VERIFICATION OF PROTECTIVE MEASURES FOR SAFETY OF DC CHARGING STATIONS FOR ELECTRIC VEHICLES

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ABSTRACT

In order to ensure long-term protection against electric shock, a periodic verification of the protective measures for safety for DC charging stations for electric vehicles is essential. This paper provides a contribution to possible fault scenarios and related test routines as well as a concept of a testing device for DC charging stations.

INTRODUCTION

Due to the rising popularity of electric vehicles (EV), the infrastructure of electric vehicle charging systems (EVCS) is also extended. The increase of connection power and number of installed charging stations leads to challenges regarding installation as well as mains operation. EVCS are electrical systems which have to ensure the operators safety during the charging process, also in case of a failure such as short circuit or a ground fault. Therefore, protective measures shall be taken into account, in particular the protection against electric shock.

The market already offers mobile testing equipment for the periodic verification of protective measures for safety of AC charging stations (230/400 VAC, up to 22 kW) based on common installation testers combined with an E-Mobility adapter box (Figure 1). For EVCS with higher charging power, especially for direct current (DC) systems with a nominal voltage up to 500 VDC, there are no comparable devices to check the safety available yet.

Figure 1: Adapter box for AC-EVCS

Therefore, the goal of the project presented is to design and construct such a testing device to ensure the operator protection as well as installation safety and availability. [1]

REGULATIONS AND TECHNICAL STANDARDS

The definitions and regulations listed in Table 1 regarding DC charging stations for electric vehicles were investigated and were taking into account for further studies:

Table 1: National and International technical standards

ABBREVIATION/ NUMBER	TITLE/ CONTENT	VAL.
IEEE C2-2017	2017 National Electrical Safety Code (NESC)	US
NFPA 70 NEC 2017	National Electrical Code (NEC) 2017	US
IEC 60364 series resp. ÖVE/ÖNORM E 8001 series	Low voltage electrical installation – measures against electric shock	Int. resp. AUT
IEC 60364-7-722 resp. ÖVE/ÖNORM E 8001-4-722	Low voltage electrical installation – supply of electric vehicles	Int. resp. AUT
IEC 62196 series resp. OVE EN 62196 series	Conductive charging of electric vehicles (connectors)	Int. resp. AUT
IEC 61851 series resp. ÖVE/ÖNORM EN 61851 series	Electric vehicle conductive charging system (charging processes)	Int. resp. AUT
DIN VDE V 0122-2-3 00:2016-04	Conformance Test Specification IEC 61851-23, Annex CC (testing standard, DRAFT)	GER
IEC 61439 series resp. ÖVE/ÖNORM EN 61439 series	Low-voltage switchgear and controlgear assemblies	Int. resp. AUT
VAL…validity Int…International	US…United States AUT…Austria GER…Germany	

These standards cover structure, construction and installation of DC-EVCS as well as the basics of charging processes. Currently, no guidelines as well as standards for initial and periodic verifications of DC charging stations are available.

FAULT CASES

Based on practical experiences combined with the investigations from various standards different fault cases were defined. Figure 2 provides an overview of these fault cases.

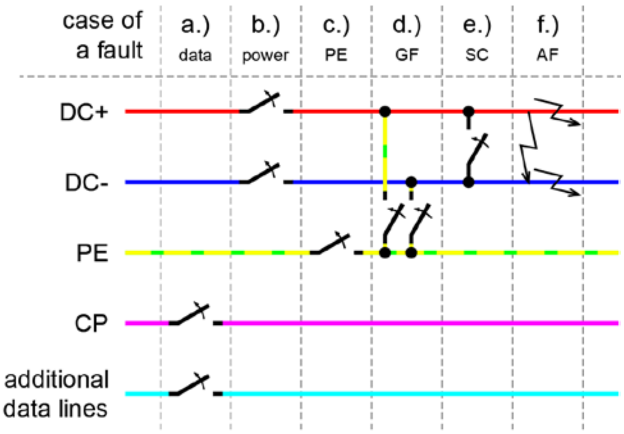

Figure 2: Different fault cases

Basically there are three main classes of possible faults:
a.) - c.) Interruption of lines (data, power, and/or PE)
d.) - e.) Ground and/or phase-to-phase fault
f.) Arc fault (lateral and/or longitudinal)

MEASUREMENT DISTRIBUTION BOX

To verify the fault definitions and to analyse in detail the behaviour of charging stations in normal operation and in case of a fault, a measurement distribution box was developed and commissioned (see Figure 3).

Figure 3: Measuring distribution box ① with accessories (line for remote control ②, charging power lines ③, measurement box ④, remote control ⑤)

The distribution box shown in Figure 3 is placed like an adapter in-between the DC charging station and the electric vehicle (see Figure 4).

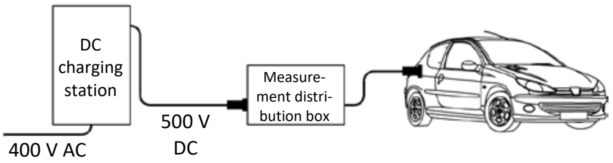

Figure 4: Principle measurement arrangement

With the distribution box measurements and analyses of faultless (normal operation) and faulty charging processes (possible fault cases, except arc faults, see Figure 2) can be carried out at charging stations of different manufacturers.

RESULTS

In the following a selected normal operation as well as a selected fault situation and the corresponding analysis measured by using the measurement distribution box are presented.

Normal operation

The following Figure 5 shows a normal/faultless DC CCS (Combined Charging System) charging process according to mode 4 in compliance with IEC 61851-1:2017-02 [2] (CCS, see Annex CC from OVE/OENORM IEC/EN 61851-23:2014-12-01 [3]). In detail, the charging voltage U_{DC} (left ordinate) as well as the charging currents I_{DC-} and I_{DC+} (right ordinate) are shown.

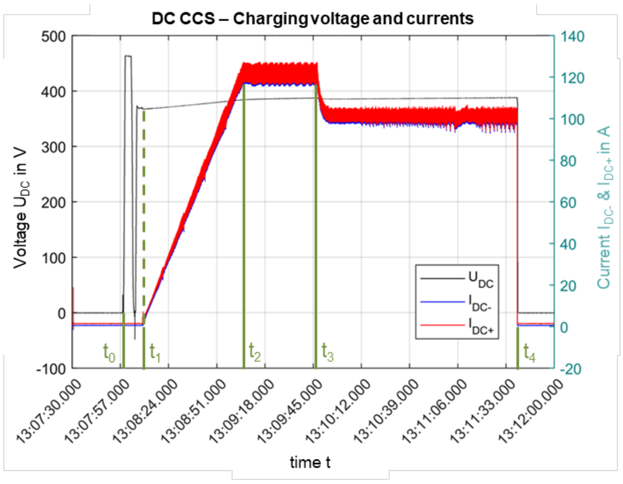

Figure 5: CCS DC charging process (faultless/normal operation), charging voltage & charging currents

The normal (faultless) CCS charging process starts at $t_0 = 13{:}07{:}57$ with a rectangular voltage peak up to a maximum value of $U_{DC,max} = 460$ V, indicating a handshake procedure between the DC charging station and the electric vehicle as well as an insulation test of the charging cable. The DC charging voltage then rises slowly from $U_{DC0} = 370$ V to $U_{DC1} = 390$ V. At this level it remains until the end of the charging process. After the handshake is completed, a steady, ramp-shaped rise of the DC charging current can be seen starting from t_1 = 13:08:10 to a maximum value of $I_{DC+,max}$ = 120 A at t_2 = 13:09:00 (this period is identical to the ramped voltage rise). From t_2 to t_3 = 13:09:45 the charging current remains constant at a value of $I_{DC+,1}$ = 120 A. At time t_3, the current is reduced to $I_{DC+,2}$ = 100 A. The charging current keeps constant until the end of charging at t_4 = 13:11:40.

Fault operation

The following Figure 6 shows a faulty (interruption of protective earth (PE) conductor) DC CCS charging process according to mode 4 in compliance with IEC 61851-1:2017-02 [2](CCS, see Annex CC from OVE/OENORM IEC/EN 61851-23:2014-12-01 [3]). In detail, the charging voltage U_{DC} as well as the charging currents I_{DC-} and I_{DC+} (both right ordinate, current scaled by factor 4) and the Control Pilot voltage U_{CP} (right ordinate) are shown.

The interruption of the PE line was triggered by the measurement distribution box described in the former section. Due to the reference of the control pilot signal (CP) to PE, the initial fault time can be identified as $t_{PE,break}$ = 13:18:12,070 which is identical to the fault occurrence time $t_{PE,off}$. The differences between the fault occurrence time $t_{PE,off}$ and the points in time $t_{I,off}$ = 13:18:12,204 (current) and $t_{U,off}$ = 13:18:12,390 (voltage) leads to the switch-off times for the current ($t_{I,switch\text{-}off}$ = 134 ms) as well as for the voltage ($t_{U,switch\text{-}off}$ = 320 ms).

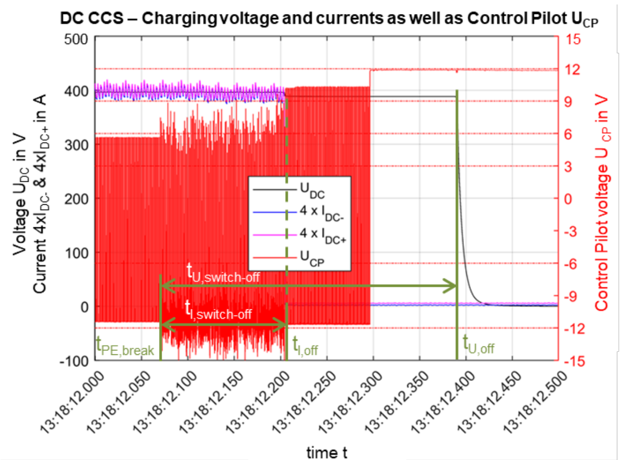

Figure 6: CCS DC charging process (interruption of PE conductor), charging voltage, charging currents and Control-Pilot-signal

Overview of measurement results

As an example Table 2 shows an overview of measurement results out from a CCS (European standard) charging process with different types of fault simulations. As an second example Table 3 shows an overview of measurement results out from a CHAdeMO (Asian standard) charging process with different types of fault simulations.

Table 2: Measured values of an example CCS charging process

Measurement no. 1 (CCS)

file: EVSU_DC_CCSTyp2_2017_11_07_0001

	Switching device	Fault time	Switch-off time	
			Current	**Voltage**
	---	**ss,hhh**	**ss,hhh**	**ss,hhh**
Interruption lock	-S33	ns	no switch-off	no switch-off
Interruption CP	-K11	ns	00,004	00,170
Interruption DC+	-K16	ns	00,000	00,214
Interruption PE [a]	-K2	ns	00,134	00,320

	Switching device	Fault time	Switch-off time	
			Current	**Voltage**
	---	**ss,hhh**	**ss,hhh**	**ss,hhh**
Ground fault 100 kΩ	-K18	18,595	no switch-off	no switch-off
Ground fault 40 kΩ [b]	-K18	ns	07,452	07,706

	Switching device	Time		
		Operation	**Handshake**	**Current ramp**
	---	**ss,hhh**	**ss,hhh**	**ss,hhh**
Ground fault 40 kΩ before start of charging [c]	-K18	09,571	03,265	05,985

In the results of the CCS charging process summarised in Table 2, the grey-shaded values were particularly noticeable:

a) During a charging process according to the CCS standard, the tested charging station has interrupted the charging process when a PE conductor interruption occurs.
b) In the event of a ground fault with a 40 kΩ series resistor (40 kΩ between PE and DC+), a CCS charging process is interrupted by the tested charging station in a range of 7,5 s.
c) Compared to b), a 40 kΩ earth fault occurring before the start of a charging process leads at first to a handshake of approximately 3 s. Following the handshake procedure, a slow-rising current ramp with a maximum value of $I_{DC+,max}$ = 16 A can be seen. After 6 s this current ramp is switched off by the charging station, all in all the faulty charging process is terminated after a total duration of about 9,5 s.

For the CHAdeMO charging process summarised in Table 3, the grey-shaded values stand out in particular:

a) An interruption of the charging enable/disable signal line leads (compared to the interruption of all other signal lines) to a relatively long shutdown time by the charging station of about 4 s.
b) When the PE conductor is interrupted, a CHAdeMO charging process (contrary to a charging process according to CCS standard) is not terminated by the analysed DC charging station.
c) Even with resistive line-to-line faults (100 kΩ, 40 kΩ and 1 kΩ), between DC+ and DC-, the analysed charging station did not interrupt a CHAdeMO charging process. It can be assumed that both, the DC charging station as well as the connected electric vehicle detect these short circuits only as a corresponding load change.

For reasons of personal and equipment safety (charging station and vehicle accumulator form the sources for a double-fed short circuit), a low-resistance short circuit between DC+ and DC- has been dispensed.

Table 3: Measured values of an example CHAdeMO charging process

Measurement no. 2 (CHAdeMO)				
file: EVSU_DC_CHAdeMO_2017_11_07_0001				
	Switching device	**Fault time**	**Switch-off time**	
			Current	**Voltage**
	---	**ss,hhh**	**ss,hhh**	**ss,hhh**
Interruption connection check	-K7	ns	00,195	01,321
Interruption charging enable/disable [a)]	-K6	ns	00,102	04,236
Interruption charger start/stop1	-K5	ns	00,006	00,139
Interruption charger start/stop2	-K10	ns	00,006	00,154
Interruption CAN-H	-K8	ns	01,028	01,222
Interruption CAN-L	-K9	ns	00,969	01,262
Interruption DC+	-K16	ns	00,002	00,131
Interruption DC-	-K17	ns	00,004	00,140
Interruption PE [b)]	-K2	ns	no switch-off	no switch-off
file: EVSU_DC_CHAdeMO_2017_11_07_0002				
	Switching device	**Fault time**	**Switch-off time**	
			Current	**Voltage**
	---	**ss,hhh**	**ss,hhh**	**ss,hhh**
Ground fault 100 kΩ	-K18	35,114	no switch-off	no switch-off
Ground fault 40 kΩ	-K18	ns	00,637	00,881
file: EVSU_DC_CHAdeMO_2017_11_07_0003				
	Switching device	**Fault time**	**Switch-off time**	
			Current	**Voltage**
	---	**ss,hhh**	**ss,hhh**	**ss,hhh**
Phase-to-phase fault 100 kΩ [c1)]	-K18	07,770	no switch-off	no switch-off
Phase-to-phase fault 40 kΩ [c2)]	-K18	04,091	no switch-off	no switch-off
Phase-to-phase fault 1 kΩ [c3)]	-K18	04,164	no switch-off	no switch-off

CONCLUSIONS AND FUTURE WORK

The evaluation of the recorded measurements shows that the investigated EVCS operates in compliance to the technical standards in almost all situations.

However, it is remarkable that an interruption of the PE conductor during a CHAdeMO charging process does not stop the charging process.

Also, in some cases the long switch-off times of the insulation monitoring system are noticeable.

In the course of initial investigations of contact faults (arc fault) in series and parallel to the battery, it has been shown that the arcs can lead to welding of the conductors or that the conductors can burn-off accompanied with considerable thermal or explosive effects. It still has to be investigated whether these fault cases involve unacceptable risks.

As a next step a cooperation with a regional, internationally established manufacturer of test beds (Kristl, Seibt & Co Ges.m.b.H.) has been established in order to develop and produce a mobile testing device for the initial and the periodic verification of DC-EVCS, regarding the protection against electric shock and arc fault. This project, based on the already achieved knowledge, is funded by the Austrian Research Promotion Agency (FFG). [4]

REFERENCES

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Daniel Herbst, born 1988 in Vienna/AUT studied electrical engineering, specialisation in power engineering at Graz University of Technology. He worked for 5 years in the team of an electrical consulter in Styria in the areas of planning, tendering and construction supervision. In the course of his current work at the Institute of Electrical Power Systems, he deals with the topics of electrical safety and grounding systems of DC charging stations for electric vehicles, measurement technology in electrical power systems and protection concepts at low voltage level.

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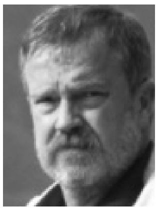

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Benjamin Jauk, born 1992 worked during his bachelor’s thesis on legal and normative compliance of DC charging stations to get requirements for verification.

He is currently studying master’s degree in electrical engineering, specialized in power engineering at Graz University of Technology.

Christian Auer, born 1982 studied electrical engineering, specialisation in electronics at the Graz University of Technology. During his studies, he worked at the high voltage institute. Since 2012 he works at Krist, Seibt & CO Gmbh as a project engineer for automotive test benches. Current tasks are in the fields of electromagnetic compatibility, battery simulators, automation and the development of an automated safety testing device for DC charging stations