Power Hardware-in-the-Loop Test Bench for Tests and Verification of EV and EVSE Charging Systems

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***Abstract*—Charging systems and charging infrastructure are key components in the development and the introduction of electric and plug-in vehicles. The relative youth of the field and a long list of stakeholders (automotive industry, energy sector, governments, policy makers and customers) make the achievement of consensus on norms and standards difficult. The facts that vehicles are intrinsically mobile and hence require compatibility between manufacturers, countries and charging points, implies that the components of the charging systems should be extensively tested and must guarantee the desired interoperability. This paper summarizes the challenges that the charging-technology systems face and uses the results to derive the requirements on equipment for conducting tests and validation in the development, certification and end-of-line production stages.**

I. Introduction

The development and the introduction of electric vehicles (EV) and plug-in electric vehicles (PEV) are dependent upon to the development and introduction of corresponding EV supply equipment (EVSE). In order to reach the numbers of EV and PEV on the roads, that governments have set as targets [1], the automotive industry has to work hand-in-hand with the energy sector (producers and distributors), end-point suppliers and policy makers [2]. For brevity, in what follows *EV* will be used to denote both pure electric as well as plug-in hybrid vehicles.

As the interest in electric mobility is relatively young, there are currently many policy makers and regulating organizations, that define norms and standards applicable to the charging systems [1], [2]. On international level the *International Energy Agency* (IEA), the *Society of Automobile Engineers* (SAE) and IEEE are active (to name a few). On regional and local level different national and international organizations are active (*American National Standards Institute* (ANSI), *Deutsches Institut für Normung* (DIN), etc.). Moreover, most original equipment manufacturers (OEM) define their own standards.

This variety of policy makers and standardization organizations leads to an even larger variety of norms and standards, that are often contradictory and may change frequently. For example, many of the norms and standards discussed in [1] are outdated today. For the type of plugs and sockets alone there are many variations (see, e.g, [1]–[3]). The difference in the power-supply systems from country to country (and sometimes even within a country) is also a well-known issue [2], [3]. Finally, different charging types (called *modes* in Europe and *levels* in USA), AC and DC charging, and communication between the vehicle and the charging point complete the picture [1]–[4].

This large variety of supply networks, charging modes/levels, communication protocols and (above all) standards, present a challenge to the development and deployment of charging devices and charging station. Vehicle manufacturers, charging station operators and certification organizations are confronted with the challenge to test and validate the equipment involved in the charging of electric vehicles, and ensure that a vehicle produced by company *A* can operate with a charging station build by company *B* and operated by company *C*. As the physical presence and tests in all possible combinations is not only infeasible but also impractical, a dedicated test equipment is required.

This paper summarizes the challenges that the e-mobility charging systems face and uses the results to derive the requirement of a test bench for conducting tests and validation during the development, certification and end-of-line production stages. Test benches that provide high flexibility and rigorous testing are nothing new for the automotive industry, where Hardware-in-the-Loop (HiL) and Power-HiL (PHiL) testing are state of the art [5]–[7]. However, the development of such test benches for the charging systems poses new challenges. It has to address and support all charging modes, communication types and power tests of the charging technology components. The test bench has to cover all tests and operation specifications described in the norms and standards, and be flexible enough so that new specifications can be incorporated. In addition to that an user interface should provide easy to use functions for profound diagnostics and fault emulations.

The paper is structured as follows. Section II gives an overview of the state-of-the-art charging technology, modes of operation, and applicable norms and standards. In Section III the relevant use-cases and the need for thorough testing are discussed, and appropriate test-environments presented. Based on that, the requirements of the individual components of the test environment are derived in Section IV. Finally, Section V concludes the paper.

II. State-of-the-Art Charging Technology

The fundamentals of battery charging technology are presented in [2], and thus, will not be repeated here. Since inductive charging methods are still being investigated and hardly applied in road vehicles yet, this paper covers only conductive charging methods for electrical vehicles.

A. Mains supply

The power source for charging a battery is the public power supply. For car makers that sell their models worldwide, this adds further variables that must be considered and new constraints that must be met. Different voltage levels and frequencies as well as EMC immunity and emission regulations (e.g. EN 61000-6 [8]) in European, American and Asian countries are just one factor. There are common problems as well: standard power sockets around the world are meant to supply small electrical loads (less than 3kW). In addition, poor electrical installations such as faulty isolation, low conductor cross-section or missing protective earthing may be present. As a result, a charging system must regard the available power as well as potential threats with corresponding safety measures. Those safety systems (e.g. residual-current-operated protective device (RCD), insulation monitor) are often designed in one place and may be prone to erroneous safety alarms in remote locations with different mains and grounding conditions. The task is to guarantee operability and safety without any compromise in usability when charging one's electrical vehicle at any place. In order to achieve that, the automotive industry is investigating numerous effects at present.

B. AC vs DC Charging

There are two different conductive charging approaches - each of those with exclusive advantages and disadvantages. In the first one, the AC/DC converter is integrated inside the electrical vehicle. Today every EV ships with an onboard charger (OBC). The main advantage is that the vehicle can be charged at any standard power socket. This way the vehicle can be driven and charged anywhere. There are a few drawbacks however: since the OBC is (in most cases) implemented as dedicated unit, the EV carries around extra hardware which is not used while driving. With it, the vehicle becomes more expensive and heavier, and therefore less economical and ecological. In order to minimize these effects, the OBC is designed as cost- and size- optimized as possible. This leads to a power limitation of typically 2 to 7kW. Hence, one AC charging cycle may take up to 10 hours, considering an average battery pack capacity of 20kWh in full electrical vehicles. Three-phase onboard chargers with more power are available for a few EVs, but do not receive a high popularity because of the substantial extra costs. Needless to say, the calculation looks different for plug-in hybrids, where electrical range and charging-time are not equally critical.

The second approach is to move the AC/DC converter out of the vehicle in order to avoid the above mentioned disadvantages. Since the (offboard) charger (also named *charging station*) can be installed permanently at one place, it can have larger dimensions and use a mains supply of 32A and more. For this reason and the fact that it may be used by several EVs per day instead of just one, charging stations are available with higher output power (e.g. 20 to 60kW). This significantly higher amount of power allows to charge an empty battery to about 80 percent state-of-charge (SOC) in just 20 to 30 minutes. This method is therefore also called "DC fast charging". The main disadvantage of this approach are the higher acquisition and ownership costs, which reduce the group of potential buyers to power suppliers and car park operators. As a result, public DC-charging stations are still rare in most countries.

AC and DC charging approaches are, and will probably stay for a while, complementary. A third charging method attempts to combine the advantages of both onboard and offboard approaches by making use of the traction inverter of the vehicle and the coils of the electric machine (see, e.g., [9]). Implementing AC/DC conversion as a secondary function of the traction inverter is not straightforward, alone for energy efficiency, safety and EMC reasons. However, a well working system may eliminate the extra cost and space for an dedicated OBC, and might be seen in more EVs in the future.

C. Charging Modes/Levels

The norm IEC 61851-1 (cf. [10]) describes the common topology between vehicle and infrastructure that is applied in most countries today. It defines the required safety measures, a basic signaling for indication of maximum available current and the charging state when connected. Furthermore, the following four charging modes are specified.

1) Mode 1: This mode will not be handled here. It is unfavorable in terms of safety and hardly applied in the industry, because of its lack of a control pilot.

2) Mode 2: This mode defines AC charging using a cable with a so-called in-cable-control box (ICCB, sometimes also referred to as IC-CPD for *in-cable control and protective device*). It is a portable cable that can be plugged into regular power sockets (in Germany CEE 7/4) on the one side, and on the other side to any EV using a type 1 or type 2 inlet according to the standard IEC 62196 [11]. Thus, the cable is stored inside the vehicle when driving and can be used at any private or public parking place, as long as a power socket is available. The maximum current is limited to 32A. The control box contains a power contactor, a protective unit and a basic communication controller that uses a dedicated control pilot. EV and mode-2 charging device are using basic signaling for information exchange. The main functional requirements in the IEC 61851-1 (cf. [10]) are:

- ensure correct connection between EV and EVSE;
- ensure proper connection of the protective earth conductor (PE);
- ensure controlled power on / off.

Mode 2 charging is the most common charging method at present, since it can be applied anywhere and is the least expensive one. Schematic diagram of Mode 2 charging is shown in Fig. 1, where COM_A and COM_B are the communication modules at the EVSE and EV side providing the basic signaling used for communication (presented in Sec. II-D), BMS is the battery management system, and the AC/DC block represents the charging device.

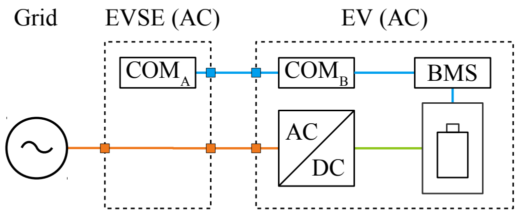

Fig. 1. Schematic diagram of on-board charging in modes 2 and 3.

In Fig. 1 and all following figures, the AC power signals will be shown in orange, the DC power signals in green and the communication signals in blue color. Furthermore, AC and DC contactors (present in the EVSE or in the battery pack) are omitted from the figures for simplicity.

3) Mode 3: Schematically Mode 3 charging can be represented again with Fig. 1. It is intended for stationary AC charging with permanent connection to the mains supply, so that there is no current limitation as in Mode 2. Furthermore, one must distinguish between a stationary AC charging station for private and public use. While the first is basically a Mode 2 ICCB charger implemented as wallbox, the latter may provide further functionalities such as multi-channel support (charging two or more EVs with one EVSE) or customer authentication and payment.

In order to enable a seamless integration of vehicle-integrated payment services or future energy-supply models, such as V2G (vehicle-to-grid: vehicle may sell energy to the grid while being connected to a bidirectional EVSE – see, e.g. [12]), Mode 3 must provide a method to exchange more data in a faster and more secure way. For that purpose a high-level communication interface is used (see Sec. II-D).

4) Mode 4: This mode, also referred to as *DC-charging*, is shown schematically in Fig. 2.

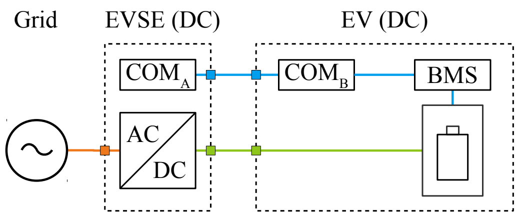

Fig. 2. Schematic diagram of DC charging in mode 4.

Here, the power electronics are integrated inside the EVSE, so that AC/DC-converter and battery are separated. Hence, the EV's charging management (including the BMS) need to exchange data with the voltage/current controller of the EVSE. For instance, the vehicle must know the voltage, current and power specifications of its supply equipment, and the EVSE continuously needs to know the actual battery voltage and the target charging current. Thus, high-level communication between EV and EVSE is mandatory in this mode.

D. Communication Interfaces

In the previous section the terms *basic signaling* and *high-level communication* have been introduced. The technology used for both interfaces is briefly presented next.

1) Basic signaling: The basic interface between EV and EVSE is based on two additional signal pins: the control pilot (CP) and the proximity pilot (PP). Both pins can be found on all common charging cables and plugs according to IEC 62196 and are compulsory for IEC 61851 charging modes 2, 3 and 4.

The EVSE generates a 1kHz square wave signal of $\pm$12V between CP and PE. When connected, the EV measures amplitude and duty cycle in order to determine operational availability of the supply equipment as well as its maximum charging current. The EV can then define its actual state by adding parallel resistance between CP and PE, which lowers the signal amplitude in defined steps, as shown in Table I.

TABLE I
CHARGING STATES BY BASIC SIGNALING

	State	CP amplitude
A	EV not connected	12 ± 1V
B	EV connected	9 ± 1V
C	EV ready for charging	6 ± 1V
D	EV ready for charging with ventilation	3 ± 1V
F	unknown state or error state	other

The PP is used for detection of connected plugs and to readout the charging cable ampacity (through resistance coding).

Due to the fact that this signaling is using the duty cycle of the generated square pulses to transport information, a pulse-width modulation (PWM) takes place. Hence, often basic signaling is simply referred to as *PWM-communication*.

2) High-level communication: This type of communication, used in modes 3 and 4, is implemented as Power-Line Communication (PLC) and specified by the ISO 15118 [13] for both - AC and DC charging. It does not replace the PWM-based basic signaling of modes 2, 3 and 4, but rather uses it as a wiring system for a high frequency modulated carrier signal. Physical and data link layers of PLC are handled by a HomePlug GreenPHY [14] in all EV and EVSE up to now.

In order to establish a Power Line Communication between two points, both sides need to use IPV6 and understand the V2G and EXI protocols as described by ISO 15118-2. EVs that support Mode 4 DC-charging are using a type 2 CCS (Combined AC/DC Charging System) plug in Europe (IEC 62196-3) and a type 1 CCS plug in the US (IEC 62196-3 [11], SAE J1772 [15]).

The IEC 61851-23/24 lists two other valid DC-charging standards, that are predominantly applied in Japan and China

TABLE II
INTERNATIONAL DC CHARGING STANDARDS IN IEC 61851

System	Region	Standard	Interface	Connector
A	Japan	CHAdeMO	CAN	JEVS G105
B	China	GB/T	CAN	GB 20234
C	US	CCS type1	PLC	SAE J1772
C	Europe	CCS type2	PLC	IEC 62196-3

as shown in Table II. Each of the two uses a dedicated CAN protocol for data exchange and a specific connector, that is not compatible with CCS.

Since the first CHAdeMO supporting EV (Mitsubishi i-MiEV) was released in 2009, it is the most established DC-charging standard yet. Currently there are about 2100 CHAdeMO DC quick-chargers installed in Japan, and 4241 in total world-wide [16]. Some DC-charging stations readily support both CHAdeMO and CCS standards.

III. TEST CASES FOR CHARGING SYSTEMS

Testing takes an important role in the V-model of product development, as well as at the end of the production lines for guaranteeing the quality of the final product. In order to guarantee the interoperability between EV and EVSE, thorough tests of the individual components must be performed and their compliance to the respective norms and standards verified.

As there are different parties involved in the interface EV–EVSE, from OEMs, Tier one companies, EVSE manufacturers and operators, to automotive clubs, also different components are in the focus of the test procedure and different test scenarios are considered. Furthermore, as, for a test facility, it is not economical to have a specimen of all possible remaining components (e.g., it is not feasible for an OEM to have samples of all charging stations and wallboxes present at the market) hardware-in-the-loop (HiL) and Power-HiL (PHiL) [5], [7] are finding increasing application. With this approach the environment of the test component can be emulated either on signal level (by HIL) or both at signal and at energy level (by PHIL) by using (typically) controlled electronic and power-electronics components.

In the following, the test cases for the charging components will be discussed and setups of the corresponding test environments presented.

A. Development and Tests of EVSE

In the case where the development and verification of a EVSE is of interest, the focus of testing is put on the validation of the main functions (power delivery, communication) and compliance with the mentioned standards and normative requirements defining the interfaces to the vehicle and the power supply.

On the primary side, the EVSEs are always connected to an AC-grid, so the charging device has to comply with appropriate worldwide standards. Test cases have to ensure, that the EMC-emission of the device under test (DUT) lie under the specified thresholds and, for testing international variants of the product, provide options for emulating international grid configurations and typical error and failure effects. Hence, for the purpose of supply-grid emulation, a parametrizable AC-source, i.e., an AC-emulator (ACE), is needed.

Furthermore, testing the EVSE requires both a model and an emulation of the EV to be charged. The model controls the power-flow from the EVSE to the emulated EV in correspondence to the communication states. As for this purpose also a communication between the EVSE and the EV should be carried on, the EV emulation should be also equipped with corresponding communication interface module(s) (PWM, PLC and/or CHAdeMO). Simultaneously, on power level, the vehicle emulation should also provide programmable AC and DC loads, that emulate the charging device (by AC-charging) and the high-voltage (HV) battery (by DC-charging).

The resulting system architecture is shown in Fig. 3, where EVSE is shown in gray, as it is the DUT. Here, COM_A and COM_B stand for the communication modules corresponding in the EVSE and in the EV, IO represents programmable inputs and outputs (such as locking device, temperature sensor, etc.), and ACE and DCE are, correspondingly, programmable AC and DC emulators.

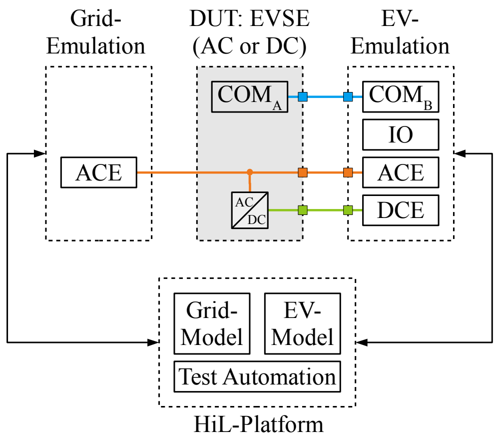

Fig. 3. Test environment for an EVSE.

It should be noted that whereas a typical EVSE will allow either AC or DC charging, the displayed configuration displays/allows both the AC and the DC configurations. Furthermore, COM_A and COM_B differ only in the setup for the PWM communication, as the EVSE (i.e., COM_A) generates the PWM signal and the EV (i.e., COM_B) switches between the resistances. Finally, the role and the requirements on the HIL-Plattform will be discussed in detail in Sec. IV.

B. Development and Tests of the Charging System of an EV

As OEMs and their suppliers are also interested in satisfying the normative requirements and in achieving a high degree of compatibility to available EVSEs, a corresponding test-bench for the charging interface of the EV is needed. Similar to

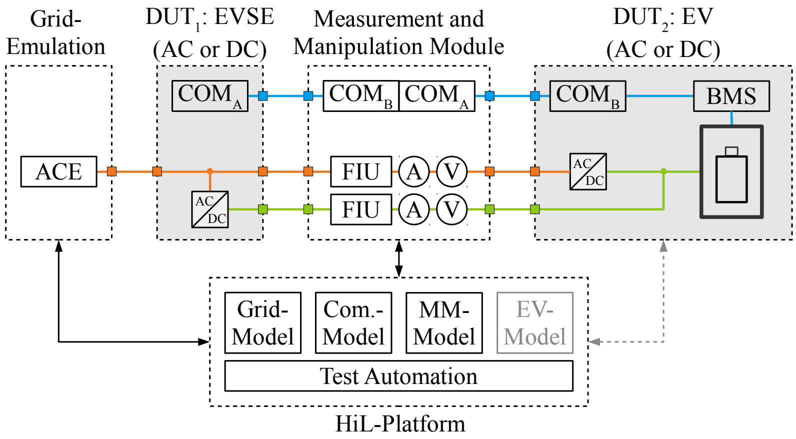

Fig. 5. Environment for combined EVSE and EV testing.

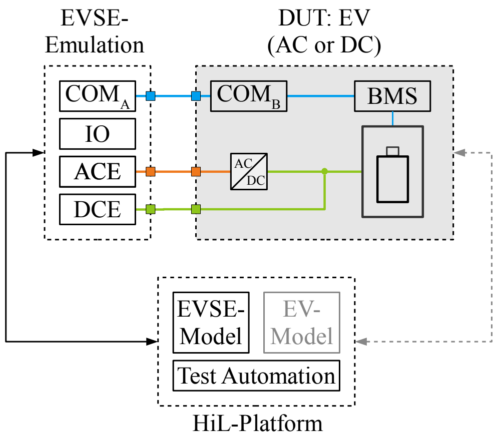

Fig. 4. Test environment for an EV.

the one presented in Sec. III-A, a test bench for the charging components of an EV (onboard charger, BMS, etc.) can be designed by emulating the function of the EVSE and the supply grid (by AC-charging).

The block diagram of the resulting test bench is shown in Fig. 4. Depending upon whether a *complete* vehicle is present or only the EV-components related to the battery-charging are tested, the block EV-Model can include different elements. In the case when a vehicle is present, the block may only control, e.g., robotic manipulators for connecting and disconnecting the charging cable. If instead, a component test must be carried on, the EV-Model may include blocks from remaining bus simulation and for control of power contactors and other consumers.

In the setup in Fig. 4, similar to the one in Fig. 3, AC and DC emulators are used to emulate the supply grid and the DC-charging point.

C. Interoperability Tests between EV and EVSE

In the later stages of the development processes of EV and EVSE, the systems may be tested in direct operation with each other. For example, a producer of charging station may be interested in experimentally demonstrating the interoperability to a set of common (for the area/country) EVs. In many cases, this can be done by emulating the behavior pattern of the EV or EVSE of interest, as described previously. However, as there may also be not yet known incompatibilities or unknown effects, and since problems may occur during the field exploitation but not in the test facility, a test environment is necessary that allows monitoring and analysis of the charging process between an actual EV and EVSE. Furthermore, for the purposes of diagnostics and tests, also capabilities to acquire and manipulate the communication between the EV and EVSE are required.

A test environment addressing these requirements is presented in Fig. 5. In this figure FIU stands for *Fault Insertion Unit*; MM-Model stands for the *Measurement and Manipulation Model* and addresses both the measurement and manipulation of power and communication signals; and the block *Com.-Model* controls the communication modules. It is important to note that the presence of both COM_A and COM_B communication modules in the Measurement and Manipulation Module is imposed by the point-to-point communication-type used in PLC-communication.

In Fig. 5 again both AC and DC charging are visualized simultaneously, but clearly during a test only one of them will be used at a time.

IV. Requirements on the Test Environment for Charging Infrastructure

In the previous section the typical test cases for the components of the charging infrastructure were presented. These can, in fact, be combined to a single test bench that encompasses all of the above scenarios. The schematic diagram of the resulting test environment is shown in Fig. 6. By inserting the DUT(s) at the corresponding position, this test bench covers all of the discussed test cases – requires at the same time the minimal number of test bench components. By omitting certain systems, this test environment may be tailored to the needs of any of the involved parties (OEMs, their suppliers, EVSE manufacturers, etc.).

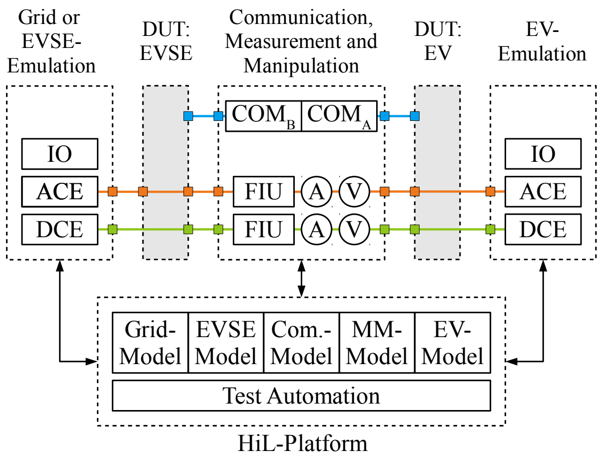

Fig. 6. Environment for testing EVSE, EV and combined EVSE and EV testing.

In the following the requirements of the individual components will be discussed, with a view at the general test environment in Fig. 6.

A. *Topology of the System*

The involved in Fig. 6 components are:

- two communication modules: type COM_A and COM_B ;
- power source for grid and AC-EVSE emulation (ACE);
- power load for EV-emulation (ACE);
- power source for DC-EVSE emulation (DCE);
- power load for battery emulation (DCE);
- realtime control unit (HiL-system) with customizable models and state machines for EV- and EVSE-emulation;
- measurements of current, voltage and communication signals;
- manipulation unit for power and signaling;
- interfaces for vehicle communication busses (CAN, FlexRay, etc.);

B. *Requirements on the Communication Interfaces*

When a EVSE or EV charging system is tested independently, the HIL System must emulate the respective missing side in order to permit a realistic operation. Together with the previously mentioned desired manipulation options, the following *must-have* requirements can be derived for the signaling side:

- support of all charging modes according to IEC 61851;
- support of ISO 15118 specific protocols, such as V2G and EXI;
- support of CAN protocol according to CHAdeMO;
- bridge-mode with extraction, interpretation and manipulation of ISO 15118-2 data and timeouts;
- high precision measurement of CP;
- EMC conform wiring of CP;
- generator of PWM basic signaling (COM_A);
- variable resistor and capacitance range for CP amplitude and slew rate manipulation (COM_B);
- variable resistor range for PP manipulation;
- real-time system with low time-delays;
- electro-mechanical integration of all relevant world-wide charging plugs and inlets;
- configurable state-machine for dynamic emulation of EV and EVSE communication modules;
- measurement and monitoring of temperature sensors of the original charging connectors;
- control and manipulation of locking actuation.

C. *Requirements on the High-Voltage Power System*

As illustrated in the previous chapter, independent testing of EV or EVSE side requires an electrical emulation of power grid, charging station, vehicle onboard charger and vehicle battery. Depending on the particular test field (EVSE-AC, EVSE-DC, EV or PHEV), the required power typically varies between 3kW and 120kW.

The AC power source for power grid emulation should provide the following capabilities:

- three power lines, neutral (N) and PE terminals;
- one-, two- and three-phase operation;
- operation with and without PE and N;
- configurable interconnection of N and PE for emulation of TN, TT and IT earthing networks;
- potential separation (necessary for safety by the configuration of the above network types);
- output power from 10kVA to 120kVA (application dependent);
- variable output frequency between 40 and 70Hz, for emulating different power grids (50, 60 Hz) and failure scenarios;
- variable output voltage of 0 to 270V (rms, phase-neutral);
- independent voltage specification for each line for emulation of phase asymmetries;
- independent phase offset for each line for emulating symmetric, asymmetric and two-phase (US) networks;
- emulation of harmonics, inter-harmonics and voltage variations according to IEC 61000-4;
- bidirectional energy flow for Vehicle-to-Grid applications.

An example of a suitable AC power source is shown in Fig. 7, where an asymmetric flat-curve supply voltage (described by IEC 61000-4) is generated.

Similarly, the AC power load, necessary for EV-emulation, must meet the following requirements:

- three power lines, N and PE terminals;
- operation as current consumer on one, two and three phases with and without N and PE (automatic recognition of the supply network);
- power rating from 10kVA to 120kVA;
- potential separation (as a vehicle is an IT-network);
- bidirectional energy flow for Vehicle-to-Grid applications.

Clearly, as both the AC-source and the AC-load must have the same power ratings and type of output terminals, they can

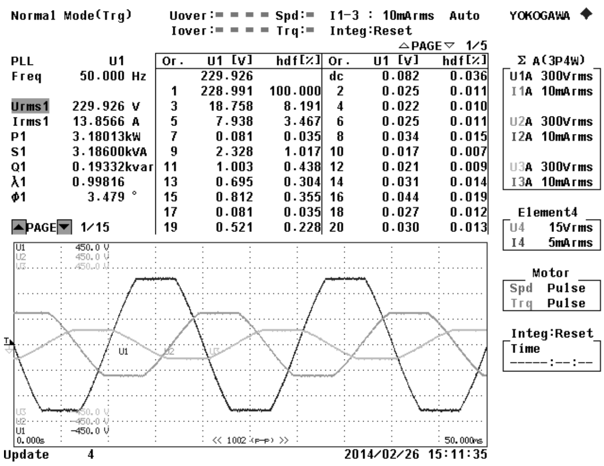

Fig. 7. Asymmetric three phase *flat curve* supply voltage, generated by an ACE, as specified by [17], [18]. At the top the first 20 harmonics of phase U1 are shown.

be constructed on the same (power-electronics) basis and differ only in the configuration of the output stages and in software.

Similar to the AC power systems, the requirements of the DC power sources (DCE) can be derived. Both the power sources for emulation of the EVSE and of the EV must meet the following requirements:

- voltage and current source operation;
- variable output voltage of 0 to 600V (and higher), for testing both 48V systems and high-volt batteries in both normal operation and failure scenarios;
- output current from ±150A to ±300A;
- emulation of AC ripple on the DC-signal;
- bidirectional energy flow for use-case dependent operation as source or load;
- integration of charging methods (e.g. CCCV) for direct emulation of any charging station;
- potential separation.

In addition there are three main non-functional requirements that should be taken into account.

- Energy efficiency. When using one or several high power systems continuously (e.g. for artificial aging tests), the efficiency factor of the power source/load has the largest impact on the energy costs (electricity and cooling). For instance: a 100kW power source with an efficiency factor of 0.8 generates annual electricity costs of 35040 EUR (24/7 operation, price per kWh 0.20 EUR). A state of the art efficiency factor of 0.9 reduces these expenses by 50%. For the same reason it is advisable to use regenerative AC and DC loads for emulation of systems with more than 10kW.
- Signal quality and EMC compliance. Efficient power sources are using modern power semiconductors (such as MOSFET and IGBT). In order to evaluate functionality and EMC behavior of the DUT without experiencing interdependencies with the test environment, it is of utmost importance that the AC and DC power sources/loads are EMC optimized and provide a low total harmonic distortion (THD $< 0.1\%$ is desirable). According EMC filters are difficult to find, because high filter quality, high nominal phase-currents and low leakage currents (necessary because of RCD and insulation monitoring in EVSE) mutually restrict each other.
- DUT protection. Since the DUT maybe be an early prototype with non-validated controllers and software, voltage and current overshoots may occur at some point during the test procedure. In such case the specimen may be irreversibly damaged if the opposite power source does not detect off-limit conditions immediately ($\ll$ 1ms) and reacts accordingly (by turning-off power or even actively discharging the DUT).

D. Further Test Bench Requirements

The given complexity of the individual test systems leads to an even higher overall system complexity. A HIL-Platform (often in combination with a Programmable Logic Controller) is a suitable computation and control center of the test bench. For an adequate degree of freedom, it should at least provide the following:

- application specific graphical user interface, with configurable controls;
- emulation of remaining EV hard- and software components (e.g. 14V/24V battery, gateway to electronic control unit, CAN/Flexray bus systems);
- interfaces to all subsystems (such as power sources);
- synchronous measurement of all relevant values;
- recording of communication, AC and/or DC signals for later analysis;
- integration and modification of component and system models (e.g. through Matlab/Simulink models);
- integration of a dedicated safety system for operator protection;
- sufficient computer power for real-time computation of the used models;
- scalable architecture for subsequent upgrades.

For example, for monitoring the charging process and analyzing possible effects, a synchronous measurement of communication and energy signals at runtime (Fig. 8-top) or later on from recorded data (Fig. 8-bottom) is instrumental.

Depending on the desired level of automation, the number of specimens, the testing scope and testing depth, additional features may also be of importance:

- definition and execution of automated test cycles;
- control of a climatic chamber (for environmental simulation);
- control of a dynamic cooling system (e.g. for onboard charger cooling);
- control of external robot manipulator (e.g. for automated plug-in/-out cycles);
- direct generation of test reports and export to databases.

Clearly, as the increased number and types of testing capabilities renders the test bench more complex and leads

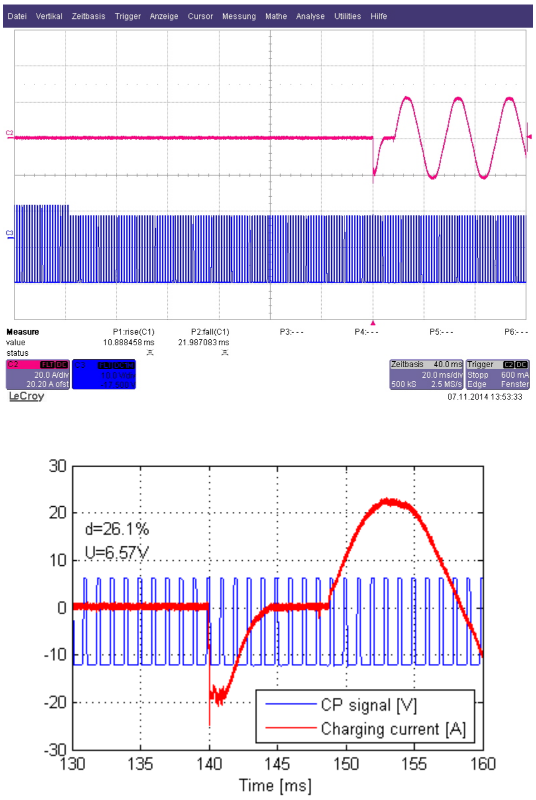

Fig. 8. Record of a CP and current at the beginning of the charging by Mode 2. Channel 1 shows the PWM communication, channel 2 the charging current.

to higher investment costs, the scope and the capabilities of the specific test bench should be selected with care in advance.

V. Conclusion

In this paper the present norms and standards of the e-mobility charging systems were reviewed and the different charging modes discussed. It was shown, that there is a large versatility of norms and standards, which are in some cases yet incomplete and so still subject to changes and development. As car manufacturers aim to reach the global market, they must guarantee safe operation and interoperability in all regions, countries and continents. This implies taking into account different power-supply grids and qualities of electrical installation.

Because these factors impose both technical and economical hurdles for the success of recent charging methods and e-mobility in general, the paper identified systematical testing and verification of the products as key strategy. Since the charging system is divided in EVSE and EV subsystems and testing takes place during the R&D, manufacturing and exploitation stages of the products, application-specific solutions, that generate repeatable and comparable results, are of need. For that purpose, a modular test bench architecture for EV, EVSE and combined EV-EVSE testing has been derived based on a unified PHIL. Furthermore, the application specific requirements of the crucial test systems have been derived.

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