White Paper of Charging Interface Initiative e.V.

Suggestions for improvement of EV charging connectors

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1. Introduction

Electric vehicle (eV) charging connectors are among the most safety-critical components along the power transmission chain in an eV charging station. Connectors are held in hand by end users and all the power transferred during a charging session (i.e. up to hundreds of kW) flows through the connector. Granted, unexpected failures or improper use of a damaged connector may seriously affect safety, potentially causing severe damage to property and/or harming end users. Notably, experience in the field so far has shown that the behavior of end users when faced to a damaged connector can be unknowingly or deliberately irresponsible, and consequently dangerous for self and others.

Most of the population of installed connectors is rather young today (i.e. ca. 2-5 years), as the DC fast charging technology only began to be commercialized on a large scale not too long ago. Despite the efforts undertaken by industrial players to understand how these electrical components may age in outdoor environments, much work still needs to be done to ensure that the safety of end-users is not affected under any circumstances, especially after long-term exposure of the components to actual operating conditions. As a matter of fact, outdoor environments can be very aggressive for electrical equipment [1,2]. Some factors that may affect ageing performance negatively include UV radiation, temperature cycles (both on a daily and seasonal basis), exposure to rain or other forms of precipitation, pollution, condensation, and salty humidity, among others. With time, these factors may lead to an overall degradation of the materials and the mechanical properties of a connector, which in turn may compromise structural integrity and, thus, safety.

Misuse (for example, connectors dropped and left lying on the ground) and vandalism are often reported as factors that negatively affect the lifetime of connectors and cannot be neglected. Some mechanisms have been proposed to reduce these factors. For misuse, it has been proposed to finalize payment procedures only once a connector has been replaced onto its charger or applying penalties if a connector is left lying on the ground. To fight vandalism, an idea is to lock connectors by default, such that only authorized people are allowed to take them from the charger, for example through RFID authentication. Authorized access also helps to avoid the propagation of damages/faults from vehicle inlets to vehicle connectors and subsequently, other inlets. The commercial implications of these suggestions remain unclear and are subject to controversy within the industry. For example, locking connectors would not allow plug-n-charge procedures, which are actually a strong trend. For this reason, improving connector resistance to misuse and vandalism is important anyhow. Further investigations need to be carried out to determine if/where comfort could have a higher priority than reliability and technical availability.

In brief, eV charging connectors must be regarded as highly performing electrical equipment typically handled by ordinary users. It is thus paramount to include and emphasize safety-by-design when engineering eV charging connectors and, even more so, when defining the relevant standards that guide the design process.

The scope of this white paper is to: (i) draw the attention of the reader on a few important issues faced in the field; (ii) suggest some general directions for improving existing standards, which could reduce the risk of facing such issues and allow the industry to better capture market needs and trends. It is recommended to carry out an in-depth analysis in the technical working groups of the responsible standardization committees in order to achieve a technically meaningful improvement of the charging infrastructure.

The focus is on CCS type eV charging connectors, hereafter “connectors”.

2. Standards

The most important standards to which connectors refer today include the following:

- IEC 62196 series, relevant for Europe
- SAE J1772, UL2251, relevant for North America

These standards cover the requirements for connectors regarding geometry and dimensions, performance, electrical safety, and mechanical integrity. For the sake of simplicity, this paper is focused on the IEC 62196 series exclusively, but the considerations hereafter could also be harmonized with UL2251, as well.

This section indicates which are, in our view, some of the clauses in the IEC 62196 series that have the highest impact on the overall safety and performance of connectors throughout their lifetime. A short (non-exhaustive) explanation is provided for what each clause states, with specific focus on the upcoming IEC 62196-1 v.2022. A summary is shown in figure 1.

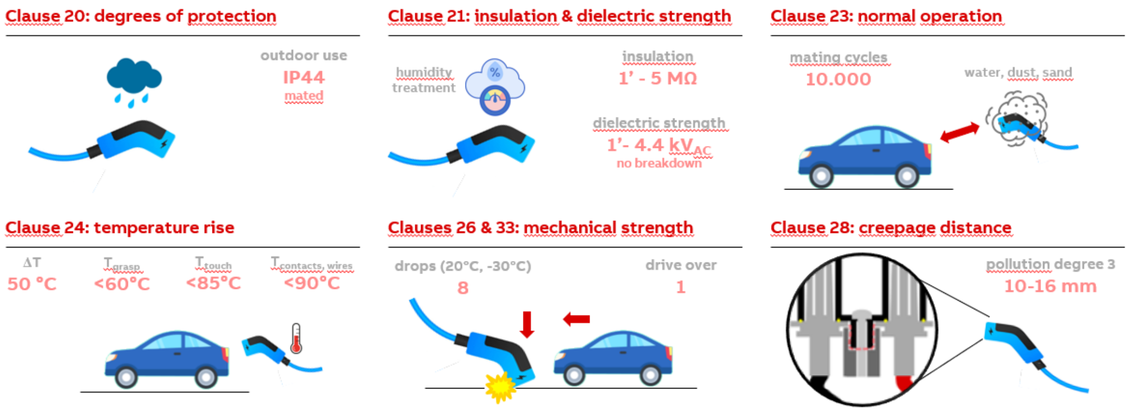

Figure 1. Summary of the clauses that have a high impact defining safety and performance in connector related standards IEC 62196 and UL2251.

2.1. Safety critical clauses

i. **Clause 20: degrees of protection**. This clause requires that connectors comply with the minimum degrees of protection indicated in IEC 61851-1 (general requirements for electric vehicle charging systems). In practice, this means that connectors in a mated condition must be at least IP44 in outdoor applications. For the reader's convenience, it is recalled that IP classes are defined by standard IEC 60529:1989, which classifies and rates the degree of protection provided by mechanical casings and electrical enclosures against dust, accidental contact and water. Thus, compliance to clause 20 is checked by testing according to IEC 60529, and by insulation resistance and dielectric strength measurements following a humidity treatment of 7 days. The former is specified in clause 21, whereas the latter is specified within the same clause 20. It is also required that samples tested shall show no damage within the meaning of IEC 62196.

ii. **Clause 21: insulation resistance and dielectric strength**. These quantities are measured after the humidity treatment of clause 20. The insulation resistance should exceed 5 MΩ after application of 1000 VDC for 1 minute. The dielectric strength, in turn, is evaluated by specifying that there should be no breakdown event following the application of increasing voltage up to 3 kV_{AC} for 1 minute, for connectors rated over 500 V. The voltage applied depends on the nominal voltage.

iii. **Clause 26: mechanical strength**. The requirements of this clause impose that the connectors must pass some mechanical abuse tests, such as ball impact (5 impacts) and drop test (8 drops), among others. In UL2251, the tests must be passed after conditioning the connectors at -30°C in a climatic chamber for at least 16h. In upcoming versions of IEC62196, this requirement will be added, too. The tests are passed if the connectors are not damaged, i.e. no part is detached or loosened, live parts are not exposed, and the IP rating is maintained.

iv. **Clause 28: creepage distances, clearances, and distances**. This clause imposes designing connectors according to standards IEC 60664-1 (insulation for low voltage supply systems) and IEC 60664-3 (use of coatings for protection against pollution). Importantly, this means that the selection of the distances depends on the rated voltage, the material group (defined by the comparative tracking index, or CTI, of the material) and the pollution degree. The connectors shall be designed with pollution degree 3 in mind unless adequate protection can be guaranteed to justify lower pollution degree. As a good example, for a voltage RMS of 1000 V, pollution degree 3 and material group IIIa (175 V ≤ CTI < 400 V), Table F.5 of IEC 60664-1 defines a creepage distance of 16 mm.

v. **Clause 29: resistance to heat and fire**. This clause simply states that accessories shall be sufficiently resistant to heat and fire. Compliance is checked by exposure to high temperature followed by a ball pressure test as specified in IEC 60695-10-2.

vi. **Clause 33: vehicle drive-over**. As the name suggests, a vehicle drive-over simulation test must be passed. The test is passed if the connectors are not damaged to the extent that risk of electric shock is increased, live parts become exposed, IP protection is lost, etc. in a similar way to clause 26.

2.2. Performance related clauses

i. **Clause 15: resistance to ageing of rubber and thermoplastic material**. This clause requires that accessories with enclosures of rubber or thermoplastic material, and parts of elastomeric material such as sealings, shall be sufficiently resistant to ageing. Compliance is checked by an accelerated ageing test at temperatures above 70°C for up to 10 days. The samples tested shall show no crack.

ii. **Clause 23: normal operation**. Here, it is stated that connectors shall withstand the mechanical, electrical, and thermal stresses and contaminants occurring in normal use without excessive wear or other harmful effect. Thus, connectors are expected to withstand up to 10.000 mating cycles with car inlets. Each mating cycle consists of one insertion and one withdrawal from a car inlet. In the specific case of UL2251, clauses 41 and 42, it is specified that after each 1.000 mating cycles, connectors must be dipped in a solution of water, sand, and dust, and then left to dry. The test is then resumed. After the test, the connector shall still be functional, and no mechanical or electrical parts shall be loose, damaged, or deteriorated to the point that the connector cannot be used any longer. Specifically, the continuity between mating signal and pilot contacts shall be maintained.

iii. **Clause 24: temperature rise**. This clause states that the temperature rise of the electrical contacts of the connectors must not exceed 50°C under steady state conditions (i.e. versus ambient temperature). Moreover, IEC 62196-3-1 (clause 16.107) states explicitly that the temperature of the electrical contacts of the connectors shall not exceed 90°C under any operating condition. Other parts that can be touched or grasped should not exceed 60°C and 85°C, or 50°C and 60°C, respectively, if the material is either metallic or plastic. In almost all cases, compliance is checked through a temperature rise test at the rated current. In such test, steady state is defined as a condition in which the temperature rise of the electrical contacts is at most 2°C over 20 minutes.

3. Field experience

Connectors installed in the field are typically designed according to the recommendations of the IEC 62196 series, SAE J1772 and UL2251. Moreover, connector manufacturers often certify compliance to such standards through thorough and independent third-party assessments. Despite this good engineering practice, field experience shows factual evidence that connectors fail more frequently than desired. Field failures which may impact end-user safety can be broadly classified into: (i) mechanical damage and (ii) electrical failures. This section shows simple examples of such situations really verified in the field. Any reference to a particular manufacturer of connectors is just casual and should only be considered as illustrative.

3.1. Mechanical failures

The most common mechanical failures can be grouped depending on the sub-components damaged as follows:

- Fracture of the mating interface
- Fracture of the handle
- Fracture of the connector housing
- Total mechanical failure
- Failure of the strain relief
- Failure or fracture of the latch mechanism
- Damages on contacts

Figure 2 shows some examples of these damage modes. It should be noted that situations shown are known by a broad audience already and belong in the public domain.

The problem of mechanical damage of connectors is that it increases the risk of incidents. Fracture of the mating interface may cause latch connection failures and/or communication issues during charge sessions. In a worst-case scenario, this could lead to hot disconnections, arcing and burning or electrocution of end-users. A fractured handle brings along an increased risk of cuts. Fracture to a connector housing, total mechanical failure and failure of a strain relief all imply a loss of IP protection in the best case, and exposed live parts in the worst case. Either way, this could lead to short-circuit or electrocution incidents.

Figure 2. Common mechanical failures of connectors, including damage to the housing (left [3]), damage to the mating interface (right [4])

3.2. Electrical failures

Electrical failures are not observed often in the field. However, electrical failures can happen and have actually happened. For example, a connector was reported to produce smoke in July 2020 (figure 3). Visual inspection revealed damage to the internals. Another electrical incident occurred in 2018 in Daegu, South Korea, where a connector explosion was reported following a charging session [9] (figure 4). Reportedly, the cause of the explosion was thought to be a short-circuit. This example highlights that the problem with electrical failures is the increased risk of physical damage, concussion, or electrocution of end-users. In a worst-case scenario, electrocution may cause death, which is obviously not an option. Other risks include fire, explosions, and the resulting damage to property.

There is one important topic that may affect electrical failures and overheating which deserves special attention -namely, degradation of the electrical contacts with time, i.e., due to ageing, cycling or misuse. This may have a severe impact on performance and failure propagations. Appropriate means to detect electrical contact degradation could be incorporated into the mating components and a quick system-level response could also be implemented to limit damage propagation.

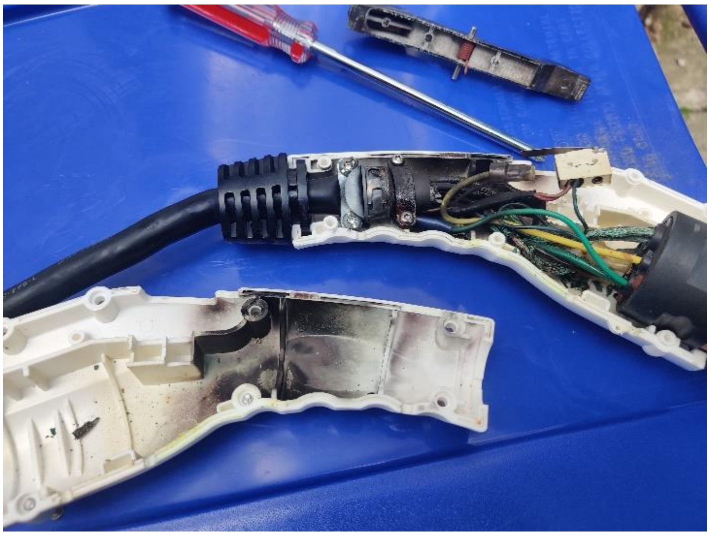

Figure 3. Inspection of a connector producing smoke during a charge session [6].

Figure 4. Exploded connector, Daegu, South Korea, 2018. The explosion was allegedly caused by a short-circuit [7].

4. Suggestions for improvement

Based on the experience available from field operations, it is clear that improving standards may bring benefits in terms of safety and performance and would allow the E-Mobility industry to better capture market needs and trends.

In this section, some suggestions are made to improve existing standards. The suggestions made must not be considered as exhaustive examples, but rather as strategic directions in the pursuit of enhanced safety and performance. Specific numbers are proposed as examples, but a detailed benchmark of what is possible and what is not possible should follow to define exact values in the frame of a standardization discussion.

4.1. Safety critical clauses

i. **Clause 20: degrees of protection**. One important point to consider when discussing degrees of protection is that for the unmated connector, as a whole, IEC 61851-1:2017 requires max. IP24 . However, improving the degree of protection of connector internals such as the pin/pin holder and contact tube sub-assemblies can have a positive impact, reducing the risk of electrical failures caused by water ingress into the connector. In this sense, it would be beneficial to require a higher degree of protection for internals, and to define an appropriate test.

ii. **Clause 21: insulation resistance and dielectric strength**. Insulation resistance and dielectric strength reflect the electrical safety of connectors, and that's why we propose to have higher requirements on such properties. The directions to be followed are the following:

   - Increase requirement on insulation resistance. For example, an increase from 5 MOhm to a resistance in the range of 100 MOhm would be a good way forward. Importantly, such values are not farfetched for commercially available connectors
   - Increase requirement on dielectric strength. For example, perform the test with 4.4 kV DC (in addition to or instead of with 3 kV AC) and add requirements on leakage currents. For example, leakage currents in the order of mA may not be acceptable
   - Perform more aggressive environmental/ageing tests. For example, perform long-term salt-fog ageing tests while DC voltage is applied, after connectors have been preconditioned with UV light and temperature cycling. In addition, apply the tougher electrical requirements mentioned above after the more aggressive ageing test

iii. **Clause 26: mechanical strength**. Mechanical strength is paramount for safety because the IP degrees of protection (indicated in clause 20) can only be guaranteed if mechanical integrity is not compromised. In order to improve the situation depicted in section 3.1, several routes are possible and worth pursuing:

   - Include specific requirements on the mechanical properties of the materials used for connectors, such as stiffness, tensile strength and so on. In the specific case of impact strength, standard IEC 62262 could be taken as a reference, and a high IK code could be targeted, for example IK10 instead of IK08. It is paramount to specify impact strength at low temperatures, as some commonly used plastic materials (such as nylon) may become particularly brittle at temperatures below 0°C
   - Redefine mechanical abuse tests referring to (a) the ChaoJi standard or (b) CharIN's recommendation on connector and cable tests of 29.11.2019 [9]. One critical point to consider is that it should still be possible to pass the tests using

plastic materials that also fulfill other conditions required in the standard, for example related to flammability, weathering resistance or resistance to tracking. It is important to stress that the choice of materials is heavily constrained if all requirements are put together. For this reason, connector manufacturers are encouraged to design connectors that can be maintained properly should mechanical damage take place.

  - Tailor requirements if it can be guaranteed that drops are limited or absent and/or differentiate between use cases (i.e. residential charging will not have the same requirements as highway charging).

iv. **Clause 28: creepage distances, clearances, and distances**. These are all very important defining electrical behavior and minimizing the risk of electrical failures. Some possible recommendations are listed below. Anyhow, it should be noted that there is no general consensus on these suggestions, as some manufacturers believe that it may be enough to stick to existing standards. The recommendation is therefore to take the discussion to the relevant standardization committees, with the goal of improving connector safety overall.

  - One way could be to increase creepage & clearance and require that creepage is higher than specified in IEC 60664-1.
  - Another way could be to select a material with a larger CTI, e.g. CTI=600, and to design for a smaller CTI.
  - Another way could be to adjust input parameters to IEC 60664-1. (overvoltage cat., rated impulse withstand voltage, …).
  - Increase requirement on pollution degree -specifically, pollution degree 3 should be mandatory for all types of connectors where the enclosure is just IP44.
  - In the specific case of the temperature sensors, a declaration (or classification) in IEC 62196 providing an indicator of the type of insulation (e.g., functional, basic or reinforced insulation) which is implemented inside the connector between sensors and DC lines would support the system integration, meeting the insulation requirement between DC lines to any other circuits as defined by IEC 61851-23 (69/702/CDV: 2020-02-07, Table 110 on minimum protective measures).

v. **Clause 29: resistance to heat and fire**. In case an electrical incident takes place, it is good engineering practice to select materials that have the highest possible resistance to heat and fire. The recommendation to improve the current situation is to uniform IEC62196 and UL2551 on specific requirements on the flammability of materials, while referring to UL746A/B and UL94.

4.2. Performance related clauses

i. **Clause 15: resistance to ageing of rubber and thermoplastic material**. The current situation can be made clearer. Our recommendation is to:

  - Refer to UL 746B or UL 746C and include a requirement on classification of materials for outdoor use, for example F1.

ii. **Clause 23: normal operation**. Normal operation can be difficult to define precisely, as it is a very broad term. Currently, a minimum of 10.000 mating cycles is required, regardless of the application. This may be somewhat excessive, for example, for private use, and insufficient, for example, for use in highways. Thus, a proposal from part of the community is to make a classification of connectors which takes use-case into account when defining normal operation. The classification would then be part of datasheets and installation manuals. However, this idea does not find generalized consensus for the time being. Regardless of this topic, it is still recommended to harmonize test conditions and pass criteria between IEC62196 and UL2251, clauses 41 and 42, which require to dip connectors in aggressive solutions every 1000 mating cycles.

iii. **Clause 24: temperature rise**. The way that temperature rise tests are defined today have important implications for the EV charging industry. The most important implication is that performance is limited: the allowable current is that which yields a temperature rise of 50°C, while contacts stay below 90°C. However, a thorough investigation, taking account the various use cases (such as a pre-heating of the system by a previous charging process), could lead to an improved set of thresholds/requirements. Another implication is that connectors are often uncapable of delivering the nominal current rating under all real operating conditions. This is due to the fact that the nominal current rating refers to a "steady state" definition which is actually still a transient. Some possible directions can be:

   - Avoid redundant requirements that limit performance just because of historical reasons (i.e. ΔT<50K even if ambient is 20°C or lower, and graspable parts are below limits)
   - Allow for and regulate boost modes, and tighten regulations on temperature sensors for this application, so that safety can be guaranteed through accurate and precise measurements, considering the inertia of the system
   - Allow the possibility of accepting higher temperatures in the copper wires or contacts. Recommendation of the contact temperature value of at least 100°C could be proposed for the next revision of IEC 62196. Provided temperature limits for graspable plastic parts are not exceeded and aging behavior is not affected negatively.
   - Review the definition of steady state, so that nominal ratings are closer to actual performance under real operating conditions. For example, define steady state as an increase of 2°C in 60 minutes instead of 20 minutes

   Note: Consider contact resistance as a key element defining safety and performance for the bullets above.

4.3. Interoperability related document – CharIN Conformance Tests

In order to quarantine a high quality of the vehicle coupler for the end user it is also necessary to establish a CharIN certification process for the independent test organizations. This process by CharIN is an important step to ensure the mechanical function and to improve the interoperability of the EV coupler. The dedicated document "Conformance Tests – Vehicle Coupler" describes these points in detail and is reachable with the link below.

https://charin-my.sharepoint.com/:f:/g/personal/coordination_charin_global/EoPVs9Z5MsREuNSUdg399PIB6Tb9_Opqv8MIAbD3sSs7zA?e=b0gqcz

5. References

[1] S. Clifford, H. Le, P. Mahonen, A. Krivda, “Evaluating the performance of outdoor apparatus in harsh environment”, *International symposium on electrical insulation*, Vancouver, Canada, pp. 453-457, 2008.

[2] A. Krivda *et al.*, “Accelerated testing of outdoor power equipment”, *2011 Annual report conference on electrical insulation and dielectric phenomena (IEEE CEIDP)*, Cancun, 2011, pp. 381-386, doi:10.1109/CEIDP.2011.6232675.

[3] https://www.plugincars.com/why-baltimores-vandalized-charging-stations-have-taken-too-long-fix-127614.html

[4] https://300mpg.org/2016/05/07/evse-repair/

[6] https://openev.freshdesk.com/support/discussions/topics/6000062136

[7] http://news1.kr/articles/?3364372

[8] CharIN, Charging interface initiative e.V. Conformance tests – Vehicle coupler, by M. Pelzl & C. Schuba of BMW AG.

[9] CharIN, Charging interface initiative e.V., 29.11.2019. CharIN recommendations on connector and cable tests for future applications related to IEC 62196-1:2014.