Analysis and Testing of U.S.-China Key Technology for Charging Interoperability of Electric Vehicles

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Abstract. At present, China has overtaken the United States to become the world's largest new energy vehicle market. Due to differences in developmental trajectory, developmental mode, and charging standards, China and the U.S. have common interests and the foundation for cooperation, which can work together for a win-win development. Charging interoperability is the basis for ensuring charging safety and interchangeability of electric vehicles. This study examined and compared the differences between China and the U.S. in the standards for conductive AC charging of electric vehicles. The requirements for a control pilot circuit, proximity circuit, current capacity, and charging-state transition timing were analysed. Hierarchical and layered interoperability test cases based on GB/T 34657 and SAE J2953 series were presented. A dual interface interoperability test system was constructed and used to verify the test method rationale. The results provided a mutual inspection solution for AC charging equipment between China and the U.S. and accelerated global application and promotion of the electric vehicle industry.

1. Introduction
Currently, the development of the global automobile industry is facing a dual challenge regarding energy supply and environmental protection pressure. Many countries have designed sustainable energy strategies and put them into practice through legislation. The Joint Statement on Climate Change was issued by China and the U.S. in April 2013. This Partnership helped both countries to implement their respective national climate change strategies and reduce exhaust emissions. The National Development and Reform Commission and the U.S. State Department have jointly led the establishment of the Sino-U.S. Climate Change Working Group. An electric vehicle (EV) team led by our laboratory worked in Smart Grid Workshops on cooperation in the interoperability testing of EV charging.

In the early stage of industry development, immature charging facilities, inconsistent charging processes, and incompatible charging interfaces seriously hindered the development of this automobile industry. Scientific research and testing institutions had included exchange and interoperability research. Zhang has proposed a charging safety mechanism from the perspective of physical connection safety, electrical connection safety, high voltage protection measures, charging interaction protection, and functional failure protection [1]. Alternating current (AC) charging auto testing platforms have been constructed by Zhu [2] and Guo [3], based on the Chinese AC charging standard. Zhang has analyzed the different AC charging states and gave the charging interoperability test method and test process of
the vehicle and charging equipment [4]. These studies only addressed domestic products in interoperability research. The differences of standards for EV conduction charge couplers in the EU, USA, Japan, and China have also been identified by Wang [5], but no solution has been offered that is compatible with different standards and charging technologies. There has been no systematic comparison of the differences toward promoting the unification of an international standard. Thus, it has remained a major challenge regarding how to harmonize compatibility tests between different charging facilities and EVs. It is also a major challenge to develop optimal allocation of resources and charging interconnections.

2. Conductive AC charging technology

2.1. Charging mode
Due to differences in the global low-voltage distribution grid, there are large differences in input voltage and frequency, which also causes differences in charging standards among countries. AC charging electrical rating should meets the requirements specified in SAE J1772:2017 [6] and GB/T 18487.1-2015 [7] (Table 1).

| Change method | Nominal supply voltage (V) | Max current (Amps-continuous) | Branch circuit breaker rating (Amps) |
|---------------|----------------------------|------------------------------|-------------------------------------|
| AC level 1 a  | 120 V AC, single phase     | 12 A                         | 15 A (min)                          |
|               | 120 V AC, single phase     | 16 A                         | 20 A                                |
| AC level 2 a  | 208 to 240 V AC, single phase | ≤80 A                       | Per NEC 625                          |
| Mode 2 b      | 220 V AC, single phase     | 8 A                          | 10 A                                |
|               | 220 V AC, single phase     | 13 A                         | 16 A                                |
|               | 220 V AC, single phase     | ≤32 A                        | Max current +2 A, Max current ≤20 A; |
|               |                            |                              | Max current×110%, Max current >20 A.|
| Mode 3 b      | 220 V AC, three phase      | ≤63 A                        |                                     |

Table 1. AC charging electrical rating

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\( ^a \) Applies for North America,
\( ^b \) Applies for China.

2.2. Charging coupler
The technical solutions for an AC charging coupler are shown in Table 2. From comparison results, the layout of the American AC charging interface is very different from the Chinese solution. For interchangeability, the Chinese AC charging interfaces cannot be directly cross-coupled with the American AC charging interface.

| Region       | Pins | Locking mechanism                      | Ease of use | IP rating                      |
|--------------|------|---------------------------------------|-------------|--------------------------------|
| U.S.         | 5 pins | mechanical locking                     | ≤75 N       | mated: 3R(IP54) unmounted: 3R(IP54) |
| China        | 7 pins | mechanical locking (max current ≥32 A) | ≤100 N      | mated: IP54 unmounted: IP55     |

2.3. Control pilot circuit
The typical configurations defined by Sino-U.S. standards include similar control pilot circuits, but state D is the state of vehicles requiring ventilation for indoor charging areas, which is not applicable to AC charging in China (Figures 1 and 2).
2.4. Proximity detection circuit

A proximity detection circuit, with no current capacity coding resistor adopted by SAE J1772-2017, is given in Figure 1. Monitoring of this circuit in the EVSE is an optional function.

China has adopted a cable-carrying capacity coding resistor Rc on the AC supply equipment side. Vehicles can determine the rated capacity of the cable based on Rc. The equivalent circuit is shown in Figure 2 and the supply current rating corresponds to the resistance value is shown in Table 3.

Table 3. Supply current rating corresponds to resistance value

| Resistance Rc (Ω) | Resistance R4 (kΩ) | Switch S3 state | Supply current rating (A) | Resistance RC (Ω) |
|-------------------|--------------------|----------------|---------------------------|-------------------|
| 1500              | 1.8                | close          | 10                        | 1500              |
| 680               | 2.7                | close          | 16                        | 680               |
| 220               | 3.3                | close          | 32                        | 220               |
| 100               | 3.3                | close          | 63                        | 100               |

2.5. Supply current rating

The mapping relationship between the pulse-width modulation (PWM) duty cycle and the current value in the Sino-US AC system are the same. The difference is that the maximum charging current allowed by SAE J1772-2017 is 80 A and the maximum charging current is 63 A in China. Thus, Chinese vehicles
need to consider, when receiving the PWM duty cycle of 80 A current from American EVSE (SAE J1772), to choose to stop charging or charge according to its specific allowed charging current.

3. AC charging interoperability

3.1. Interoperability test list
SAE J2953 clearly specifies 3 tiers of interoperability [8–9]. The differences between both sides’ interoperability test items breaks down into 3 tiers of interoperability, with the tests associated with each tier (Table 4). Tier 1 tests focus on the basic functionality of the charge system. Tier 2 testing is used to gauge the robustness of the charge system under nonideal conditions. Finally, Tier 3 testing is used to check nonstandard feature functionality.

| Tier | SAE J2953 test                                      | GB/T 34657 test [10–11]                      |
|------|---------------------------------------------------|---------------------------------------------|
| 1    | mechanical interoperability                       | charging coupler interoperability            |
|      | charge functionality                             | charging state transition timing            |
|      | safety feature functionality                      | charging normal shutdown                    |
|      | indefinite grid events                           | not defined                                 |
| 2    | dynamic grid events                               | not defined                                 |
|      | ampacity control                                 | charging control output                     |
|      | scheduled charge                                 | charging state transition timing            |
| 3    | staggered scheduled charge                        | not defined                                 |
|      | charge interrupt/resume                          | charging error shutdown                     |

3.2. Charging coupler interoperability
SAE J2953-1 requires that the coupling and decoupling force of the system coupler be less than 75 N. GB/T 34657 proposes interchangeability requirements for dimensional tolerances in standards GB/T 20234 [12–13] and also provide gauges requirements for the charging connector and inlet.

3.3. Charging control state
EVSE and the EV can exchange each charging state by monitoring the PWM signal and voltage at the detection point. Acceptance criteria for control pilot state voltages are shown in Table 5. Voltage limits of Chinese EVSE are within the range specified by SAE J2953.

In the case a proximity state transition occurs, one data point on each side of the transition is excluded; these binned values are shown in Table 6. As the pull-up voltage of Chinese EVs is determined by the car manufacturer, the value of the detection point is not specified in GB/T 18487.1-2015.
Table 5. Control pilot state voltage reporting bins

| Control pilot state | Voltage range SAE J2953-2 | Voltage range GB/T 34657.1 |
|---------------------|---------------------------|---------------------------|
| State A             | 10.5 V ≤ V ≤ 15 V         | 11.40 V ≤ V ≤ 12.60 V    |
| State B             | 7.5 V ≤ V ≤ 10.5 V        | 8.20 V ≤ V ≤ 9.80 V      |
| State C             | 4.5 V ≤ V ≤ 7.5 V         | 5.20 V ≤ V ≤ 6.80 V      |
| State D             | 1.5 V ≤ V ≤ 4.5 V         | Not defined               |
| State E             | -1.5 V ≤ V ≤ 1.5 V        | Not defined               |
| State F             | -15 V ≤ V ≤ -1.5 V        | Not defined               |

Table 6. Proximity detection state voltage reporting bins

| Proximity detection state | Voltage range SAE J2953-2 | Voltage range GB/T 34657.1 |
|---------------------------|---------------------------|---------------------------|
| EVSE unplugged           | 3.5 V < V ≤ 6.0 V        | ≠ 0 V, not defined        |
| EVSE plugged S3 open     | 2.0 V < V ≤ 3.5 V        | = 0 V                     |
| EVSE plugged S3 close    | 0 V < V ≤ 2 V            | ≠ 0 V, not defined        |

3.4. Charging state transition timing

A list of transitions that are triggered either in parallel with data capture or post-process are show in Table 7, with all completed transitions logged. The measured times are binned based upon the transition timing requirement they belong to.

Table 7. Charging state transition timing

| Charging state transition | Acceptance criteria (s) SAE J2953-2 | Acceptance criteria (s) GB/T 34657.1 | Description |
|----------------------------|-------------------------------------|--------------------------------------|-------------|
| State B1 to State B2      | none                                | none                                 | Timing from plug-in to PWM oscillator |
| State B2 to C/D           | none                                | none                                 | Timing from PWM oscillator on to S2 closed |
| State C/D to mains voltage| ≤ 3                                 | ≤ 3                                  | Timing from S2 closed to EVSE AC contactors close |
| State C/D to State B2     | ≤ 3                                 | Not defined                          | Timing from AC contactors open in response to S2 open |
| State X to State A        | ≤ 0.1                               | ≤ 0.1                                | Timing from plug disconnect to EVSE opening AC contactors |
| State X to State A        | ≤ 2                                 | ≤ 0.1                                | Timing from plug disconnect to EVSE oscillator off |
| Invalid pilot to State B2 | ≤ 3                                 | ≤ 3                                  | Timing from EVSE invalid pilot frequency to EV opening S2 |
| State E/F to zero line current | ≤ 5                           | ≤ 3                                  | Timing from EVSE fault state to EV terminating charge (zero charge current) |
| Duty Cycle change response| ≤ 5                                 | ≤ 5                                  | Timing from EVSE PWM modification to EV current draw adjustment |
| State C/D to State B      | ≤ 0.1                               | ≤ 1                                  | Timing from S3 open to EV terminating charge (zero charge current) |

4. AC charging interoperability test

4.1. Test configuration
Based on the above analysis, a test setup was proposed here for the portions of interoperability testing that require the use of an interface fixture to obtain EVSE and EV signaling to data acquisition and logging equipment. The constructed interoperability test system mainly included a programmable supply, EV simulator, data acquisition system, and main control PC (Figure 3). The test box with dual interface met the requirements for a connected GB or SAE connector to support tier 1 (except charging coupler interoperability), tier 2, and tier 3 tests. The proximity detection circuit and control pilot circuit on the vehicle side in the test box was based on the AC level 2 system configuration in SAE J1772-2017. The interoperability test setup was modified slightly to accommodate a programmable AC power supply. The data acquisition system was used to monitor test interactions between an EVSE and EV simulator. The artificial load input current was adjusted through the main control PC to meet the needs of the test case.

![Figure 3. Dual interface interoperability test system.](image)

**Figure 3.** Dual interface interoperability test system.

### 4.2 Test environment conditions
All tests are performed at room temperature (25 ± 10°C) and under 45–75% relative humidity.

### 4.3 Test procedures
Any of the connectors was plugged into the inlet to complete the corresponding interoperability test. Conduct interoperability tests on AC supply charging equipment in accordance with GB and SAE standards separately. The voltage data of DP1 and DP3 (if possible), the frequency, duty cycle, rise time/fall time of output PWM signal, AC charging voltage and charging current were collected by the data acquisition system. At the same time, abnormal trigger signals and the charging state transition time should be recorded. The adapter was also used to connect to the different inlet and complete the other party's standard conformance.

All data signals were recorded by data acquisition system at a rate of once per 100 ms or at 10 Hz. For PWM rise/fall/settling parameters, this meant that all measurements were logged by the main control PC. For signal parameters measured at a higher frequency then 10 Hz, all measurements since the last logged value were averaged to a single value. All signal interface and test flow control, database management, and results were displayed and stored using the main control PC.

### 4.4 Charging state transition timing test
A test sample that conformed to GB standards was connected via the adaptor to the SAE inlet of the test device, used to simulate the vehicle's charging process according to different charging states, and then checked regarding whether the voltage change of DP1 and DP3 (if possible) and state transition time were within the standard range. The results of a normal charging state transition timing test, including the vehicle reservation charging process, are shown in Figure 4.

The tested sample had a single-phase charging and maximum rated current is 32 A. Test results of a control pilot state voltage are shown in Table 8. During charging (state C), the voltage of DP1 was within the allowable charging range of the AC EVSE. These results also met the requirements of the corresponding sections in SAE J2953-2.
Table 8. Control pilot state voltage test results

| Control pilot state | Detection point 1 | PWM |  |
|---------------------|-------------------|-----|---|
|                     |                   | duty cycle | frequency | rise/fall time |
| State A             | 11.98 V           | /            | /           | /            |
| State B1            | 8.89 V            | /            | /           | /            |
| State B2            | 8.80 V/-12.1 V    | 53.41%       | 1000 Hz     | 5.552 μs/6.905 μs |
| State C1            | 5.91 V            | /            | /           | /            |
| State C2            | 5.76 V/-12.0 V    | 53.40%       | 999 Hz      | 5.614 μs/6.627 μs |

4.5. Charging error shutdown test

Charging error shutdown tests were also performed (Table 9). In the case of disconnection or open switch S2, the timing from plug disconnect to EVSE opening of AC contactors and oscillator off met the requirements of the standard.

Table 9. Charging error shutdown test results

| Charging state transition       | Acceptance criteria (s) | Results |
|---------------------------------|-------------------------|---------|
| SAE J2953-2 GB/T 34657.1       |                         |         |
| State B1 to State B2           | none                    | none    | /       |
| State B2 to C/D                | none                    | none    | /       |
| State C/D to mains voltage     | ≤ 3                     | ≤ 3     | 131.2 ms|
| State C/D to State B2          | ≤ 3                     | not defined | /     |
| State X to State A             | ≤ 0.1                   | ≤ 0.1   | 65.27 ms|
| State X to State A             | ≤ 2                     | ≤ 0.1   | 45.32 ms|

4.6. Test results analysis

Based on the above tests, the results of the charging interoperability of the samples met the requirements of Chinese standards as well as American standards, because through previous research and comparison the acceptance criteria given by the Chinese standard were seen to be stricter than that of the U.S. Of course, the physical interface styles of the Sino-U.S. are not the same and the Chinese AC charging SE can charge to American vehicles through the adaptor.

5. Conclusions

This study deeply analyzed the differences between the Chinese and U.S. AC charging interoperability technology through examination of charging coupler interoperability, control pilot circuit, and charging
state timing. Most test cases and requirements were the similar. The present proposed dual interface test system met the charging interoperability test requirements of AC EVSE based on SAE J2953-2 and GB/T 34657.1 and was used to further verify the charging capacity between AC charging equipment and an EV. With the development of EVs, people pay increasing attention to the compatibility of charging systems. Although the AC charging interfaces used in various countries and regions cannot form a unified structure and shape, the control and communication methods have tended to be consistent.

Harmonization of the standards is conducive to the universal interchange of products and is of great significance for products entering the international market. At present, China is actively participating in IEC 61851-1 [14], continues in comparison work of the standard systems, carries out test verification on key indicators, introduces Chinese AC charging circuits into international standards, and improves China’s influence on international standardization around the world.

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