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Power Hardware-in-the-Loop Demonstrator for Electric Vehicle Charging in Distribution Grids

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***Abstract*—A simple and low-cost Power Hardware-in-the-Loop (PHIL) demonstrator is developed for the purpose of studying the impact of Electric Vehicle (EV) charging on low voltage distribution grids. An energy saving power circulating method with potential bi-directional function is proposed in this study as well. The distribution grid under test runs on a Digital Real Time Simulator (DRTS), and a controlled 3-phase voltage at one of the nodes is formed using a power amplifier. The practical setup consists of Electric Vehicle Supply Equipment (EVSE) and a system which emulates the charging behaviour of an EV, referred to as an EV emulator. These are integrated using a 15 kW back to back ac-dc converter based power router. Structure, performance and limitations of the test-bed components, communication protocols and signal processing are discussed.**

I. Introduction

Transportation is currently responsible for approximately 27% of greenhouse gas emissions in the EU [1]. Electrification of this sector can greatly reduce its emissions and help meet climate goals. However, the expected exponential increase in Electric Vehicle (EV) penetration will likely present significant challenges for distribution grids. With charging powers of AC chargers commonly reaching 22 kW each, uncontrolled charging of EVs at home or at the workplace will increase peak loading and place significant strain on local distribution grids [2]. The impact of increasing EV penetration on voltage deviations and distribution losses are investigated in [3], [4].

Many potential solutions for reducing the impact of EV charging on the distribution grid can be found in literature. For example, electricity price based demand response is used to define a chargeable region to improve EV hosting capacity [5]. Using flexibility in EV charging demand, potential cost savings of 10-50 % can be achieved depending on the considered scenario [6]. Coordinated EV charging using priority based scheduling is studied in [7]. An energy management system to optimize EV charging at workplaces based on PhotoVoltaic (PV) forecast is discussed in [8], showing an increase of 8.8 % increase in self consumption compared to uncontrolled charging. Integration of PV to EV charging based on energy price and Vehicle to Grid (V2G) application is presented in [9]. Smoothing of voltage fluctuations caused by Renewable Energy Sources (RES) in distribution grids by considering the EV charging plan is shown in [10].

Simulation studies have shown potential for cost savings and ancillary services for improving grid performance with smart charging algorithms. In [11], a detailed survey is done on the differences in objective function of smart charging algorithms based on specific goals such as load regulation, ancillary service provision, reduction of grid congestion, maximization of self consumption and operational cost minimization. Experimental validation using demonstrators and pilot projects are, therefore, the next step towards facilitating the practical implementation of these concepts [12], [13]. The study in [14] experimentally validates the improvement in voltage quality using a smart charging algorithm and highlights some differences from simulations, for example unwanted controller oscillations and variation in reaction times. This paper represents each component, including a wind-turbine with actual component in laboratory environment. Power Hardware-in-the-Loop (PHIL) can be useful for studying the impact of smart concepts on large-scale grids in real-time in a laboratory environment under a wide range of conditions and in a repeatable, safe, and economical manner [15].

Therefore, the focus of this paper is the development of a 15 kW PHIL based demonstrator as a test-bed for EV charging applications. Herein, the Digital Real-Time Simulator (DRTS) is used to simulate the use-case grid while the Electric Vehicle Supply Equipment (EVSE) is implemented as physical hardware. Even though the current testbed focuses on AC charging under the IEC 61851 standard, a bi-directional power circulating method is proposed, which provides a V2G function test possibility in the future. Section II gives a top-level overview of key components in EV charging. Section III details each system component of the PHIL testbed and their integration withing the larger system. Section IV presents measurement results when the connected EV is operated with uncontrolled charging. Section V highlights the conclusions and future work of this paper.

II. System Description

Fig. 1 shows the key components in EV charging. The Electric Vehicle Supply Equipment (EVSE) is connected to the local distribution grid via a single- or three-phase connection. In the case of AC charging, the EVSE does not contain any power electronics; only the necessary interfacing hardware. This includes hardware to communicate with the

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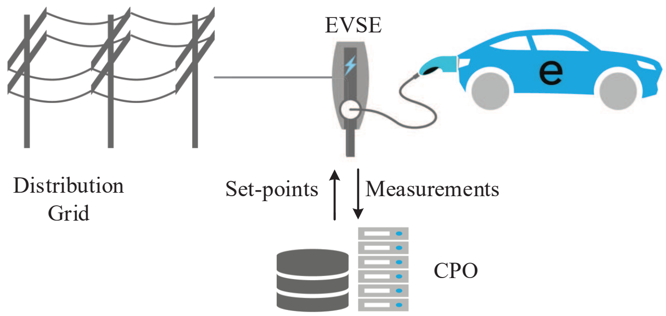

Fig. 1: Key components in EV charging

EV and Charge Point Operator (CPO), relays to disconnect power to the EV, and measurement equipment. The conversion from AC to DC happens within the EV, using its On-Board Charger (OBC). This OBC is responsible for charging the EV's battery to the State Of Charge (SOC) requested by the user. Under the IEC 61851 standard, the communication between EVSE and EV is relatively limited; the EVSE can communicate a maximum allowable AC current to the OBC, but the OBC cannot provide any information about the battery's size or SOC. The CPO manages the EVSE and plays a role in authorizing and billing transactions. It can receive measurements, stop/start the charging process, and adjust the maximum charging current.

III. PHIL Test-bed Components

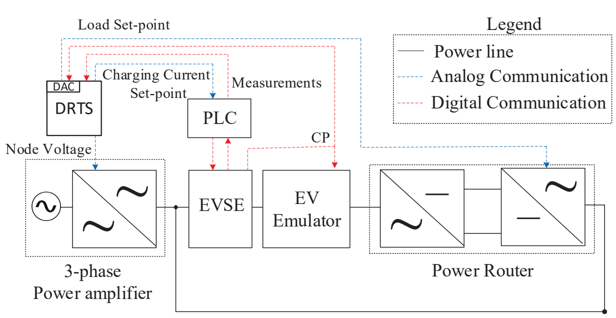

Fig. 2: Block diagram of the experimental implementation of Fig. 1. Solid lines represent power flows and dotted lines information flows.

The practical implementation of the system discussed in section II can be seen in Fig. 2. The heart of the setup is a Digital Real-Time Simulator (DRTS). This DRTS runs a grid simulation and interfaces with all other subsystems. Based on the results of the grid simulation, the amplitude of three low-voltage sine waves is adjusted. These are amplified by the power amplifier in order to create a three-phase grid with controllable voltage. The EVSE is plugged in to this grid. The combination of an EV-Emulator and two back-to-back DC power supplies forms an emulated EV. The EV-Emulator communicates with the EVSE as per IEC 61851 and the back-to-back power supplies form a controllable AC regenerative load which sinks the power that would otherwise go into an EV's battery.

A. Digital Real-Time Simulator (DRTS)

The DRTS used is an OPAL-RT OP5700. It runs a Newton-Raphson power flow analysis of a given distribution grid, shown in Fig. 3. This grid is based on a real Dutch grid and contains 19 nodes with lines of known resistance and reactance between them. Based on the load at each node, the grid simulation outputs the nodal voltages. The simulated voltage at a chosen node determines the amplitude of three sine waves with 120 degrees phase difference, which is amplified by the power amplifier. The DRTS also communicates with the EVSE and is able to read its measurements and adjust the maximum allowed charging current. There is a possibility to use an Application Programming Interface (API) to run a Python algorithm which can manipulate this maximum current. This opens up the possibility for this testbed to be used for smart charging in the future. A Python algorithm could use the API to read measurements and signals from the real-time Simulink model, combine this with external data such as solar irradiance forecasts, and calculate optimal charging setpoints for each moment in time. The setpoints can then be sent to the DRTS via the same API, at which point they will be communicated to the EVSE.

Additionally, the DRTS controls the power drawn by the AC load. It does this by converting the duty cycle of the Control Pilot (CP) Pulse-Width Modulation (PWM) signal generated by the EVSE into an analog voltage which controls the DC/AC converter. This is similar to what happens in a real EV; the EV's OBC uses the CP duty cycle to determine the maximum AC current which it is allowed to draw to charge the battery. This relationship is shown in table I.

TABLE I: Relationship between CP duty cycle and maximum allowed current [16]

Duty cycle interpreted by EV	Maximum current
Duty cycle <8 %	0 A
8 % $\leq$ duty cycle <10%	6 A
10 % $\leq$ duty cycle $\leq$ 85 %	(% duty cycle) x 0.6 A
85 % <duty cycle $\leq$ 96 %	(% duty cycle - 64) x 2.5 A
96 % <duty cycle $\leq$ 97 %	80 A
Duty cycle >97 %	0 A

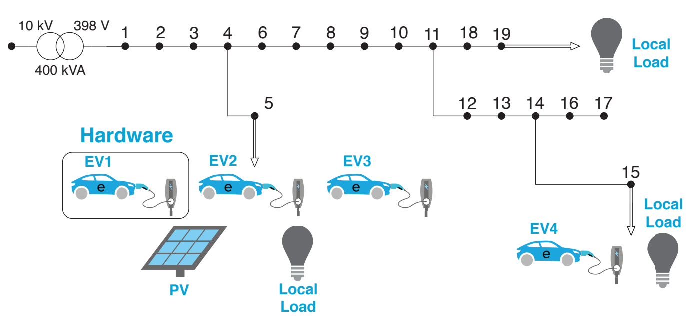

Fig. 3: Single-line diagram of a Dutch grid used for grid simulation

B. Power Amplifier for Nodal Voltage Emulation

In order to emulate a three-phase distribution grid node, the three low-voltage sine waves produced by the DRTS need to be amplified to a nominal phase voltage of 230 V. To do this, three California Instruments AST1501 AC power sources are used, one for each phase. These power sources act as a power amplifier and amplify the low-voltage waveforms produced by the DRTS by a fixed factor.

Figure 4 shows the RMS bus voltage for a certain load profile of node 5 of the distribution grid shown in figure 3, calculated by the Newton-Raphson power flow analysis running on the DRTS. The base value is a phase voltage of 230 V. The plot also shows the corresponding measured output of the power amplifier. As can be seen, the power amplifier can accurately produce the nodal voltage calculated by the power flow analysis. There is a mean absolute error of less than 0.3 % between the simulated set-point and the output of the power amplifier.

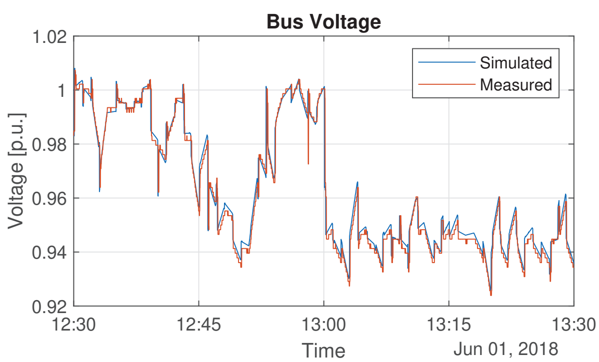

Fig. 4: Simulated (Newton-Raphson) and measured phase voltage (output of power amplifier). The base value is 230 V.

C. Electric Vehicle Supply Equipment (EVSE)

The EVSE used is a commercially available product, namely the Alfen EVE Single Pro-Line. It is an AC charger that supports both single- and three-phase charging up to 32A. It has one socket for a type 2 charging cable and supports the IEC 61851 for communication with the EV, as well as Modbus TCP and Open Charge Point Protocol (OCPP) version 1.6 for communication with external devices or a CPO. The EVSE is connected to the emulated distribution grid node created by the power amplifier.

D. EV Emulator

The EVSE cannot be connected directly to an AC load because, as per the IEC 61851 standard, specific resistors should be connected between the Control Pilot (CP) and Proximity Pilot (CP) communication lines and the Protective Earth (PE). To implement these resistors and to provide a physical interface between the type 2 charging cable the AC input of the load, a Walther-Werke EV emulator box is used. This device contains only passive components and does not process any power or signals, but it does allow the user to select the EV's charging status and the maximum current carrying capacity of the cables.

E. Communication and Signal Processing

In Fig. 2, the information flows are represented by dotted lines. Firstly, the current setpoint is communicated from the DRTS to the EVSE. The protocol chosen for communication with the EVSE is Modbus TCP, a widely-used communication protocol for industrial devices that operates over Ethernet. However, the DRTS available in the laboratory does not currently have the possibility to implement Modbus TCP communication. The simulator only has analog and digital inputs/outputs available. To circumvent this issue, a Programmable Logic Controller (PLC) is used. This PLC does have the ability to communicate with the EVSE over Modbus TCP, and it has 2 analog inputs and respectively 2 and 4 PWM-capable outputs and inputs available. Therefore, it is used to convert the input/output signals of the EVSE to analog and digital signals. Specifically, the current setpoint is communicated from the DRTS to the PLC as an analog voltage and the phase voltage and current measured by the EVSE are communicated as a digital PWM signal. The two-way communication between PLC and EVSE is through Modbus TCP.

Based on the setpoint received over Modbus TCP, the EVSE adjusts the duty cycle of its Control Pilot (CP) signal. In a real-world implementation, this duty cycle is read by the EV's OBC and it will adjust the charging rate of the battery accordingly. However, in this experimental setup, the CP duty cycle must be converted to a setpoint for the AC load. This is done by the DRTS, which reads the duty cycle and converts it to an analog voltage which controls the power of the load. Additionally, the DRTS implements some typical EV charging behaviour within this conversion, such as the Constant-Voltage charging characteristic when the battery is almost full.

F. Power Router for EV charging

1) Structure: Fig. 5 shows the different power routing options considered for the demonstrator.

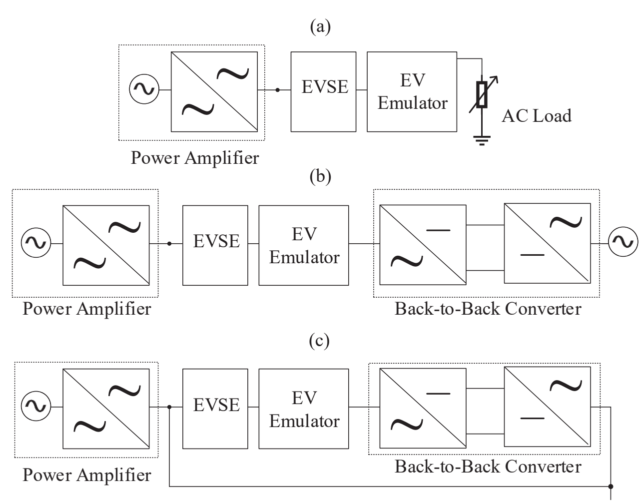

Fig. 5: Available power routing options (a) AC Load (b) grid-connected (c) circulating power

While the controllable ac load shown in Fig. 5(a) has minimum conversion stages, all energy is lost as heat. This is not desirable because the set-up is expected to operate at high power (several kWs) for significant periods of time (several hours). The conventional solution is to use a grid-connected Back-To-Back (BTB) converters with AC-DC-AC stage to return this power to the laboratory network as shown in Fig. 5(b). However, in this case the entire power has to be supplied by a fully rated bidirectional power amplifier, which can significantly raise the cost of the demonstrator. An interesting power-routing solution is proposed in this paper, as shown in Fig. 5(c). Two bidirectional Delta Elektronika SM15K DC power supplies are used to realize this operation. The benefits, limitations and possible modifications are discussed in the subsequent subsections.

2) Performance: Fig. 6 shows the power supplied by the power amplifier as a function of the (circulating) load power.

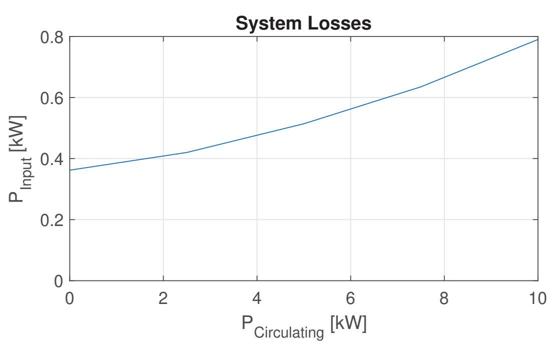

Fig. 6: Power Amplifier output as a function of circulating power

It can be seen that the power amplifier supplies only a fraction of the circulating charging power in the setup. For example, when 10 kW is circulated using the power router, the amplifier output is approximately 8 % of this value, corresponding to the losses in the system. The power amplifier equipment can consequently be significantly undersized, which is useful for minimizing the cost of developing the demonstrator. Further, the supplied power is unidirectional, independent of the direction of the circulating power flow in the router. This means that the V2G function can be easily tested with the same test-bed without a significant reconfiguration to the setup.

3) Limitations and Possible Solutions: A potential operational challenge is when the circulating power loop is broken during high power flow in the router, as shown in Fig. 7.

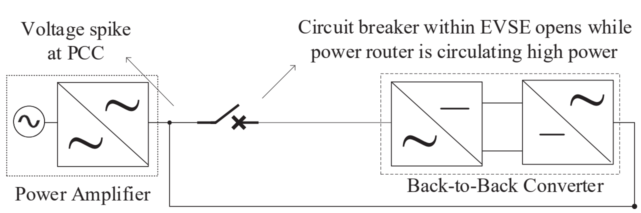

Fig. 7: Breaking the loop at high ciculating power.

The energy stored in the power routing elements results in a voltage spike at the Point of Common Coupling (PCC) in case the response of the amplifier is relatively slow. This scenario is possible not only during fault studies, but also during normal operation because when the EVSE receives a setpoint of 0 A, it adjusts the CP duty cycle accordingly and simultaneously opens the internal relays. The measured instance of this unwanted effect at the PCC voltage is seen in Fig. 8. The sudden interruption of current causes a voltage spike in the system to which the power amplifier reacts very slowly. It takes approximately 2 seconds for all phase voltages to return to their nominal value. More importantly, there is a voltage spike of 868 V. This grossly exceeds the rated operation range of all devices attached to the emulated grid and can potentially cause damage to the equipment.

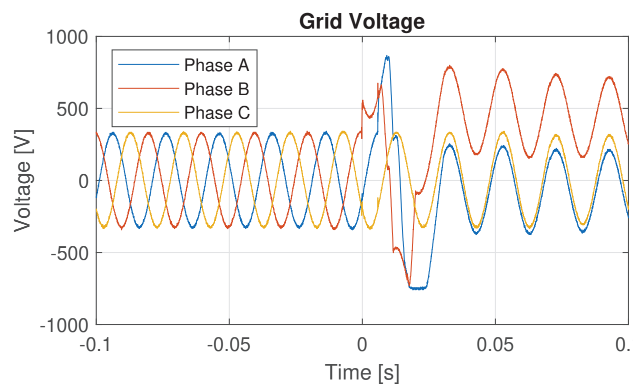

Fig. 8: Phase voltages when current is interrupted at t = 0.

This issue is specific to the demonstrator, and not the EV charger in practice. The voltage spike was not observed when the laboratory grid was directly connected to the PCC, indicating that a strong voltage source or a power amplifier with faster response can be used to avoid this behaviour. In the current test-bed, a small delay was implemented in the DRTS model such that when a zero setpoint is given by the user or by the Python API, the load power will first be set to zero and five seconds later the zero setpoint will be sent to the EVSE. By doing this, the relays only open when there is no significant current flowing. This solution is acceptable for the current requirements because these tests are related to normal operation with a time-step of 1 min.

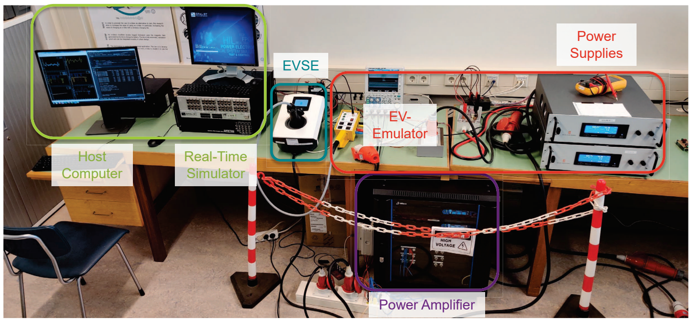

Fig. 9: Picture of experimental setup

IV. Preliminary results for Uncontrolled Charging

Fig. 10 shows preliminary measurement results from PHIL experiment for uncontrolled charging. Herein, Fig. 10 (a) is the node voltage measured at the output of the power amplifier and Fig. 10 (b) is the circulating EV charging power in the power router. The local load and generated PV power are shown in Fig. 10 (c).

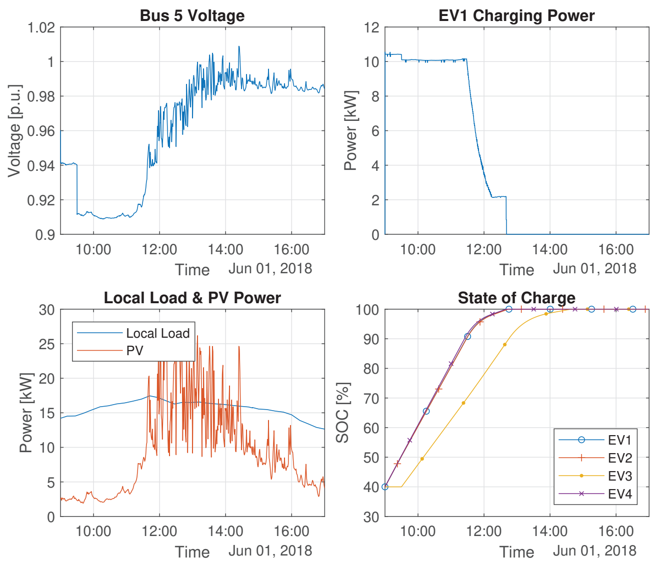

Fig. 10: Experimental results for uncontrolled charging with demonstrator EV attached at node-5 in the test-grid. EV 1, 2 and 4 have a capacity of 50 kWh and arrive at 9:00. For EV 3 this is 100 kWh and 9:30.

It can be observed that node voltage fluctuations follow the power fluctuations due to varying PV generation. Furthermore, the time taken to fully charge the EV is approximately 3 hours which occurs outside the peak generation hours because uncontrolled charging is used.

V. Conclusions and Future Work

In this paper, a low-cost and low-loss PHIL demonstrator for EV integration in distribution grid studies is developed. All components are connected and synchronized with various communication protocols. An uncontrolled EV charging case study was tested with the system, which proves the proper functioning of the system with expected outcomes. The benchmark results for uncontrolled charging show a specific energy cost of 10.7€-cents/kWh with a minimum voltage of 0.91 p.u. As part of future work, we want to implement the smart charging algorithm to potentially reduce the charging cost and local grid energy exchange to improve energy efficiency by limiting grid import as well as reducing the voltage dips in the system. Additionally, other functions we would like to implement in the future include integration with a back-office through OCPP, implementation of the ISO 15118 protocol, V2G functionality and a DC charging capability.

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