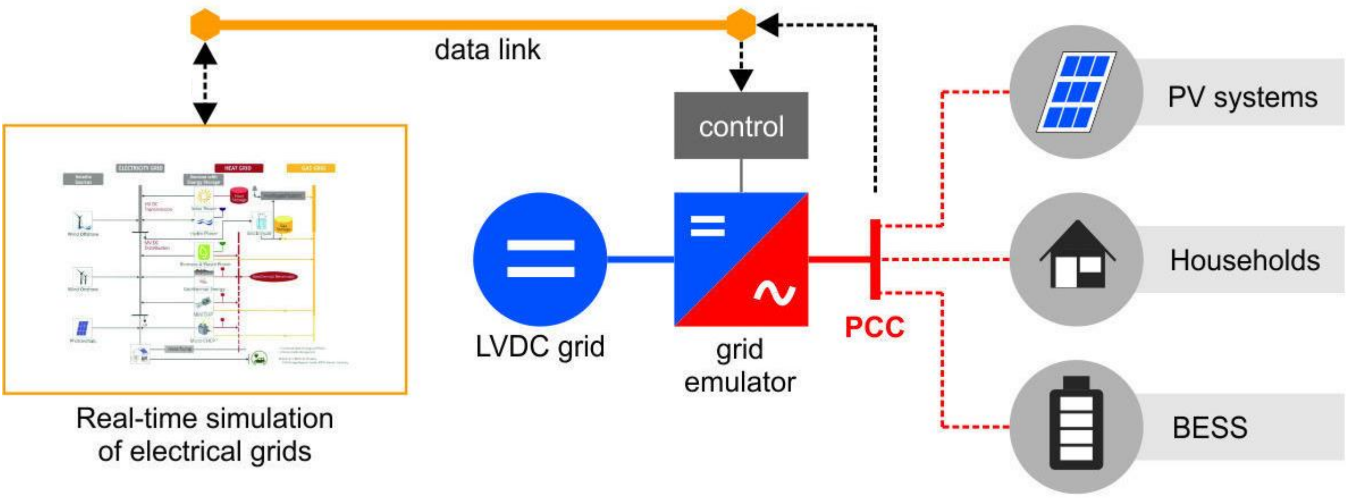

Figure 1: Schematic setup of the InFIS infrastructure. Real-time simulation of the electrical grids, PV generation and parts of household loads are simulated while the grid emulator, parts of household loads and the battery electric storage system (BESS) are implemented in hardware

The monolithic simulation model is partitioned into two subsystems where the first subsystem is simulated in DRTS while the second represents the physical DUT. Thus, the first subsystem includes the distribution grid and simulated devices. A current controlled source is introduced in the distribution grid model at the point of decoupling to impose the measured behaviour of DUT. GEM emulates the grid following the voltage reference measured in DRTS at the point of decoupling.

A benchmark system for PHIL testing in the context of distribution grids was suggested in [18]. The simulated electrical grid in the proposed benchmark is based on the European Low-Voltage (LV) CIGRE network benchmark, which is designed for studies of increasing penetration of power electronics devices [19].

2) Data link

The data link is the real-time connection between the grid model and the physical hardware, namely the grid emulator and any auxiliary signals, which the connected devices might require. This link is implemented using the Villas framework [20] developed at the institute for Automation of Complex Power Systems. The link differentiates between two types of real-time, named soft and hard real-time. Soft real time is a connection, which is not time critical in the sense that it would affect the waveform of the grid voltage and current. An example for such a soft-real time device would be any linear load or any device without a consumption large enough to significantly influence grid operation. Hard real-time on the other hand refers to a component which will significantly influence voltage and current waveform such as a battery storage. In hard real-time, instantaneous voltages and currents are shared across the system. In contrast to [11] we decided to transmit information in the time-domain instead of the frequency domain. The added benefit of this approach are less calculation requirements and no filtering of behaviour, which could not be transmitted as a frequency information. The drawback of this approach is that a highly reliable communication line with low latency between the devices is required. This limits the allowed physical distance between the DUTs, but this is acceptable in our application.

B. Sol-Ion model

The model used in this project is largely based on work by Dr. Dirk Magnor [21]. The system models a DC-coupled system of a PV generator, a BESS and a central inverter. All models are empirically parametrised.

Solar irradiance data used for this project originates from the Photovoltaic Geographical Information System created by the Joint Research Centre of the European Commission, at Ispra [1]. The tool has access to several radiation databases covering specific world regions and their data is interpolated to provide a continuous dataset for most of the world. Figure 2 shows the European solar irradiation values as taken from PVGIS. Hourly data was downloaded from the database CMSAF for Aachen, Germany and parsed into Matlab©.

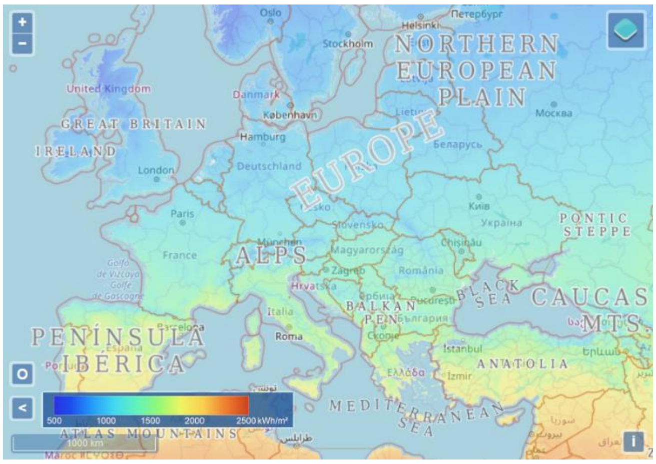

Figure 2: PVGIS map for Europe [1, 22, 23]

The household load used for this paper is the BDEW standard household load profile [24].

C. Battery Energy Storage System (BESS)

The battery energy storage system (BESS) used in this project is PV home storage. The battery storage is a single-phase lithium ion battery with 4.5 kWh storage capacity (3.5 kWh usable) and an inverter power of 2.5 kW [25]. The system uses power meters connected to the mains supply of the house as well as the PV generation to determine the current power flows in the household and to adapt its operational strategy accordingly

D. Grid emulator

In this chapter, we would like to introduce the relevant aspects of the employed grid emulator. In 1) we outline the functional principle of a grid emulator and in 2) some criteria of how proper performance are defined. 3) provides some insights of how communication was realized.

1) The function of a grid emulator

A grid emulator (GEM) emulates the grid behaviour using power electronic converters. The GEM generates a voltage sinusoidal-like waveform. A filter is utilized to eliminate the harmonics of the generated waveform. The GEM must be able to imitate situations where the grid is in a critical state such as a sudden voltage drop or a frequency deviation – situations the devices to be tested could experience. The specifications of our GEM are given in Table 1.

Table 1: Grid emulator specifications

Item	Specification
DC link max. voltage	1600 V
Link voltage tolerance	+/- 10 %
Submodule number	4
Max. apparent power	120 kW
The apparent power of DUT	1-20 kW
Grid frequency	50 Hz
Switching frequency	10 kHz

2) Criteria for a grid emulator

To evaluate the grid emulator, we have to establish the standard upon which the evaluation is done. Existing standard for the low voltage grid are IEEE 519 as the US-American standards and EN 50160 as the German standard for low voltages. For the grid emulator, standards must be exceeded in order to benchmark the devices under test (DUT) performances. Based on the above standards, reasonable requirements for the projects are taken as:

- The dynamic requirement is a settling time (i.e. time to reach reference) of 1 ms.
- The phase delay and the attenuation should also be taken into consideration.

The GEM performs as a grid forming voltage source inverter, which takes voltage amplitude and reference frequency as reference. A conventional cascaded double loop control could be implemented as in [28]. However, a PI controller could be slower than expected. The possible solutions could be either to use an model-based control such as state space or model predictive control, which is already implemented in [29].

3) *Communication and time delay*

The reference values are the voltages at the point of common coupling (PCC). The setpoint values are sent by the digital real time simulator (DRTS) to the center control module (CCM). The communication happens within a the Villas framework [20], which uses the TCP/IP protocol. The CCM combines up to 16 slave modules and processes the data. The values are sampled and processed by a zero-order holder, and then sent via the MerkurLink to the MerkurBox. The MerkurBox (AixControl) is a commercial product from the company AixControl GmbH and works as a universal interface box for stacks. It interfaces the controllers with a MerkurLink to the DUT driver boards [30]. There is one MerkurBox installed for each submodule and one for the PCC, thus 25 MerkurBoxes are needed. The signals are processed to be the PWM signals, which controls the insulated-gate bipolar transistors (IGBTs) of the submodules to turn on and turn off. The voltages and currents at PCC and the voltages at the inverter side are measured. These measured values are sent back to the DRTS to verify the grid simulation operates well. The submodule voltages and arm currents are also measured and sent back to the MerkurBox, to confirm that the voltages of submodules on each arm and of each phase are well balanced.

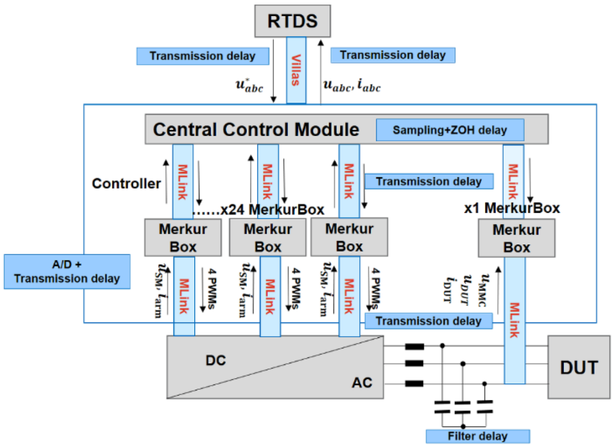

Figure 7: Structure of the communication of the grid emulator

As shown in Figure 7, the DRTS sends the reference values every 50 µs. This implies that all of the delays of our grid emulator must be less than 50 µs to avoid any aliasing or processing fewer reference values. There are transmission delays between the DRTS and CCM. Within the CCM the sampling and zero-order holder (ZOH) leads to a 1.5 timestep delay with a double edge modulation. Between the MerkurBox and the MMC, there is also the A/D and transmission delay.

V. Preliminary Results

This chapter shows the results obtained until the writing of this paper. As the overall system is not yet operational, only device-specific results can be presented. System results will be shared upon project completion in 2021.

A. *Projected available capacities over the year*

Figure 4 shows an overview of the SoCs at which the BESS operates over the course of a year given the model setup described in IV.B. It can be seen that unless a very high peak PV power has been installed, the storage spends much time

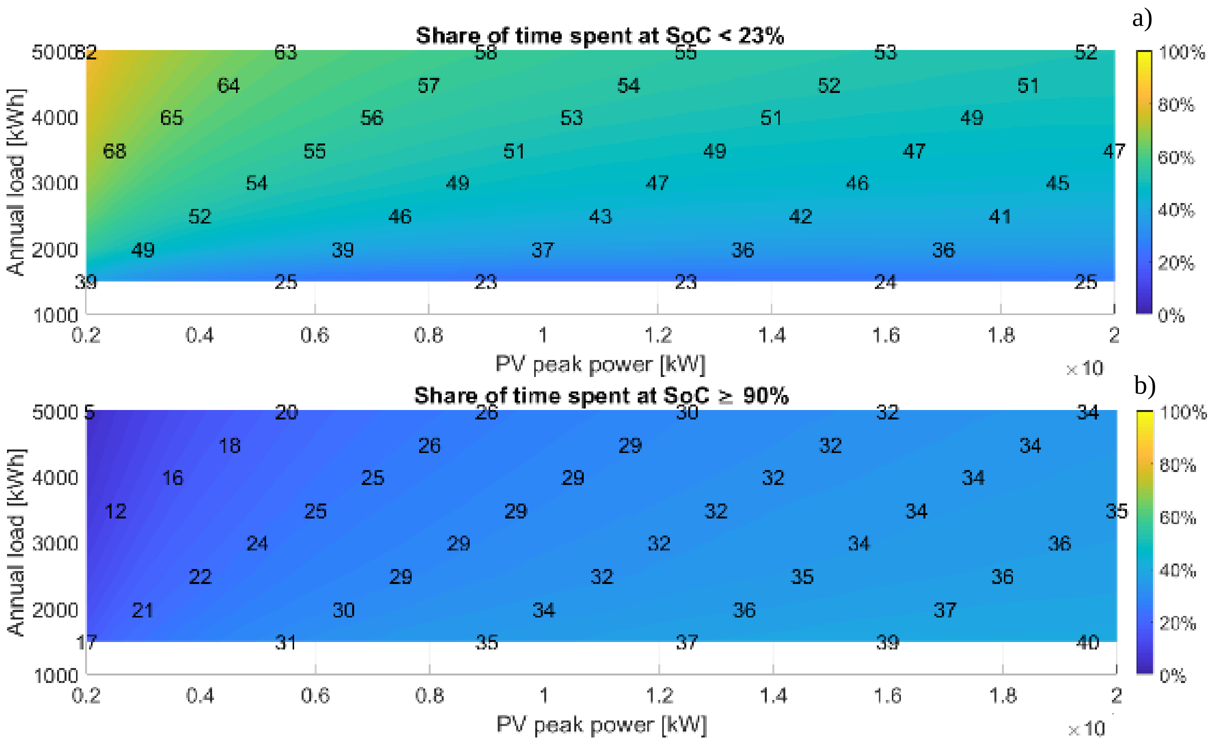

Figure 3: Overview of SoCs as a function of annual load and installed PV power. a) shows how much time was spent at SoCs below 23% (i.e. empty, as 22% are the lowest allowed value) and b) the amount of time spent at an SoC ≥ 90% (i.e. full).

either empty or full. This can be explained by the storage strategy employed where the storage tries to maximise self-consumption by discharging as soon as consumption is above PV generation and by charging as soon as PV generation is above consumption. In this mode, the storage will reach the full and empty state as early as possible.

For grid simulations, this means that as long as there has been sufficient sun, it is reasonable to simulate all storages in a distribution grid as full or nearly full. Similarly, storages may be regarded as empty during a dark winter day. For PHiL applications such as the one outlined, this also means that the extreme SoCs cover most real-life scenarios.

B. Grid emulator

In the following, we present some insights into the current development progress of the emulator and give some recommendations on how an emulator should be built by other research groups attempting similar goals.

1) Topology and components

Most GEMs in literature are two level voltage source converters (2L-VSC, see [31]) or three level voltage source converters (3L-VSC). Researchers have also investigated the possibility of using IGBTs to perform the high-power and low-frequency components while using MOSFETs to perform the high-order harmonics with low amplitude [32]. In the course of this project, a modular multilevel converter (MMC) is utilized to satisfy the requirements of the grid emulator, e.g. low harmonics. As the MMC has more voltage levels than the 2L-VSC and 3L-VSC, it can generate a sinusoidal like waveform with less low frequency harmonics at the same switching frequency. An MMC has more DC link capacitors to share the voltage stress and generates more voltage levels than the other described topologies.

In this project, full-bridge submodules are used to establish the MMC. As shown in Figure 4, the MMC consists of six arms. Each arm contains four half-bridge submodules (SM). There are four IGBTs and one submodule capacitance in each submodule. By sorting the submodules according to the capacitor voltages, the submodule capacitors can be equally charged and discharged and thus, the voltages of each arm can be balanced.

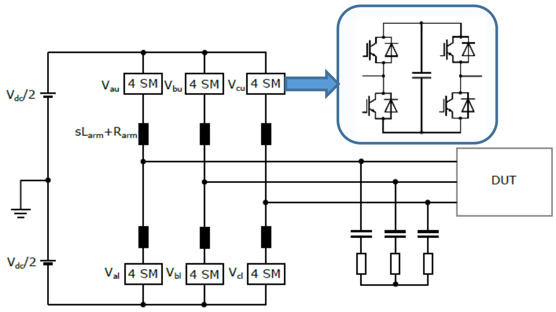

Figure 4: Topology of the MMC in the project

Based on the results from simulation and calculation, Table 2 illustrates the comparison among three GEM topologies with the same switching frequency of the harmonic distortion with different frequency without control. A 2L-VSC has more harmonics, especially in the low frequency range, (under the switching frequency range), while a MMC has less harmonics, and it appears mainly at twice the switching frequency. For the MMC, we have smaller THD, therefore, we need only a filter with higher cut-off frequency as compared to the 2L-VSC and 3L-VSC. Thus, smaller inductor and capacitor are needed to satisfy the requirements of a grid emulator. Take the conventional cascaded double control loop for example, the bandwidth should be designed 10 times smaller than the filter cut-off frequency, to ensure the system can be regarded as a simple system. A controller with larger bandwidth means a faster time response. From this perspective, the MMC with controller responses faster than the other two topologies.

Table 2: Comparison among three topologies

Freq. [kHz] / HD [%]	9	10	11	20	20.5	THD
2L-VSC	17.59	58.9	81.03	85.16	94.04	112
3L-VSC	0	55.97	79.15	79.77	80.08	88.22
MMC	0	0.21	0.63	0.64	11.03	29.6

An MMC is often used as a grid converter instead of a GEM [25], which has a more strict standard than the former one. According to the specifications, a lower number submodules is applied in the project because of the low voltage level. Therefore, a high switching frequency is implemented in order to achieve the high THD requirements of a GEM. Thus, a filter is implemented after the MMC topology. And as there are already arm inductors in MMC, extra inductors are not imperative to establish the filter. Capacitors are utilized to filter the switching frequency harmonics and smoothen the voltage waveform. An LCL filter could not act as a better filter than the LC filter. The DUT side inductor could only be a grid impedance. Therefore, an LC filter is implemented in the project.

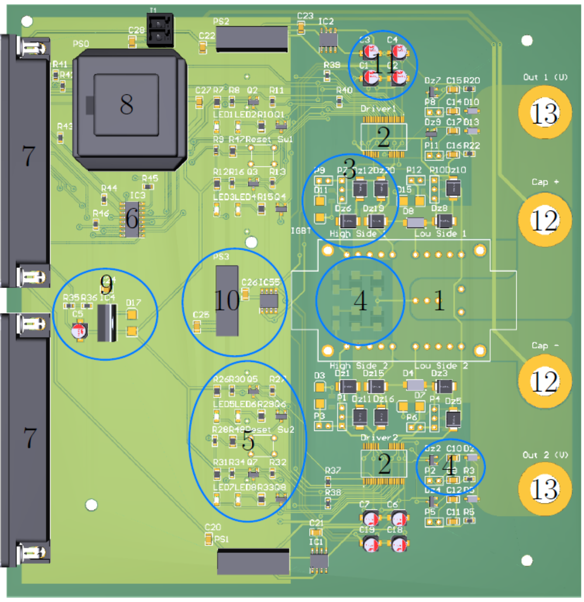

Figure 5: PCB of the auxiliary power supply circuit, the gate driver circuit and the IGBT modules (see Table 3 for details)

In Figure 5 the model of the printed circuit board for the gate drive units of the IGBT full-bridge is shown. The power to operate the PCB and to run the submodule control is supplied by the submodule capacitance. The modular structure of the converter and the auxiliary power supply via the submodule capacitance facilitate the reduction of isolation efforts. A DC-DC converter transforms the voltage from an average submodule voltage of ca. 400 V to the supply voltage for the auxiliary circuitry of 24 V. The submodule control is connected to the 24V output of the DC-DC converter and transfers the voltage to the rest of the PCB via the connectors labeled “7” in Figure 5. This voltage is then transformed further in order to meet the requirements of the gate drive units, which need a voltage level of 15V for switching the IGBT on and -8V to switch it off, as well as a 5V supply voltage. Further, the PCB also has protection circuits in order to protect the IGBTs from overvoltage and excessive currents such as active clamping, gate clamping and desaturation protection. Table 3 depicts an overview of the gate drive circuit elements.

Table 3: PCB Elements

Number	Component
1	IGBT
2	Gate Drive unit
3	Gate resistance network and gate clamping
4	Active clamping
5	Reset switch for desaturation protection, LEDs
6	Level converter from 15V to 5V
7	DSub connection for submodule control
8	DC-DC converter from 400V to 24V
9	Linear regulator to 5V
10	DC-DC converter to 15V and -8V
11	Smoothing capacitors at the driver output
12	Connection to submodule capacitance
13	Connection to other submodules

C. Grid simulation

The simulated distribution grid represents LV CIGRE network benchmark illustrated in Figure 6. Two inverters with rated power of 8.5kW are integrated in the distribution grid. The first inverter is interfaced to the bus R15 as PCC, while the second inverter is interfaced to the bus R18.

In the context of preliminary analysis of the PHIL concept, a simulation-based analysis of the stability and fidelity of PHIL is provided. Namely, a simplified PHIL setup is simulated. The simulated PHIL interface includes ITM IA, and time delay for communication between GEM and DRTS while GEM is assumed to be completely transparent. The two mentioned inverter are considered as potential DUT together with the corresponding loads connected to the same bus.

Three simulation models are considered. First, a monolithic simulation, where both inverters are naturally coupled to the corresponding PCC without any interface. The monolithic simulation represents reference results to determine fidelity of PHIL. In the second simulation model, DUT is considered to be the first inverter connected to the R18. Third simulation model assumes DUT to be the second inverter connected to the bus R15.

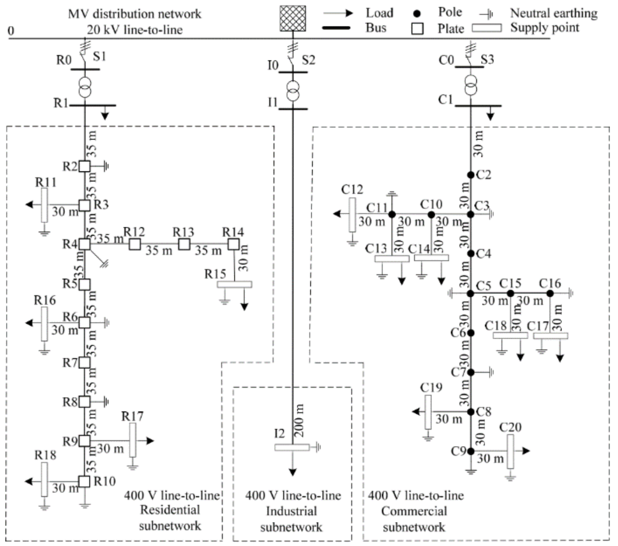

Figure 6 - CIGRE European LV distribution network benchmark [19]

The obtained simulation results given in the Figure 7 indicate that the degree of simulation fidelity depends on the location of DUT in the distribution grid. Therefore, a holistic analysis that incorporates the dynamics of the simulated distribution grid, location of the DUT and knowledge on GEM is required for the design of PHIL setup.

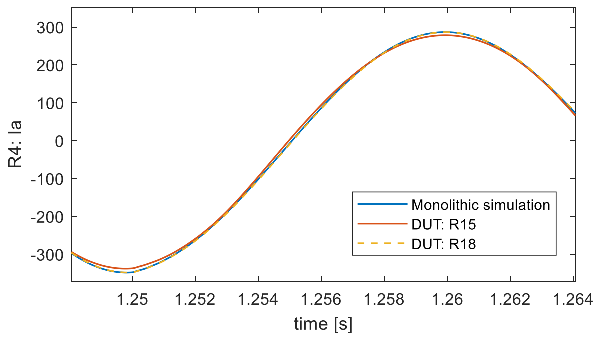

Figure 7 – Simulation results for time delay of $50\mu s$

VI. Discussion

In this paper, we have outlined how researchers currently try to make statements regarding grid behaviour with a large number of smart (power) electronic devices in the grid. Building on these contributions we outline the approach chosen in the InFIS project as well as some initial design considerations based on simulation results and theoretical derivations. As the project is still in an early stage, no final results can be presented yet, but are expected to be available in the coming two years. We hope that the progress reported does aid other researchers and industry professionals when attempting similar projects.

VII. Acknowledgements

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