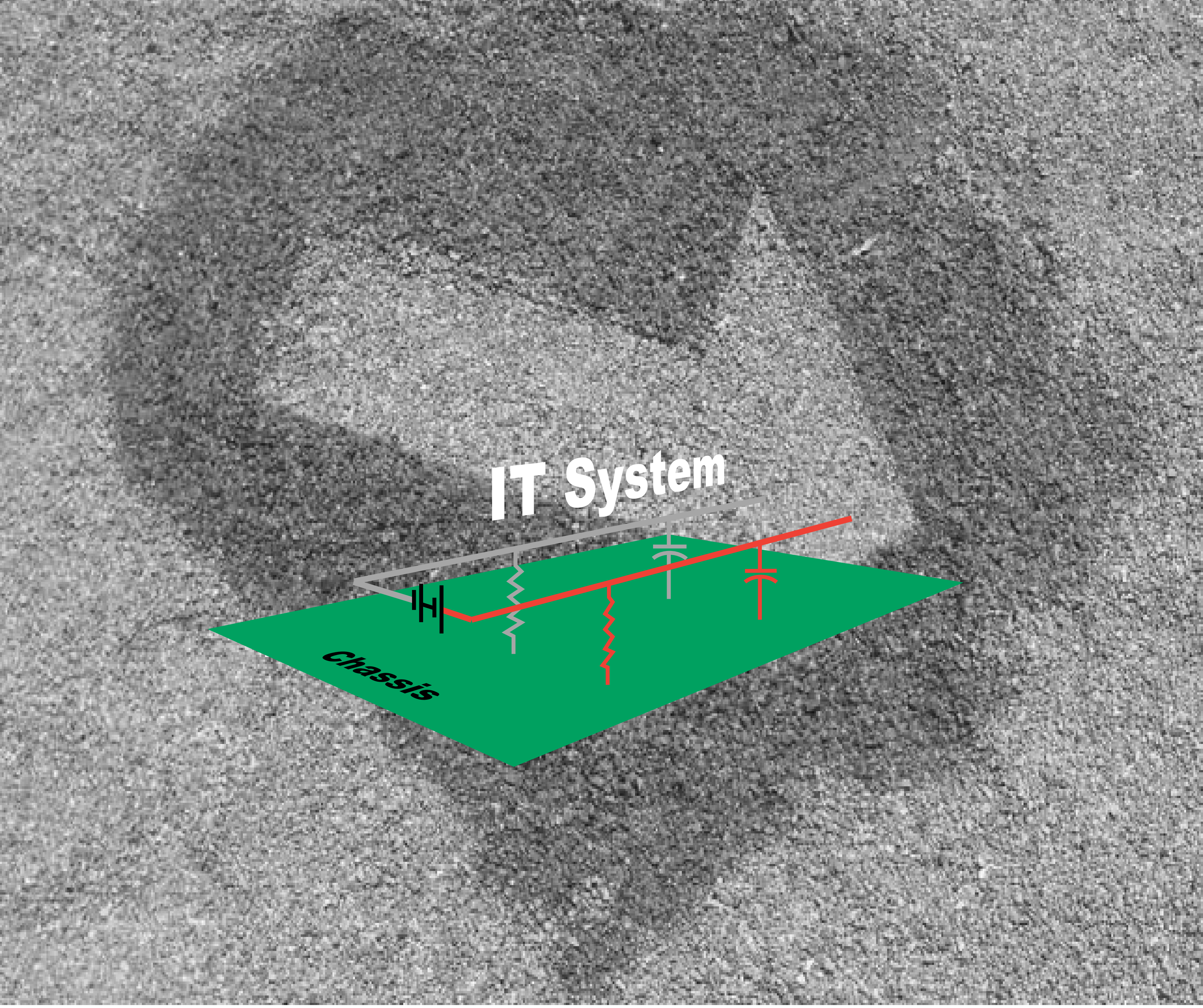

Sendyne®

White Paper

Insulation Monitoring of DC Charging Stations

Insulation Monitoring of DC Charging Stations

Standards and compliance requirements

Abstract – Proliferation of quick charging stations is essential for the wide spread adoption of e-mobility. Interoperability of charging stations and EV/PHEVs is promoted through industry associations like CHAdeMO and CharIn. As Electric Vehicle Supply Equipment (EVSE) requirements move to higher DC voltages in order to accommodate heavier vehicles, safety of EVSEs is elevated as one of the first priorities for the industry. An Isolation Monitoring Device (IMD) is the device assigned with the task of monitoring for potential electrical hazards each EVSE. In this paper we will present the international standards requirements for this safety monitoring function and we will discuss the effectiveness of technologies in fulfilling these requirements. Along the way we will illustrate how Sendyne's SIM100MOD isolation monitor complies with the present and evolving requirements of international standards.

Keywords: isolation monitor, isolation monitoring device, IMD, insulation monitor, ground fault, earth fault

WARNING: *Information presented in this paper expresses the opinions and interpretations of the authors and shall not be used for design as substitute for the international and national standards which specify safety requirements for DC charging stations.*

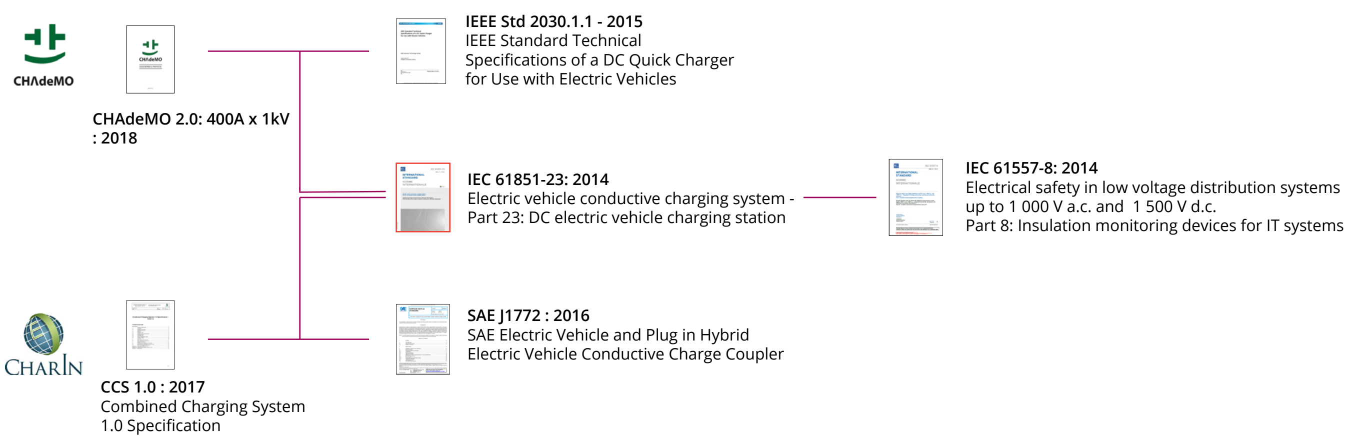

Figure 1: Relationship between protocols and international standards

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The international standards landscape

CharIn and CHAdeMO are the two main competing industry associations promoting global interoperability specifications between EVSEs and EV/PHEVs. The Chinese GB-T standards body is currently in discussion with CHAdeMO for harmonizing the two specifications. While CharIn and CHAdeMO are mainly tasked with interoperability, regarding safety they rely on international standards organizations which lay down prescriptive steps for achieving the safety goals. Such organizations are the International Standards Organization (ISO), the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronic Engineers (IEEE), Underwriters Laboratories (UL) and the Society of Automotive Engineers International (SAE International). The industry associations work with these international standards organizations to produce "standards" specific to the protocols adapted in their implementations. Standards are of course not static, especially in a young industry, and there is a constant revision process ongoing across the whole board.

A snapshot of the current relationship among the relevant standards safety requirements and industry initiatives is shown in Figure 1.

In addition, UL publishes 2232-2 "Standard for Safety for Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits: Particular Requirements for Protection Devices for Use in Charging Systems", which, while not referenced in either the CHAdeMO or CharIn specifications, provides a guideline for qualifying IMDs. The Chinese GB/T 18487.1-2015 "Electric vehicle conductive charging system—Part 1: General requirements" and the Indian AIS-138 Part 2: 2017 "Electric Vehicle Conductive DC Charging System" are similar in the requirements of the IEC 61851-23 2014 standard and as such they are not explicitly referenced in this paper.

The list of standards referenced in this document are the following:

- CHAdeMO 2.0: 2018
- CCS 1.0: 2017
- SAE J1772: 2016 (CharIn)
- IEEE 2030.1.1: 2015 (CHAdeMO)
- IEC 61851-23: 2014 (CHAdeMO and CharIn)
- IEC 61557-8: 2014 (Specifically for insulation monitoring devices)
- UL 2232-2: 2012

Since most of the standards have similar safety requirements, a distinction and reference to specific standards will be made only in areas that there is a difference in the requirements. The terms isolation and insulation are used interchangeably in the remaining of this paper.

The boundary diagram of IMD

The monitoring function of an IMD includes issuing insulation warnings sent after:

- A new fault is detected
- A previously detected fault is cleared
- After a reset

Warning includes visual indications through the Human-machine interface (HMI) to persons operating the charger and, depending on the warning, may lead to charging control actions that must be executed by the EVSE control unit.

IEC 61557-8 specifies that such warnings can be Local Insulation Warnings (LIW) handled directly by the IMD or Remote Insulation Warnings (RIW) relayed through a data communication channel to a device responsible for the final issue and mitigating actions. The Sendyne SIM100MOD implements RIWs and relies on periodic polling from the control ECU to communicate through CAN bus the isolation status of the monitored station. Figure 2 illustrates the boundary diagram of SIM100MOD.

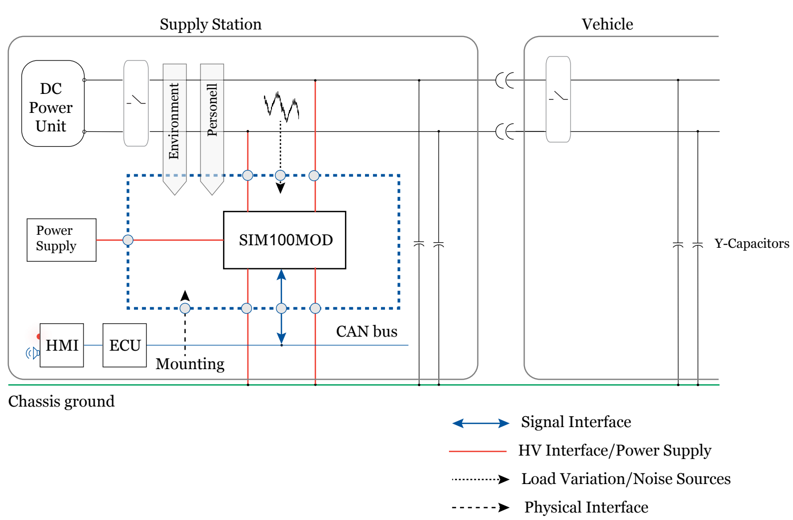

Figure 2: Boundary diagram of Sendyne SIM100MOD in a charging station

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EVSE Isolation Monitoring States

Both CharIn and CHAdeMO define four EVSE isolation monitoring states. The "Invalid State" is the default state entered after a charge is completed or within a period of one hour. The EVSE will remain in this state for as long as the IMD self-test has not completed or if it has failed (Fault or Warning State). In the latter case it will remain in this state until the EVSE is serviced. The EVSE enters the "Valid State" where it can provide charge after it has checked the EVSE isolation status and the IMD has performed successfully its self-test procedure. If during charging any isolation resistance drops to less than 500 Ω/V calculated at the maximum EVSE voltage, the EVSE issues a warning and after completion of charging enters the "Invalid State". If during charging any isolation resistance drops to less than the 100 Ω/V limit for more than 2 consecutive minutes (IEC 61851-23) charging is interrupted and the EVSE enters the "Invalid State" for as long as the fault persists. Figure 3 illustrates the state transition diagram.

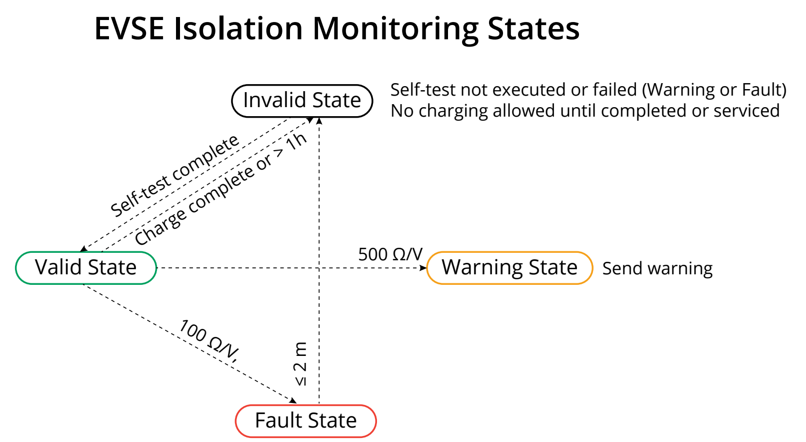

Figure 3: EVSE isolation monitoring states

The SIM100MOD along with each estimate on the elements of the isolation system, issues a status byte. The EVSE Electrical Control Unit (ECU) can use the information provided by the warning and fault flags in the status byte to determine transition between states.

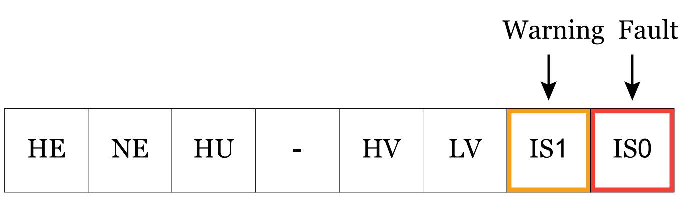

Figure 4: Warning and Fault flags in the SIM100MOD status byte

The "Warning" flag is set when the minimum isolation resistance (between positive or negative rail and chassis) becomes ≤ Umax · 500 Ω/V. The "Fault" flag is set when the minimum isolation resistance becomes ≤ Umax · 100 Ω/V, where Umax is the maximum value between the programmed Vbat,max or the maximum actual voltage recorded by the SIM100.

The SIM100MOD comes preprogrammed with Vbat,max = 0 V. If Vbat,max is not set through a CAN bus message, Umax will set itself automatically during a charging session to the value of test voltage pulse during the isolation test. Umax will maintain the highest voltage recorded until a "Reset" command is issued to SIM100 in which case Umax will revert to the programmed and maintained in flash memory value of Vbat,max.

The coefficients for determining the response values Ran with units Ω/V cannot be changed. The Vbat,max is programmable but the SIM100MOD keeps track of the actual supply voltage and it will update the Umax value upwards if it detects a higher voltage than the one programmed, ensuring that the system is safe at all times.

IMD test function

IEC 61557-8 specifies that: "An IMD shall comprise a test device, or be provided with means for the connection of a test device, for detecting whether the IMD is capable of fulfilling its warning functions. The IT system to be monitored shall not be directly earthed when the test function is activated and the test function shall not negatively influence the IMD and the IT system. This test is not intended for checking the uncertainty of the response value."

The SIM100MOD is utilizing as a the "connected test device" the Y-capacitors of the EVSE power supply. Both are non-interfering to the IT system and independent of the IMD. During the self-test, the SIM100MOD performs an 100% assessment of its capability to correctly estimate the isolation components of the IT system. The hosting ECU can use the SIM100MOD voltage measuring capability as an extra step of verification of its proper operation. The self-test of SIM100MOD is described in more detail in the "SIM100MOD

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Safety Manual”. Figure 5 illustrates the steps for verifying the IMD’s capability. Reading the power supply test voltage from the IMD can provide one extra level of verification.

Self-check of SIM100MOD

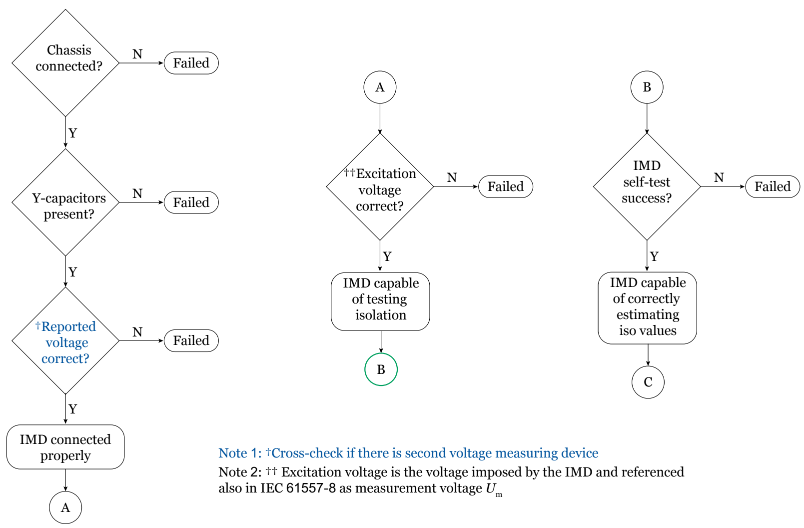

Figure 5: Flowchart for SIM100MOD test function. At point B the IT system has verified that the IMD is capable of fulfilling its warning function. At point C the IMD has verified that it can fulfill this function with the required accuracy.

Failure detection of ground fault detection circuit

CHAdeMO 2.0 specifies that the charger shall check the integrity of the fault detection circuit in the period between the transmission of charge start signal (switch (d1) ON) and the charger set-up completion signal (switch (d2) ON). During this period the charger shall perform its insulation test on the output DC circuit.

The charger shall at least diagnose the defined items listed in Table 1.

If any of the self-tests fails, SIM100MOD will set the (HE) bit in the status register.

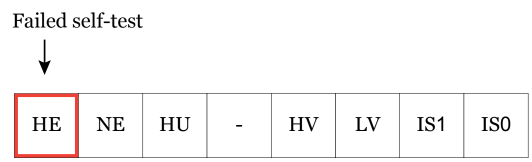

Figure 6: A failed self-test will set the hardware error (HE) bit in the status register

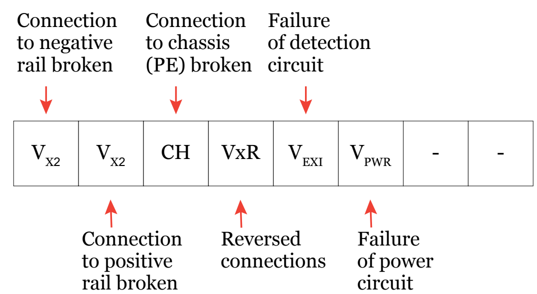

Figure 7: SIM100 self-test error flags

Table 1

CHAdeMO diagnostics	**SIM100MOD self-test**
Open failure and short circuit failure of resistance R	R refers to the resistances connecting the IMD to the IT power rails. SIM-100MOD verifies this connection by the presence of Y and parasitic capacitances between each rail and the PE. In case of disconnection IMD will stop sensing capacitances. In case of a short it will report it as an isolation fault.
Open failure of ground fault detection circuit (e.g. open detecting resister of ground fault current)	Refers to IMD’s sensing circuit. SIM100MOD checks validity of connection of both the sensing circuit and excitation voltage circuit
Open failure of power lines	SIM100MOD monitors quality of power lines
Open failure of protective earthing conductor	Connection to chassis (PE) is at two points. SIM100MOD checks for continuity between these two points
Voltage abnormality of control power (including short circuit of power lines)	Check to be carried by charger ECU

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Time management of self-diagnostic function

CHAdeMO	IEEE 2030.1.1	SAE J1772	IEC 61851-23	SIM100MOD
Prior to each charging cycle	Before the start of charging	Prior to supply cycle or at regular intervals with a max period of 1 hr	1) directly prior to supply cycle with vehicle connector plugged into vehicle inlet; 2) at regular intervals with maximum period of 1 h;	Continuously

Insulation test before charging

This test is performed before the EV contactor is closed. Insulation test voltage is 500 V for IT systems of 500 V (450 V in Japan) or the lower of the Target battery voltage and the Available output voltage (CHAdeMO).

The pass/fail criterion is defined as:

IEC 61851-23: R ≥ 100 Ω/V × U, where U is rated output voltage of DC EV charging station

SAE J1772: R ≥ 100 Ω/V × U. If Fault state occurs during energy transfer, the EVSE will remain in the Invalid State if the subsequent insulation test performed results in Fault or Warning state.

Check timing: Each time before charging starts

Period of test voltage application: Longer than "false operation prevention time" (200 ms). Connector lock, insulation test and output voltage brought to less than 20 V after the test has to be completed in less than 20.0s (CHAdeMO).

SIM100MOD: Self-test and Isolation test ≤ 5.0s

Resistance R

Resistance R as shown in Figure 6 is the resistance used by the IMD to connect to the power rails of the EVSE. CHAdeMO 2.0 specification states, regarding Resistance (R), that: "The resistance shall be installed to limit the maximum ground fault current to 12.5mA. e.g. In the case of a charger with DC 150 V to DC 1000 V, the resistance value is 80 kΩ or more."

It is obvious that for a charger with DC 1000 V, an insulation value of 80 kΩ is smaller than 100 kΩ, which according to the 100 Ω/V insulation requirement, shall trigger an insulation fault alarm. For this reason CHAdeMO 2.0 (6.1.10) specifies an operating time for such a circuit to be "Less than or equal to 1.0s".

SIM100MOD utilizes 2.7 MΩ resistors for its connection to the power rails. In a DC 1000 V system the maximum ground fault current through these resistors is limited to 0.37 mA (0.185 mA typical). The high resistances used by SIM100MOD determine that it can safely remain connected for continuously monitoring the isolation state of the EVSE.

Self-test by applying defined fault resistor

IEC 61851-23 (CC.4.1.a) states "A self test of the insulation monitoring function of the d.c. supply shall be done by applying a defined fault resistor between d.c. output rail and equipotential bonding (e.g. PE)."

The same specification refers to IEC 61557-8 which requires as a mandatory function (4.2.2.1) for an IMD to issue a warning signal "when the insulation resistance RF between the system and earth falls below the response value Ra". There is no explicit requirement for reporting the actual value of the insulation resistance RF unless it drops to the defined Ra value. Early IMD implementations provided just this function and the only way to test their function was by inserting a fault resistor and monitoring the IMD's response. The SIM100MOD has built-in mechanisms to test its proper functionality described in the "SIM-100MOD Safety Manual".

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The IEC 61851-23 Earth Fault Monitoring by Detection of DC Leakage Current

All related standards define as an EVSE earth fault the condition where the insulation resistance value between either the DC+ or the DC- power rail and the enclosure or the vehicle chassis becomes less than VSUPPLY,MAX*100 Ω/V, where VSUPPLY,MAX is the maximum output voltage of the EVSE. This specification ensures that the body current through a human is less than 10 mA.

This requirement originates from IEC/TS 60479-1:2005 "Effects of current on human beings and livestock" which specifies, among other things, human tolerance on body current vs duration of current flow. Figure 9 shows Zones I and II for AC and DC currents. In Zone I current is imperceptible. In Zone II current becomes perceptible and beyond Zone II it becomes hazardous with increasing levels of severity. As can be seen in this diagram a current more than 25 mA cannot be tolerated for more than 2 seconds.

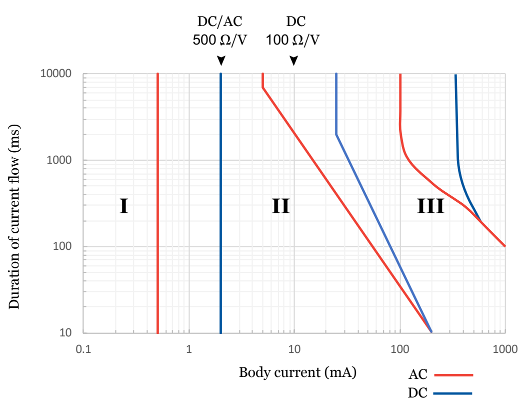

Figure 8: Zones I and II of time/current effects on human body when passing from left hand to feet.

EVSE specifications require preventive action as soon as body current has the potential to become more than 10 mA (2 mA for AC systems).

IEC 61851-23 illustrates a method for detecting DC leakage current as shown in Figure 9 (A detailed description on the potential hazards in an IT power system is provided in Sendyne's "Safety of IT Systems" white paper).

The same circuit showing a fault between the DC- power rail and chassis is shown in Figure 10.

It can be shown that the leakage current i_g is related to R_F through the following equation:

$i_g = V_{dc} \ / \ (R + 2 \cdot R_F)$

If the values of V_{dc} and R are known, by measuring the current ig one can provide an estimate of the value of R_F.

One of the early IMDs implementing this method was the SEIKO SDL0A-1A-E.

The method of Figure 9 appears in several IEC 61851-23 dependent EVSE specifications sometimes creating confusion regarding the implementation of an IMD.

Role of grounding resistors R

CHAdeMO 2.0 (6.1.10) states: "The resistance shall be installed to limit the maximum ground fault current to 12.5mA. e.g. In the case of a charger with DC 150 V to DC 1000 V, the resistance value is 80 kΩ or more."

The resistance the standard is referring to is the resistance of the Figure 10 measurement circuit. In the same table the standard defines "Operating time: Less than or equal to 1.0 s". The way it should be interpreted is that these resistances cannot be connected for more than 1 sec at a time. The reason is that ground fault current is defined

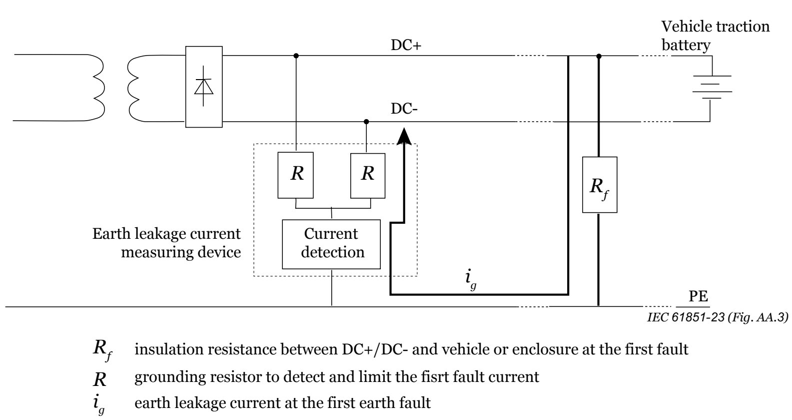

Figure 9: A method to detect DC leakage current for the first earth fault

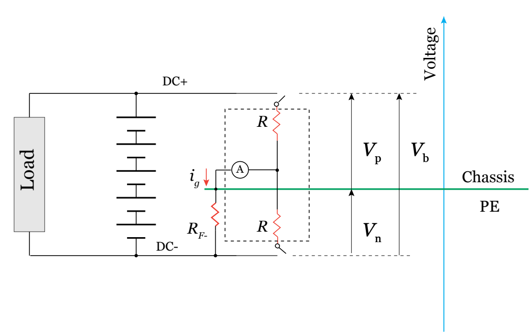

Figure 10: Leakage current detection method. Note the presence of switches which disengage the measurement circuit as soon as the measurement is complete

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as 10 mA (100Ω/V) and permanent connection of such low value resistances allowing 12.5 mA will violate the isolation state of the charging system.

4.17.6 requirement of the CHAdeMO 2.0 Test specification and 6.1.10 of the CHAdeMO 2.0 specification is satisfied by the 2.7 MΩ Resistances (R) of SIM100MOD which limit ground fault current to 185 μA in a 500 V supply and 370 μA in a 1000 V supply. Designers should not permanently install any other Resistors (R) (40 kΩ or 80 kΩ per 12.5 mA limit), as permanent installation shall initiate the "Stop process" per requirement 4.17.3.a. which states: "(a) Stop process shall be carried out when insulation resistance between the output circuit and the enclosure including the vehicle chassis has deteriorated to less than or equal to 100Ω/V. The threshold of the error detection shall be "applied voltage × 100Ω/V"."

The detection method described in IEC 61851-23 and appearing in subsequent standards is one of the many methods to detect ground faults and it has serious drawbacks described in the "Safety of IT systems" white paper. Nevertheless, the authors of the standard took the precaution to limit the operating time of this type of device to less than one second, as while it is in operation the safety of the IT system is compromised.

The "applied voltage" value

The Ra fault response value is calculated by the SIM100MOD as "applied voltage x 100 Ω/V". It is possible that a high voltage charging session preceding a lower voltage charging session will set the value of Ra to a higher value than the one required for the current session.

For example if the Vb,max of SIM100MOD is set at 800 V, the SIM100MOD will set the fault response value to 800 x 100 = 80 kΩ and the warning response value to 800 x 500 = 400 kΩ. In a subsequent charging session at 500 V (Ra, fault = 50 kΩ, Ra, warning = 250 kΩ) , if the session voltage is not set anew, the SIM100MOD will still use the 80 kΩ value to set the Fault flag.

In this situation, an estimated RF isolation resistance of 300 kΩ will set the warning flag, if the Vbat,max is not refreshed, even if the new session is performed at the lower voltage of 500 V.

If the Vb,max is set to a lower voltage (e.g. 500 V) and a new session is performed at 800 V, the SIM-100MOD will automatically adjust the Vb,max value, during the test pulse, and subsequently adjusting Ra fault and warning values to 80 kΩ and 400 kΩ respectively.

The SIM100MOD provides estimates of each isolation resistance value, which can be used to validate the proper operation of the warning and fault flags.

Applied voltage	800 V	500 V
$R_{a,warning}$	400 kΩ	250 kΩ
$R_{a, fault}$	80 kΩ	50 kΩ

Glossary

EVSE	Electric Vehicle Supply Equipment
HMI	Human-machine interface
IMD	Isolation Monitoring Device
LIW	Local Insulation Warnings
PE	Protective earth
R	Resistance used by the IMD to connect to each power rail
R_{an}	Response value of isolation resistance for issuing a fault
R_F	Actual insulation resistance between a rail and chassis
RIW	Remote Insulation Warnings
Umax	Maximum EVSE voltage used f or calculating warning and fault levels
$V_{bat,max}$	Programmable value of maximum EVSE supply voltage in SIM100

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