EVS26
Los Angeles, California, May 6-9, 2012

Safety Design of Electric Vehicle Charging Equipment

Ming-Hung Lu[1], Ming Une Jen[2]
[1,2]*Mechanical and Systems Research Laboratories, Industrial Technology Research Institute*
195, Sec. 4, Chung Hsing Rd., Chutung, Hsinchu, Taiwan
[1]*Minghung-Lu@itri.org.tw;* [2]*MUJen@itri.org.tw*

Abstract

Besides cost issue, the charging infrastructures popularization and charging safety assurance are two major concerns for promoting electric vehicles (EVs). Several pilot-run programs, such as in the U.S., Europe, Japan, China, and Taiwan as well, enforce the safety compliance of EVs and infrastructures as an implementation policy. To be part of the players, it is essential to have the comprehensive understanding of the standard differences among IEC, SAE/UL, GB and JEVS. The way to compile the issued standards in different regions, however, is time consuming and may get limited helpful hints until tried and tested. Based on above-mentioned standards, this study summarized an overview in aspects of construction, function, performance and safety for charging equipments. To facilitate as a competent safety design, key requirements of electrical safety were presented. These crucial design rules included functional requirements, constructional requirements, personal protection against electric shock, insulation coordination, electromagnetic compatibility and charging control. The rationale and compliance requirements were highlighted to assist as design guidelines. In addition, learning from the past is always a good approach to build confidence to comply with the safety requirements. Based on the standards—follow most IEC and some SAE/UL—for pilot-run project in Taiwan, a case study of an AC charging stand provided the safety faults encountered and solutions in designing a new product that can meet safety requirements effectively. With these design guidelines and the case study, this paper provided a solid basis of safety design for electric vehicle charging equipments.

Keywords: BEV, Infrastructure, Conductive charger, Safety

1 Introduction

Oil shortage impact and the desire for more sustainable vehicle solutions accelerate the demands and deployments of electric vehicles (EVs) globally. On one hand, safety assurance of Li-ion battery in an EV was and is foremost concern. At the same time, the safe and convenient charging infrastructures, to transfer electric energy from the mains and/or alternative power sources through charging equipment and connector to an EV, are also a key factor to promote the EV sustainability. In order to obtain the safety certification for different regions, charging equipments shall be designed to comply with the safety requirements addressed in the regional standards. The way to compile the issued standards in different regions, however, is time consuming and may get limited helpful hints until tried and tested. In addition, literature review shows that very few papers discuss about failure case studies that may offer the best learning means to build confidence to pass the safety validation tests efficiently. The purpose of this paper, therefore, is to provide the cornerstone of safety design for electric vehicle charging equipment by delivering the overview of global standards, the crucial design guidelines and a case study.

Nowadays, the major emerging markets for electric vehicles are North America, Europe, China and Japan. As an overview, this paper first highlighted the up-to-date international and regional standards. Based on comparisons among the global standards, this study summarizes an overview in aspects of construction, function, performance and safety for charging equipments. To facilitate as a competent safety design for dedicated charging equipments, this paper then focused on key requirements related with electrical safety. The rationale and compliance requirements were offered to assist as safety design guidelines. Specifically, design features of charging control/communication between a charging equipment and an EV were delivered to fulfil the electrical safety completely.

Before any new designs are initiated, it is practical and wise to check what we can learn from the previous development efforts. This is the reason for providing a case study in the fourth section. Based on the standards—follow most IEC and some SAE/UL—for pilot-run project in Taiwan, this case study of an AC charging stand covered construction review, major faults, feasible countermeasures and validation results. The illustration of such a case, providing safety faults and countermeasures, offered additional information in designing for safety compliance.

2 Overview of Charging Standards

Several pilot-run programs, such as in the U.S., Europe, China, Japan, and Taiwan as well, enforce the safety compliance of EVs and infrastructures as an implementation policy. The corresponding regional standards for EV infrastructures are SAE/UL, IEC, GB, JEVS/CHAdeMO and CNS, respectively. In order to obtain the safety certification for different regions, charging equipments shall be designed to comply with the safety requirements addressed in the regional standards. Table 1 shows the up-to-date international and regional standards for EV conductive charging system, and the terminology used is illustrated in Fig 1. The most important international standard for EV charging equipments is IEC 61851 series [1-3], which was published in 2001. Since 2008, there have been several vigorous standardization activities about the EV infrastructures all over the world; the release of SAE J1772: 2010, IEC 61851-1:2010, IEC 62196-1:2011, IEC 62196-2, CHAdeMO, GB/T 20234 and CNS 15511 confirms the efforts.

The most important regional standards for EV charging equipments for America, China and Taiwan are NEC 625 [4]/UL 2202 [5]/ UL 2231 [6, 7]/UL Subject 2594 [8], GB/T 18487 series and CNS 15511 series, respectively. In Japan, the JEVS G101-G105 standards dedicate to EV quick charging stations. The IEC 62196 series is the most important international standard for EV charging connector. The published IEC 62196-2 standardizes the connectors for EV ac charging; while IEC 62196-3, under developing, standardizes the connectors for EV dc charging. The communication protocol IEC 61851-24 is still under developing; the corresponding standards for America, Japan and China are SAE J2847-2, CHAdeMO and GB/T 27930, respectively.

To be part of the players, comprehensive understanding of the standard differences among different regions is essential. Table 2 highlights the similarities and differences in aspects of construction, function, performance and safety related for the requirements of global standards. For all standards, three common aspects about the safety compliance are required for charging equipments. Those are electrical safety, mechanical safety, and environmental safety regarding climatic and electromagnetic compatibility.

For dedicated charging equipments, the electrical safety is the major concern because of high voltage and high current involved. To facilitate as a competent safety design for such charging equipments, this paper then focused on key requirements related with electrical safety.

Table 1: Electric vehicle infrastructure standards—conductive charging

	International/Europe	America	Japan	China	Taiwan
General requirements	IEC/EN 61851-1	NEC 625[a] SAE J1772 UL 2231-1 UL 2231-2	JEVS G109	GB/T 18487.1	CNS 15511-2 CNS 15511-3
Electric vehicle requirements for connection to an EVSE	IEC/EN 61851-21			GB/T 18487.2	CNS 15511-3
AC charger, AC charging station	IEC/EN 61851-22	UL Sub. 2594		GB/T 18487.3	CNS 15511-3
DC charger, DC charging station	IEC 61851-23[b]	UL 2202	JEVS G101 JEVS G103 CHAdeMO	GB/T 18487.3	CNS 15511-3
Communication protocol	IEC 61851-24[b]	SAE J2293-1 SAE J2293-2 SAE J2847-2	CHAdeMO	GB/T 27930	
Plugs, socket-outlets, couplers and cable assembly	IEC/EN 62196-1 IEC 62196-2 IEC 62196-3[b]	SAE J1772 UL 2251	JEVS C 601 JEVS G105	GB/T 20234.1 GB/T 20234.2 GB/T 20234.3	CNS 15511-2 CNS 15511-3

[a]: U.S. National Electrical Code, Article 625: Electric Vehicle Charging System
[b]: not published yet

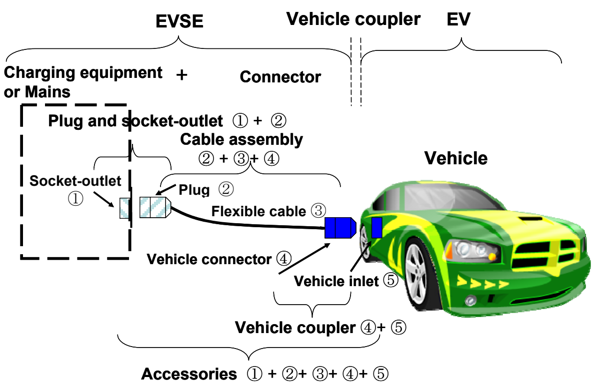


Figure 1: Terminology used in conductive charging system

3 Key Design for Safety Compliance

To meet national or international standards requirements, it is essential to get products through steps of design review, product testing, approval and listing. Learning from key design rules can dramatically reduces design mistakes and expense. For the design of an AC charging stand, as an example, Fig. 2 illustrates the schematic diagram of major units inside the charging equipment associated with detachable or permanently attached cable assembly. In general, there are three modules—power unit, control unit and user interface—inside the charging equipment. The power unit usually includes a power breaker, a proximity detection switch, a magnetic contactor and a leakage current detector. Operation of control unit is based on a digital signal processor (DSP). It provides AC-DC power conversion, communication, digital control, analog control and charging sequence control. The user interface may consist of user/vehicle identification means such as by RFID reader, the display of charging status and fault/warning messages, the means for emergency stop, etc.

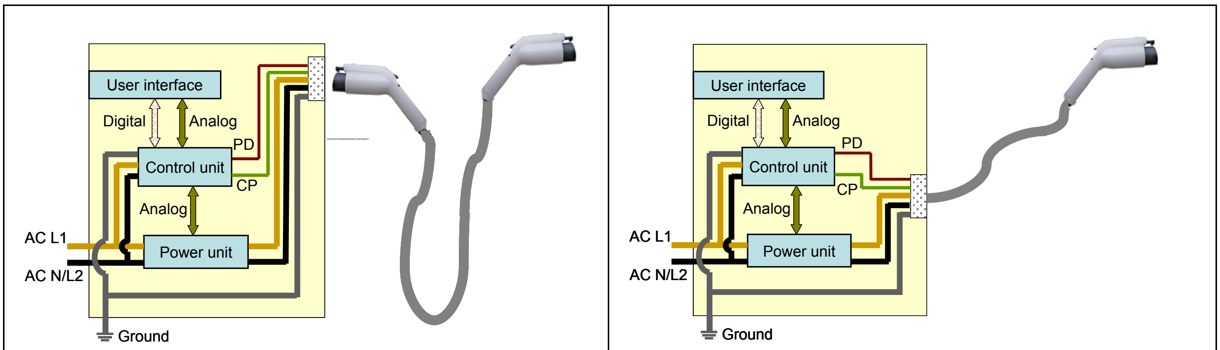
Electric shock hazard, fire hazard and injury hazard are three major concerns for all EV charging system standards. The corresponding design requirements to prevent above-mentioned hazards are also addressed for most of standards. To assure the design of safe charging equipments, complete understanding and compliance of the requirements stated in major standards are vital. These crucial design rules include construction of exterior and interior, personal protection against electric shock, insulation coordination, electromagnetic compatibility, charging control, and the like. Checking exceptions listed in test items are deserved to avoid the unnecessary testing. Besides, interlock or communication between a charging equipment and an EV as well as the automatic de-energization features when charging fault occurs are two promising means to assure charging safety.

Table 2: Overview of the requirements on global standards

O: required; Δ: refer to UL; ×: no requirements

System/subsystem	Requirements	North America		EU	Japan	China
		SAE	UL	IEC	JEVS	GB
Charging equipment (on-board & off-board) JEVS (off-board only)	Construction	NEC[a], Δ	O	O	O	O
	Function	Δ	O	O	O	O
	Performance					
	Electrical	×	×	×	O	×
	Noise	×	×	O(EN[b])	O	×
	Safety					
	Electrical safety	Δ	O	O	O	O
	Protection against electric shock	Δ	O	O	×	O
	Mechanical safety	Δ	O	O	O	O
	Climatic safety	×	×	O	×	O
	EMC	O	O (immunity)	O	O (emission)	O
Connector	Function					
	Physical interface dimension	O	×	O	O	O
	Contacts and its function	O	×	O	O	O
	Communication	O	×	O	O	O
	Safety					
	Electrical safety	Δ	O	O	O	O
	Protection against electric shock	O	O	O	×	×
	Mechanical safety	O	O	O	O	O
	Climatic safety	O	O	O	O	×
Connection of an EV to a charging equipment	Function	O	×	O	×	O
	Safety					
	Electrical safety	O	×	O	×	O
	EMC	O	×	O	×	O

[a]NEC: U.S. National Electrical Code.
[b]EN: European standards.



CP: Control pilot; PD: Proximity detection

(a)

CP: Control pilot; PD: Proximity detection

(b)

Figure 2: Schematic diagram of major units for an AC charging stand: (a) IEC 61851-1 Case "B" connection; (b) IEC 61851-1 Case "C" connection and SAE J1772

For compliance to most of standards, the crucial designs that deserve to pay attention or may fail to meet the requirements are highlighted as follows:

3.1 Functional and constructional requirements

Functional requirements include mandatory and optional functions; the requirements depend on the national codes and standards. It is important to note that there are two functions of an enclosure. One is to protect the user from contact with hazardous circuits or moving parts. The other function is to constrain a fire and not allow the propagation outside the enclosure. As a result, if non-metallic materials are used to form enclosures, they shall meet the requirement of flammability ratings, especially for North America market. Besides, any ventilation openings or seal design in enclosures shall provide an appropriate degree of protection against ingress of solid objects and ingress of water. The accessibility to hazardous parts through ventilation openings is also not permissible.

Specifically, it is important to note that a component that produces arcing or sparking, such as a snap switch, a relay or a receptacle, shall be inherently located at least 457 mm above the floor, according to the requirement of UL 2202 and UL Subject 2594 for North America market. In addition, conductors' size of socket-outlet depends on the severe case of charging voltage and current. Circuit breaker rating of 125% of input is a must to protect units. The other protective measures against overvoltage and overcurrent shall be provided with suitable rating as well.

3.2 Personal protection against electric shock

The basic requirement to protect persons against electric shock is that hazardous live parts shall not be accessible. Moreover, exposed conductive parts shall not become a hazardous live part under operating conditions and under single-fault conditions. To ensure the proper protection of personnel against electric shock both in normal service and in case of a fault, the application of appropriate protection systems is essential. Protection system usually consists of devices or insulation or a combination of both. Insulation is the primary means to guard against the physiological effects of electric shock; protective devices can be a charging circuit interrupting device, a grounding monitor/interrupter, or an isolation monitor/interrupter. Protection system can use either grounded system or isolated system.

In order to eliminate the risk associated with potential loss of ground, the leakage current of a device shall be limited to a level, trip current below 30 mA in IEC standard, which is safe to touch.

3.3 Insulation coordination

Insulation coordination implies the selection of the electric insulation characteristics of the equipment with regard to its application and its surroundings [9]. Basic considerations include voltage, insulating materials, time under voltage stress and degree of pollution in the micro-environment. Clearance, shortest distance in air between two conductive parts [9], shall be dimensioned to withstand the required impulse withstand voltage; creepage distance, shortest distance along the surface of a solid insulating material between two conductive parts [9], shall be dimensioned to withstand the long-term r.m.s. value of the across voltage.

Creepage distances and clearance required between circuits and spacing to metal enclosures are important requirements for insulation coordination. An adequate creepage distance protects against tracking. One of the most common design mistakes stems from designers failing to fully investigate clearance and creepage distances. Thus calculation and measurement of clearance and creepage distances, in accordance with requirements, are one of the significant parts of safety standards.

3.4 Electromagnetic compatibility

Compliance of electromagnetic compatibility (EMC) is a global requirement. Some of the validation conditions in SAE [10]/UL standards, such as immunity to electrostatic discharges, immunity to radiated electromagnetic disturbances and immunity to voltage surges, are severe than IEC standards.

The fundamental EMC issues can be decomposed into three elements as interference source, coupling path through conducted/radiated paths and receiver. Control interference at the source by shield/filter is a preferred approach of EMC design. For instance, using metal or plastic with conductive coating for enclosure can offer a good shielding. In addition, good and robust circuit board layout—component selection, placement,

trace routing, etc.—is most efficient and crucial for EMC control. There are basic EMC guidelines in books or papers, whatever the difficulties, which can be applied to most of systems to minimize the effects of electromagnetic interference and achieve compliance.
In practice, "cause analysis" and "usable measures" are essential to control EMC issues. As an example, failure to comply with requirement for conducted emission of AC input terminal may be solved by attaching a capacitor between line and neutral terminal with or without parallel connection of an inductor. For radiated emission issue, clamping a core at concerned emitted signal cable is proved to work. For failure of immunity to electrostatic discharge (ESD), apply a Mylar at surface of charging equipment will be helpful to protect against ESD. Moreover, adding local filters or shield clamps is another helpful means for EMC control at source or receiver. Both good EMC design and effective countermeasures techniques, whatever the issues, are necessary to provide best EMC control.

3.5 Charging control/communication

The energization and de-energization of charging process shall commence sequentially according to the requirements of each national or international standard. For charging control, control pilot circuit is the primary control means to ensure proper and safe operation when connecting an EV to an EV supply equipment (EVSE). The major functions of control pilot include: (a) verifies the EV presence and connected; (b) permits energization or de-energization; (c) transmits current rating of charging equipment to the EV; (d) monitors the presence of the equipment ground; (e) establishes EV ventilation requirements. Working together with other contacts—earth/ground, proximity detection and power—the control pilot is able to perform functions of (a) to (e) by clear definition of key parameters. Typical control pilot circuit and parameters setting can refer to the related standards for each market [1, 10].
Supply current rating will be determined by duty cycle of control pilot circuit. Note that the overall tolerance (EVSE and EV) of control pilot is within ±2% for interpreting the maximum current to be drawn by vehicle. From steps of confirmation of charging start till terminating the charge process, control pilot plays as a safety guard. Thus the pilot signal shall be monitored continuously during charging process. Once loses pilot signal, the EVSE must terminate the charging process and show the fault condition.

4 Case Study: AC Charging Stand

4.1 Construction review and remedy action

The construction review typically evaluates the proper design and assembly of enclosures, the compliance of flammability requirements of materials, the propriety of internal wiring, and the like. Figure 3 shows the outlook and interior layout of an AC charging stand for this case study. Rated operating voltage is 220 V single phase and rated current is 32 A. The enclosure was consisted of stainless body with one plastic cover in front of the socket-outlet, one top panel for RFID identification and charging status indication, and an emergency stop device. Interior of the enclosure contains circuit breaker, overcurrent protection device, contactor, grounding, PCB, communication circuit board, LED circuit board, AC-DC and DC-DC converters.
Because of the arguments of the front ABS cover and top panel serving as part of the enclosure or decorative parts, one concern was raised as those non-metallic materials can not comply with the 5V flammability class—flammability requirement for enclosures. Although it was finally clarified that top panel was not belong to part of the enclosure, its materials were changed and met the flammability class of 5V. For the ABS cover, since the certification laboratory thought the cover was a decorative part, the materials were also changed to 5V rating.

Figure 3: Outlook and interior layout of AC charging stand

4.2 Safety faults and countermeasures

Based on the standards—follow most IEC and some SAE/UL—for pilot-run project in Taiwan, six major safety faults, feasible countermeasures and validation results of such a case are investigated as follows:

- IP degrees test failed:
  Foam-based gaskets were applied between the maintenance back door and inner panel. During the validation test for IPX4 compliance, the water contained inside the foam penetrated into the interior after saturation. Besides, the interface between top panel and metal enclosure also showed the phenomenon of water leakage. These water leakages were caused by the prototype product being made without mass production tooling. Thus the contact surfaces were not smooth as expected. After careful modification and reinforced seals usage, we achieved the degree of protection by enclosures as IP44.
- Dielectric withstand voltage test failed:
  According to IEC 61851-22, 4 kV dielectric withstand capability, between power circuits and extra low voltage circuits, is required. This requirement, however, is reduced to a less level as $2 \times (U_n + 1.2\ \text{kV})$ and U_n being nominal line to neutral voltage in the latest version of IEC 61851-1. To comply with the initial 4 kV requirements defined in IEC 61851-22, the original AC-DC converter was replaced by a qualified one. Associated with a little modification at the PCB, this test of dielectric withstand eventually passed after tried and tested.
- Creepage distances failed:
  There was one area at one corner of power circuit board that creepage distance is below the requirements. This was solved by increasing the length of one fixing screw. In addition, some of the creepage distances at the backside of power circuit board were at the margin of requirement. In such situation, this study performed glue filling over the backside of circuit board to keep adequate distances among welding points.
- Short circuit test failed:
  The protective device against overcurrent was failed under the condition of short-circuit test currents. A certified fuse was adopted as supplementary overcurrent protection instead of a circuit breaker alone.
- Mechanical impact test failed:
  The study used impact energy of 20 J, as specified in IEC 61851-22, to perform the mechanical impact test; the original non-metallic ABS front cover and top panel were damaged after test. If we adopting impact energy around 6.4 J as specified in the IEC 61851-1:2010, these two non-metallic parts may pass the test. Design modification with flammability rating 5V material at both parts as well as reinforced steel frames below the top panel were implemented. Following that, both parts were survived very well after 20 J impact.
- High frequency conducted disturbances and radiated electromagnetic disturbances test failed:
  The AC charging stand and a vehicle charging simulator were tested together as a unit for EMC compliance. As shown in Fig. 4, when operating with a resistive load at 6 A, conducted emission below 0.8 MHz at AC input terminal line 2 already exceeded the quasi-peak limits specified in IEC 61851-22. Moreover, radiated electromagnetic disturbances at 10 m were also beyond the limits 1.6 dB (μV/m) at 50 MHz under vertical polarization condition.
  To comply with the requirements of radiated electromagnetic disturbances, this study first tried to append a ferrite core around the line input. There was, however, no prominent improvement for the modified one. The simulator then was tested alone to separate the potential causes. The test results found that the simulator was the major source of emission problem. Since this simulator was not part of charging stand, after deducted the effect of simulator, both EMC requirements of radiated and high frequency conducted disturbances were satisfied for AC charging stand itself. Figure 5 shows the test results of high frequency conducted disturbances when operating with a resistive load at 32 A and deducting the influence of simulator. From this practice, it implies that the radiated or conducted emission of the simulator should be further controlled. Although the simulator is not part of AC charging stand, it is a must to start the charging process for validation tests.

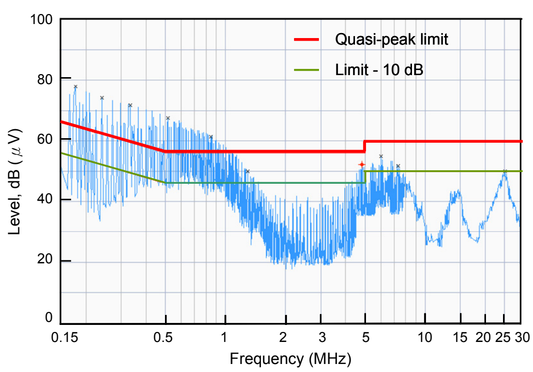


Figure 4: Conducted emission at AC input terminal line 2, operating with 6 A load

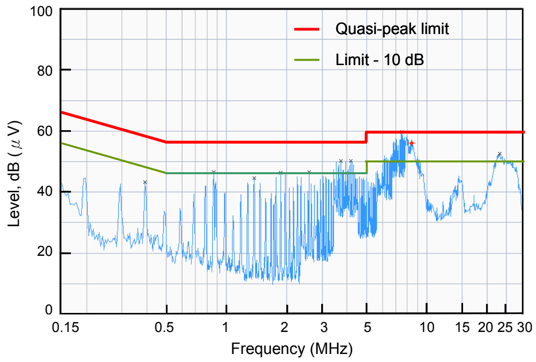


Figure 5: Conducted emission at AC input terminal line 2, operating with 32 A load and deducting the influence of simulator

5 Conclusions

Valid certifications of electric vehicle charging system are critical to penetrate and sell products in the global markets. It is essential to familiarize the related test standards and implement them into the design for each targeting market. Based on comparisons among the global standards, we summarize an overview in aspects of construction, function, performance and safety for charging equipment. To meet the criteria defined by the major standards, this study establishes key design guidelines for safety compliance. As a result, launch of a certified product in short development time can be under control.

A case study of an AC charging stand illustrates the safety faults and countermeasures during a new product certification. Such remedy actions can also apply to DC fast charging equipments if there are similar issues. With these design guidelines and the case study, this paper provides a solid safety design foundation for electric vehicle charging equipment.

Acknowledgments

The authors gratefully acknowledge the financial assistance of this project by the Industrial Development Bureau, Ministry of Economic Affairs.

References

[1] *IEC 61851-1, Electric vehicle conductive charging system – Part 1: General requirements*, ISBN 978-2-88912-222-6, Geneva, IEC Central Office, 2010

[2] *IEC 61851-21, Electric vehicle conductive charging system – Part 21: Electric vehicle requirements for conductive connection to an a.c./d.c. supply*, ISBN 2-8318-5733-3, Geneva, IEC Central Office, 2001

[3] *IEC 61851-22, Electric vehicle conductive charging system – Part 22: a.c. electric vehicle charging station*, ISBN 2-8318-5735-X, Geneva, IEC Central Office, 2001

[4] *National Electrical Code 2011 Handbook*, ISBN-13: 978-0877659167, Quincy, Massachusetts, National Fire Protection Association, 2011

[5] *UL 2202, Electric Vehicle (EV) Charging System Equipment*, ISBN 0-7629-0362-7, Northbrook, Illinois, Underwriters Laboratories Inc, 2006

[6] *UL 2231-1, Personnel Protection Systems for EV Supply Circuits: General Requirements*, ISBN 0-7629-0769-X, Northbrook, Illinois, Underwriters Laboratories Inc, 2002

[7] *UL 2231-2, Personnel Protection Systems for EV Supply Circuits: Particular Requirements for Protection Devices for Use in Charging Systems*, ISBN 0-7629-0770-3, Northbrook, Illinois, Underwriters Laboratories Inc, 2002

[8] *UL Subject 2594, Outline of Investigation for Electric Vehicle Supply Equipment, Issue Number:1*, Northbrook, Illinois, Underwriters Laboratories Inc, 2009

[9] *IEC 60664-1, Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests*, ISBN 2-8318-9137-X, Geneva, IEC Central Office, 2007

[10] *SAE J1772, Electric Vehicle and Plug-in Hybrid Electric Vehicle Conductive Charge Coupler*, Warrendale, Pennsylvania, SAE International, 2010

Authors

Ming-Hung Lu is a researcher at Industrial Technology Research Institute, Taiwan. He earned his B.S. and M.S. degrees in Mech. Eng. from the National Chiao-Tung Univ. in Taiwan. His research areas include the safety of charging system, NVH development for EV, motor, engine and conventional engine vehicle.

Dr. Ming Une Jen is a senior researcher at Industrial Technology Research Institute, Taiwan. Dr. Jen received her Ph.D. degree in Mech. Eng. from the Univ. of Maryland. Her research areas include vehicle NVH engineering, EV infrastructures and chassis engineering. Dr. Jen has published over 50 technical papers concerning her research.