Artvin Çoruh Üniversitesi
Mühendislik ve Fen Bilimleri Dergisi
Cilt:2 No:1, 2024 (50-79)

Artvin Coruh University
Journal of Engineering and Sciences
Vol:2 No:1, 2024 (50-79)

Review Article / Derleme Makale

Review of the Charging System and Communication Protocols of the Electric Vehicles

Mehmet Burak ARSLAN[1], Şaban ÖZDEMİR[2*]

[1] Department of Electrical & Electronics Engineering, Graduate School of Natural and Applied Sciences, Gazi University, 06500, Ankara, TÜRKİYE
[2] Deptartment of Electrical &Electronics Engineering, Faculty of Technology, Gazi University, 06500, Ankara, TÜRKİYE
mburak.arslan@gazi.edu.tr, sabanozdemir@gazi.edu.tr

Received/Geliş Tarihi: 20.12.2023 **Accepted/Kabul Tarihi:** 08.03.2024

Abstract: Today, factors like global warming, climate change have heightened environmental awareness. Consequently, the demand for electric vehicles is steadily rising due to considerations such as environmental impact, economic factors. In this regard, it is estimated that 125 million electric vehicles will be on the roads worldwide by 2030. The primary reason for the lag in electric vehicle technology is that the technology in this field has not yet reached a sufficient level. Especially in battery technology, factors such as power density, safety and charging time have affected this situation. Additionally, a common charging and communication standard has yet to be developed. Furthermore, there is no a standard for medium voltage and megawatt class charging system. In this study, international standards used for charging systems of electric vehicles were studied. Commonly used charging standards are divided into three subdivisions: wired, wireless and battery replacement. Also, charging standards such as CHAdeMO, GB/T, US -COMBO CSS1, EURO-COMBO CSS2, TESLA and Chaoji are studied. These standards categorized in terms of maximum power they provide, connector type, and communication protocols. Hence, the general characteristics of the standards, their electrical capabilities, connection types, communication protocol structures, and the general structures of these communication standards are introduced.

Keywords: Battery, CAN-Bus, Charging systems, Electric vehicle, Power line communication

Elektrikli Araç Şarj ve Haberleşme Protokollerinin Gözden Geçirilmesi

Özet: Günümüzde küresel ısınma ve iklim değişikliği gibi etkenler çevresel farkındalığı artırmıştır. Buna istinaden çevresel, ekonomik ve kaynak kıtlığı gibi sebeplere bağlı olarak elektrikli araçlara olan talep her geçen gün artmaktadır. Bu doğrultuda dünya genelinde 2030'lara kadar 125 milyon elektrikli aracın yollarda olacağı tahmin edilmektedir. Elektrikli araç teknolojisinin şu ana kadar petrol kaynaklı yakıt tüketen araçlara göre geride kalmasının ana nedeni, bu alandaki teknolojinin henüz yeterli seviyeye ulaşamamasıdır. Özellikle batarya teknolojisinde güç yoğunluğu, güvenlik ve şarj süresi gibi etkenler bu durumu daha çok etkilemiştir. Ayrıca tüm elektrikli araçlar tarafından kullanılan ortak bir şarj ve haberleşme protokolü henüz kabul görmemiştir. Dahası orta gerilimden ve megawatt sınıfında şarj konusunda henüz bir standart dahi bulunmamaktadır. Bu doğrultuda batarya ve şarj sistemleri devamlı gelişmektedir. Bu çalışmada elektrikli araçların şarj sistemleri için kullanılan ulusal ve uluslararası standartlar incelenerek karşılaştırma yapılmıştır. Yaygın olarak kullanılan şarj standartları kablolu, kablosuz ve batarya değişimi olarak üçe ayrılmaktadır. CHAdeMO, GB/T, US -COMBO CSS1, EURO-COMBO CSS2, TESLA ve Chaoji gibi güncel kablolu şarj standartları incelenmiştir. Böylece, elektrikli araç şarj sistemlerinde kullanılan standartların genel özellikleri, elektriksel kabiliyetleri, bağlantı tipleri, haberleşme protokolü yapıları, hangi standardın hangi haberleşme protokolünü kullandığı ve bu haberleşme standartlarının genel yapıları incelenmiştir.

Anahtar Kelimeler: Batarya, CAN-bus, Elektrikli araç, Güç hattı haberleşmesi, Şarj sistemleri

1. Introduction

The first electric vehicle model was developed by Professor Stratingh in Netherlands in 1835 (Ünlü et al., 2003). Robert Davidson produced an electric locomotive that could reach a speed of 6,4 km/h

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**: Sorumlu Yazar (Corresponding Author)* in 1838 (Chan, 2012). In 1882, Siemens produced the world's first electric trolleybus which is called as Elektromote, in Berlin. This vehicle had two 2,2 kW engines, was powered by 550 VDC, and could reach an average speed of 12 km/h (Singh, 2013). These studies continued until the 1920s, but there was a stagnant period for electric vehicle studies between 1925 and 1960, and development activities in this regard were carried out less frequently between these years (Sayin and Yüksel, 2011).

In the 1980s, governments began to provide economic support from official sources to increase the interest in electric vehicles due to their environmental friendliness (Kerem, 2014). Many electric vehicle models such as Ford - Think City, Nissan - Altra EV and Peugeot 106 - Electric were launched by manufacturers with newly developed battery technologies after 1990 (Ünlü et al., 2003).

Despite its limited technical capacity, the General Motors EV1 became the first mass-produced electric vehicle with a range of up to 169 km. Initially, 1,117 units of this vehicle were produced, primarily due to sales conditions (Ekici et al., 2021). In 2008, Tesla produced a significant number of its first electric vehicle, the Tesla Roadster, which featured Lithium-Ion (Li-ion) batteries and had an approximate range of 320 km on a single charge. The Roadster was initially introduced in 2006 (Chan, 2012). Such studies and similar efforts have continued to increase up to the present day. According to a report on electric cars by the International Energy Agency (IEA), an intergovernmental organization providing data, analysis, and policy recommendations on the global energy sector, as of 2023, there are currently 16,5 million electric vehicles on roads worldwide.

In electric vehicles, there are generally components such as the electric motor, battery pack, inverters/converters, regenerative braking system, vehicle body, cooling liquids, lubrication system, wiring harness, necessary equipment for electronic control modules, sensors, and other similar components. By integrating software into some of these components, structures such as the electronic control module, intelligent battery management system, and smart charging system are activated. Electric vehicles, operating as a whole with such hardware and software, distribute the generated electrical energy to the propulsion systems and control systems through powertrain systems, enabling them to function. Electric vehicles enable system control through communication protocols such as inter-system CAN-Bus, Power-line Communication (PLC), Ethernet, guided by the vehicle computer's directives. The general topology of the structures studied in the research is shown in Figure 1.

In order to ensure the portability of electric vehicles, batteries must be rechargeable. In this case, there is a need for charging stations to shorten the charging times. Charging process generally involves the following steps in sequence: initiating the charging process, performing charge balancing near completion, and concluding the charging process (Ekici et al., 2021). Electric vehicle charging can be broadly categorized into three main methods: wired charging, wireless charging, and battery swapping (Rachid et al., 2022). In the literature, for the wired charging system, two different methods are commonly used: alternating current (AC) and direct current (DC). For wireless charging systems, the fixed frequency method is typically employed (Ekici et al., 2021). In this paper, electric vehicle charging methods were generally examined under the headings of wireless and wired charging systems. Additionally, communication protocols used in wired charging systems, such as CAN-Bus and PLC, were also investigated.

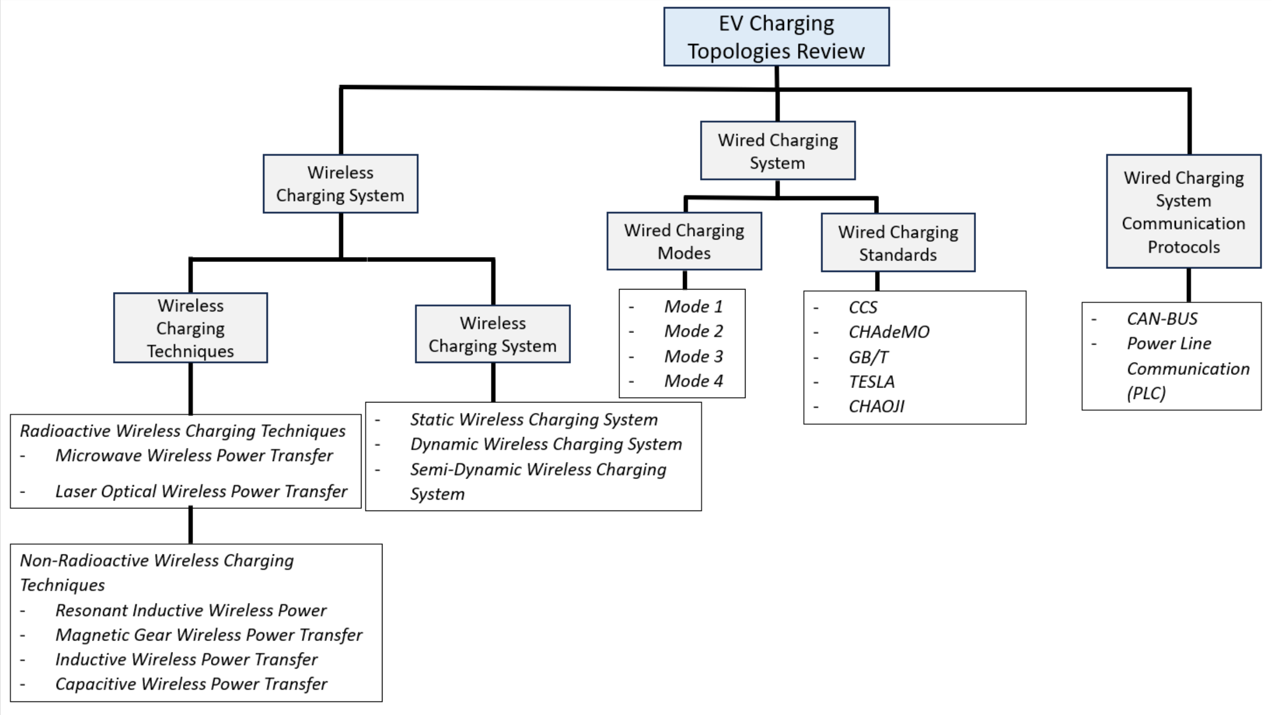


Figure 1. Classification of EV charging topologies review

In this study, international standards used for EV charging systems were studied. Also, these standards categorized in terms of maximum power they provide, connector type, and communication protocols. Hence, the general characteristics of the standards used in electric vehicle charging systems, their electrical capabilities, connection types, communication protocol structures, and the general structures of these communication standards are introduced. In this study, international standards used for EV charging systems were studied. Also, these standards categorized in terms of maximum power they provide, connector type, and communication protocols. Hence, the general characteristics of the standards used in electric vehicle charging systems, their electrical capabilities, connection types, communication protocol structures, and the general structures of these communication standards are introduced.

2. Wireless Charging System

Research and development efforts continue on the wireless charging of electric vehicles, driven by reasons such as safety, comfort, convenience, and environmental cleanliness. As electric vehicles become more widespread, the use of wireless charging has become increasingly popular. During this period, there has been and continues to be more research and development work on wireless charging technology (Musavi & Eberle, 2014). The currently used wireless charging techniques include Microwave Wireless Power Transfer, Laser Optical Wireless Power Transfer, Inductive Wireless Power Transfer, Capacitive Wireless Power Transfer, Resonant Inductive Wireless Power Transfer, and Magnetic Gear Wireless Power Transfer (Manivannan et al., 2023).

2.1. *Fundamental Principles of Wireless Charging*

The principles of wireless charging technology are based on Faraday's laws of electromagnetic induction and Ampere's laws (Manivannan et al., 2023). Wireless power transfer contains receiver-transmitter coils, AC/DC high frequency (HF) converters, compensation elements to use in the power transmission process between the source and the load. These components enable power transfer without the need for a physical connection. The basic diagram for wireless charging of electric vehicles is illustrated in Figure 2. The receiver and transmitter coils used in wireless communication are referred to as charging pads. The transmitter coil is connected to the source coming from the grid. The receiver coil is connected to the battery management system of the electric vehicle to which the load is attached.

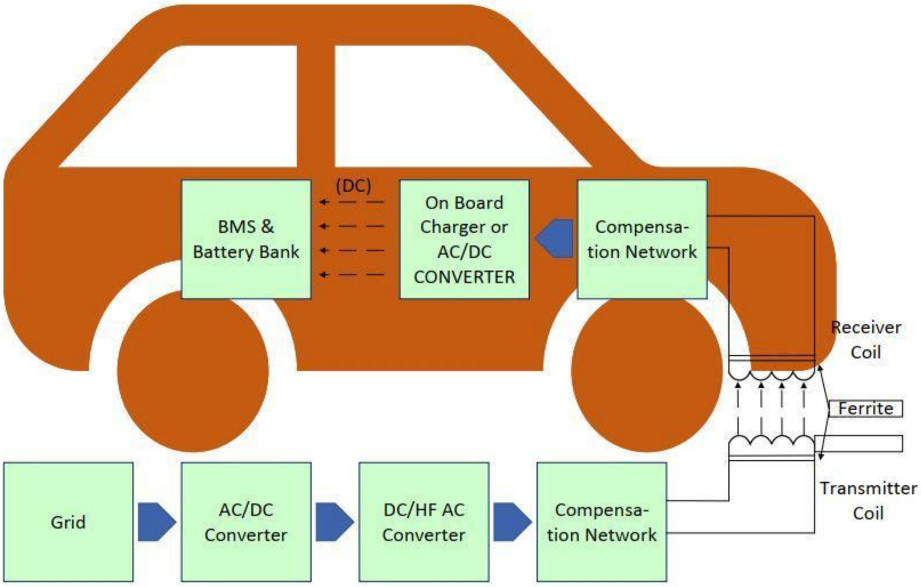


Figure 2. Basic block diagram of wireless charging for electric vehicles

To facilitate power transfer from the transmitter coil to the receiver coil, the power from the grid is converted to high-frequency AC through AC/AC, AC/DC, and DC/AC converters. To enhance the overall efficiency of the system, both the receiver and transmitter sides employ series and parallel structures based on compensation topology. The receiver coil, typically mounted under the vehicle, converts oscillating magnetic flux fields into high-frequency alternating current. Subsequently, the direct current used by the built-in charging device is obtained by converting the high-frequency AC. Power control, communication, and battery management system structures are utilized within the system to ensure healthy and reliable power transfer. Magnetic planar ferrite plates are used on both the transmitter and receiver sides to reduce any kind of harmful leakage current and improve magnetic flux distribution (Panchal et al., 2018).

2.2. *Wireless Charging Techniques*

Wireless charging techniques are fundamentally divided into Radioactive and Non-radioactive methods. Radioactive methods are often used when the distance between the transmitter and receiver is more substantial. Within radioactive methods, there are Microwave Wireless Power Transfer and Laser Optical Wireless Power Transfer. Non-radioactive methods are further categorized into Resonant Inductive Wireless Power Transfer and Magnetic Gear Wireless Power Transfer for medium distances, and Inductive Wireless Power Transfer and Capacitive Wireless Power Transfer for short distances (Manivannan et al., 2023). The summary of wireless charging techniques shown in Table 1.

It is divided in two categories as radioactive wireless charging techniques and non-radioactive wireless charging techniques. Due to their power capacity, EVs subject to non-radioactive wireless charging techniques.

Table 1. The summary of wireless charging techniques

Wireless Charging Techniques
Radioactive Wireless Charging Techniques - Microwave Wireless Power Transfer - Laser Optical Wireless Power Transfer
Non-radioactive Wireless Charging Techniques - Magnetic Gear Wireless Power Transfer - Capacitive Wireless Power Transfer - Inductive Wireless Power Transfer

2.2.1. Microwave Wireless Power Transfer

The electrical energy from the source is converted into microwave energy and transmitted from the transmitting antenna to the receiving antenna for long distances. The microwave energy received by the receiving antenna is then converted back into electrical energy at the target. The frequency range of electromagnetic radio waves can be adjusted to a value between 1 GHz and 1000 GHz (Hu et al., 2021). From the standpoint of using Microwave Wireless Power Transfer, there should be no obstacles between the receiver and transmitter. This topology is considered harmful to human health and the environment due to the risk of radioactive emissions. Considering these potential harms to humans and the environment, this topology is not yet commercially utilized (Ahmed et al., 2020).

2.2.2. Laser Optical Wireless Power Transfer

In Laser Optical Wireless Power Transfer, power is transmitted from the transmitter to the receiver using laser beams. On the transmitter side, electrical energy is converted into a laser beam through a laser diode. A laser beam director is used to adjust the direction of the laser beam (Mahesh et al., 2021). On the receiver side, a solar panel and a rectifier are used. The laser beam sent from the transmitter first reaches the solar panel, where the light energy is separated from the laser beams. Subsequently, the rectifier converts this energy into direct current and delivers it to the battery (Hongzuo et al., 2021). Laser Optical Wireless Power Transfer technique also requires an unobstructed line of sight between the receiver and transmitter for effective use. However, this topology is considered harmful to human health and the environment due to the risk of radioactive emissions. Due to these potential risks to humans and the environment, this topology is not yet commercially utilized (Ahmed et al., 2020).

2.2.3. Magnetic Gear Wireless Power Transfer

The schematic diagram for the Magnetic Gear Wireless Power Transfer technique is presented in Figure 3, as indicated by (Panchal et al., 2018). As evident from Figure 3, the Magnetic Gear Wireless Power Transfer technique differs structurally from both Inductive Wireless Power Transfer Techniques and Capacitive Wireless Power Transfer Techniques. In this method, two synchronized permanent magnets are positioned side by side, in contrast to other coaxial cable-based charging techniques. The main power serves as the current source, applied to the transmitter winding to generate mechanical torque in the primary magnet. By utilizing mechanical torque, the primary magnet rotates and, through mechanical interaction, generates torque on the secondary magnet. The primary magnet operates in a transmitter-producer mode, while the secondary magnet receives the power and transfers it to the battery via power converters and the battery management system (Panchal et al., 2018) . The receiver executes the steps of converting mechanical energy to electrical energy, rectification, and charging the battery in three stages (Qiu et al., 2013).

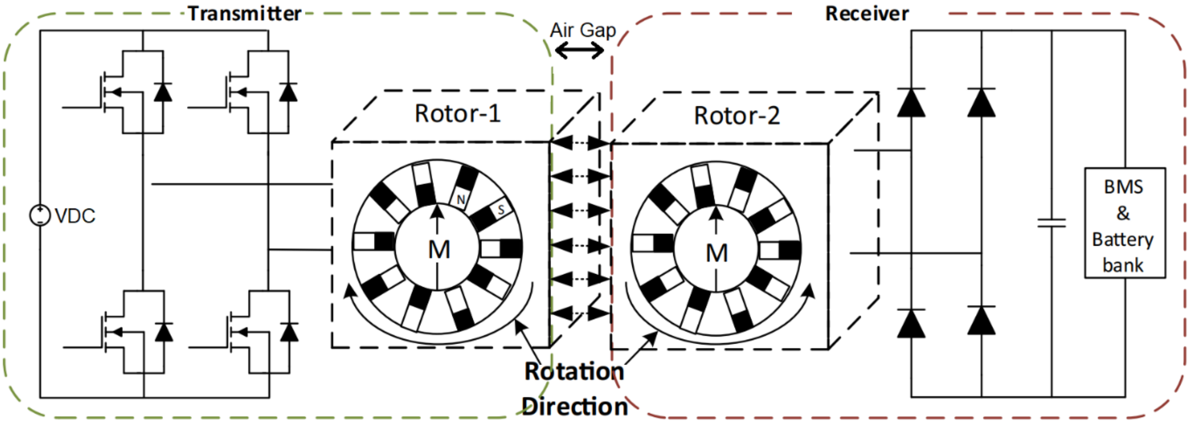


Figure 3. The schematic diagram of Magnetic Gear Power Transfer technique (Panchal et al., 2018)

2.2.4. Inductive Wireless Power Transfer

The schematic diagram of the Inductive Wireless Power Transfer technique is shown in Figure 4. In this technique, power transfer is achieved through mutual induction (L. Zhang et al., 2021). In this method, two separate coils, namely transmitter and receiver coils, are used. The distance between the coils directly affects the system efficiency (Jeon and Seo, 2022). The coil on the transmitter side is connected to the charging station, while the coil on the receiver side is connected to the vehicle. Bridge structures with MOSFETs are used on both the receiver and transmitter sides for power conversions (Grbovic, 2013).

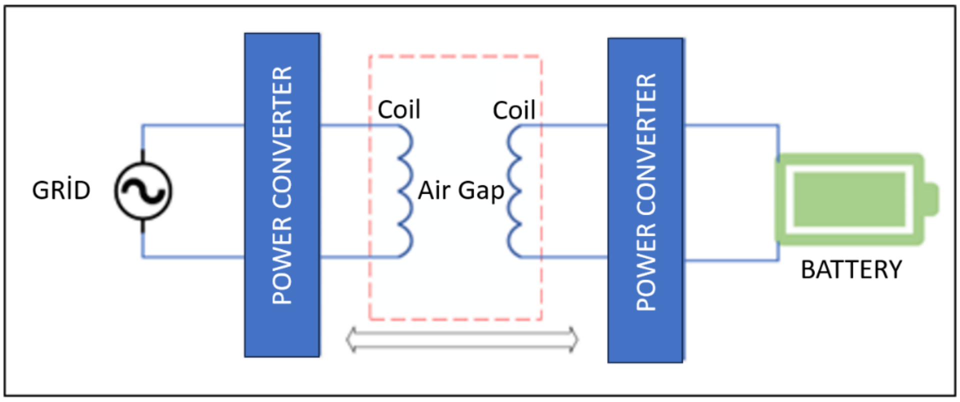


Figure 4. The schematic diagram of the inductive wireless power transfer technique

The Resonant Inductive Wireless Power Transfer technique is an advanced version of the common traditional Inductive Wireless Power Transfer method, primarily used in power electronics and for wireless power transfer with transformer coils (Panchal et al., 2018). In this technique, similar to other wireless power transfer methods, it converts the received voltage from the grid into high-frequency alternating current. The power transmitted from the transmitter coil to the receiver coil through the air is then converted to direct current on the receiver side. To enhance impedance matching between the coils, different series/parallel combinations of capacitors and inductors are connected together or separately (Mahesh et al., 2021). The schematic diagram for the Resonant Inductive Wireless Power Transfer technique is illustrated in Figure 5 (Panchal et al., 2018). In fact, this method is a method to reduce inverter losses and is similar to inductive power transfer.

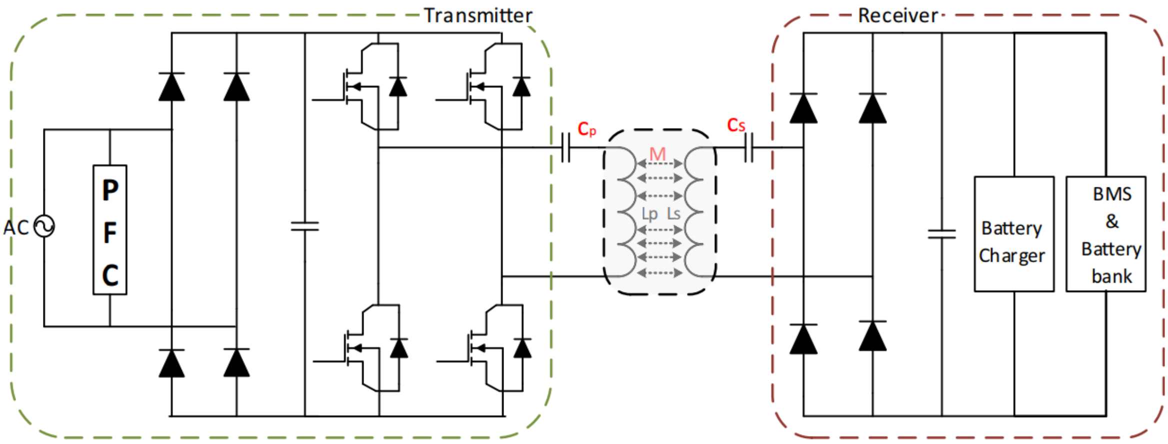


Figure 5. The schematic diagram for Resonant Inductive Wireless Power Transfer technique (Panchal et al., 2018)

2.2.5. *Capacitive Wireless Power Transfer*

The schematic diagram for Capacitive Wireless Power Transfer technique is illustrated in Figure 6. In this method, a pair of compact metallic plates creates an electric field between the receiver and transmitter charging pads, facilitating power transfer (Yang et al., 2021). In this technique, after power conversion and compensation processes from a high-frequency AC power source, wireless power transfer and charging are achieved through a capacitive intermediary consisting of copper-coated panels and aluminum plates (Huang and Hu, 2015).

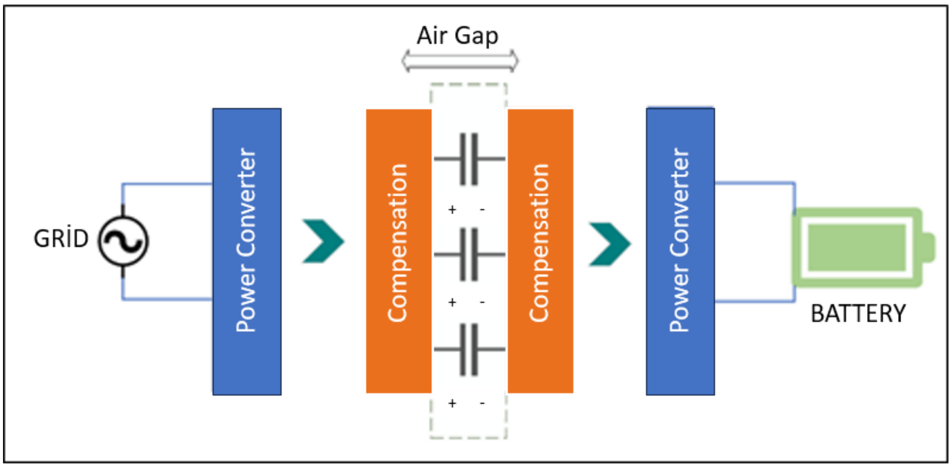


Figure 6. Technique of Capacitive Wireless Power Transfer

2.3. *Type of Wireless Charging Systems*

Wireless charging systems are divided into three categories: Static Wireless Charging System, Dynamic Wireless Charging System, and Semi-Dynamic Wireless Charging System (Machura et al., 2020). These systems are developed to enable charging when the vehicle is stationary or in motion. The summary of wireless charging systems is shown in Table 2.

Table 2. Type of Wireless charging systems

Wireless Charging Systems
- Static Wireless Charging System - Dynamic Wireless Charging System - Semi-Dynamic Wireless Charging System

2.3.1. Static Wireless Charging System

Vehicles and the charging station are stationary in Static Wireless Charging Systems. The transmitter coil is mounted under the road or ground with additional power converters and circuits. The receiver coil is installed on the underside of electric vehicles, either in the front, rear, or center (Panchal et al., 2018). The power from the transmitter is converted into a suitable form according to the wireless charging technique used and the charging process is carried out under the control of the battery management system. An example visual for the Static Wireless Charging System is shown in Figure7. The charging time varies depending on the battery capacity and the distance of the air gap between the receiver and transmitter. In passenger vehicles, this distance typically ranges from 150 to 300 mm (Klontz et al., 1993). Static wireless electric vehicle charging systems can be installed in homes, parking lots, shopping centers, and parking areas.

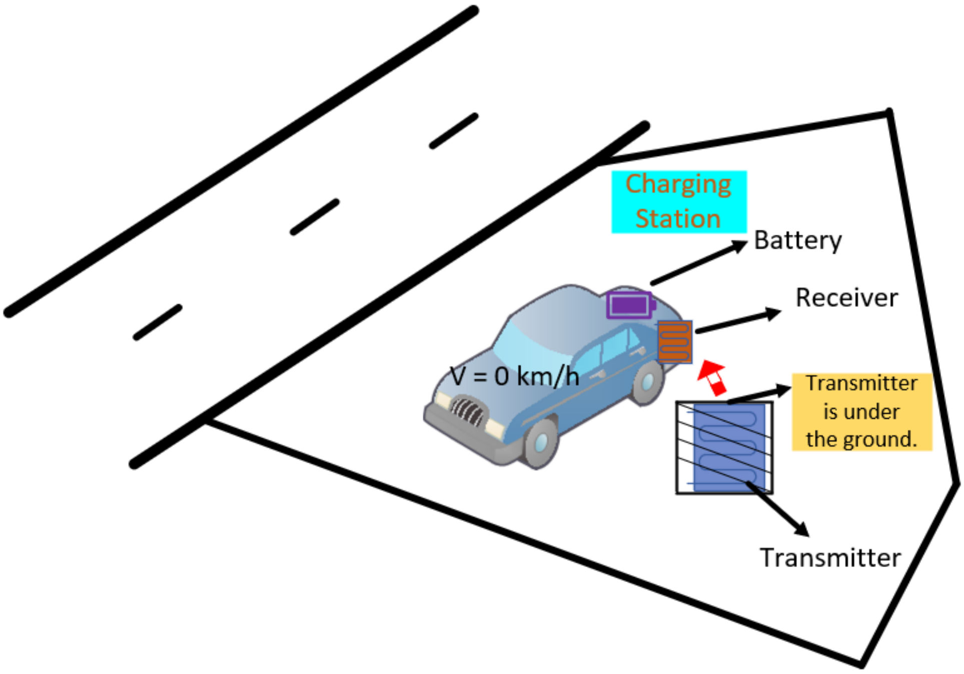


Figure 7. Static wireless charging system

2.3.2. Dynamic Wireless Charging System

Considering the stationary nature of the Static Wireless Charging System and the criteria of pause and charging time, manufacturers have begun to focus on developing the Dynamic Wireless Charging System to prevent time loss (Shanmugam et al., 2022).

An example visual for the Dynamic Wireless Charging System is shared in Figure-8. In the Dynamic Wireless Charging System, the charging process continues while vehicles are in motion. The widespread adoption and improvement of the Dynamic Wireless Charging System can reduce the need for large-scale integrated battery capacity, potentially increasing driving range and thereby reducing the weight and charging costs of the vehicle (Kalwar et al., 2018).

The transmitter coils are embedded beneath the road at a specific distance, connected to the grid with a high-frequency alternating current source and compensation circuits. The receiver coil is attached to the underside of electric vehicles, either in the front, rear, or center. When electric vehicles pass over the transmitter, the receiver coil captures power from the magnetic field it generates and converts it into direct current. The battery is then charged under the control of the battery management system. The Dynamic Wireless Charging System, when considering existing electric vehicles, reduces the total battery requirements by approximately 20% (Musavi et al., 2012).

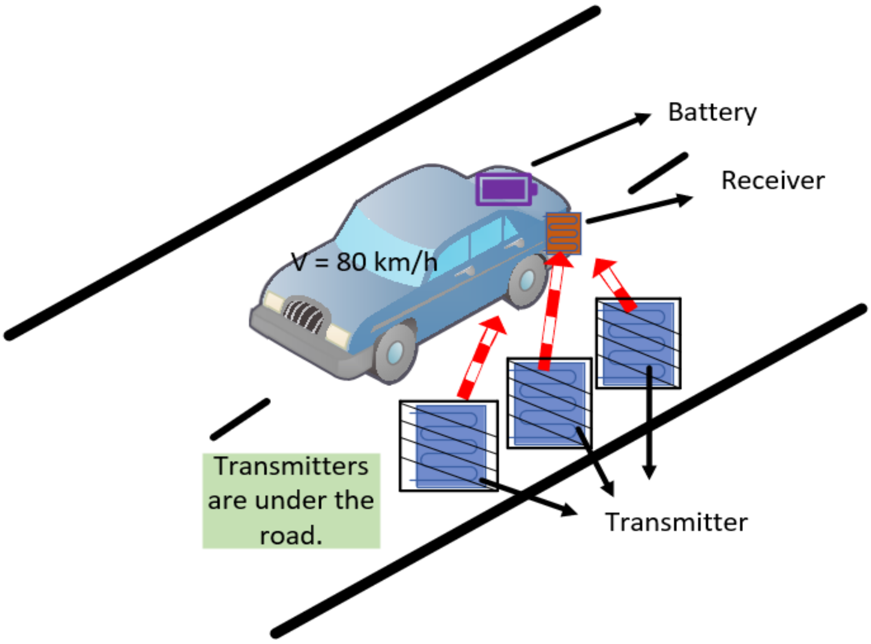


Figure 8. Dynamic wireless charging system

2.3.3. Semi-Dynamic Wireless Charging System

While the Dynamic Wireless Charging System is most suitable for highways, for urban environments, the Semi-Dynamic Wireless Charging System, which is a hybrid of Static and Dynamic systems, is more appropriate (Mohamed et al., 2017).

This system, which combines the advantages of both Static and Dynamic Wireless Charging Systems, provides relief for manufacturers in terms of massive installation costs. While electric vehicles are charged with Dynamic Wireless Charging in specific areas of the roads, the Charging During Breaks concept allows vehicles to charge when they come to a stop at traffic lights, buses at stops, taxis at stands, and similar stopping areas. This method is employed in various stopping locations (B. Zhang et al., 2021).

2.4. *Standards of Wireless Charging*

International Electrotechnical Commission (IEC), Underwriters Laboratories (UL) and similar organizations have published standards for wireless charging of electric vehicles, some of which are shown in Table 3. The most accepted ones IEC and UL standards are originated in Europe and USA, respectively. Although these two standards are accepted worldwide, countries publish their own standards based on these standards. These standards cover aspects related to wireless charging structures, safety measures, use cases, connection structures, charging protocols, and similar specifications.

Table 3. Standards of wireless charging

Organization	Standard Code	Standard Description
International Electro-mechanical Commission (IEC)	IEC 63245-1 (IEC 63245-1:2021, 2021)	Spatial wireless power transfer based on multiple magnetic resonances - Part 1: Requirements / IEC 63245-1:2021 specifies requirements for spatial wireless power transfer based on multiple magnetic resonances (SWPT-MMR), which is a non-radiative wireless power transfer (WPT).
International Electro-mechanical Commission (IEC)	IEC/IEEE 62704-2 (IEC/IEEE 62704-2:2017, 2017)	Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz - Part 2: Specific requirements for finite difference time domain (FDTD) modelling of exposure from vehicle mounted antennas / IEC/IEEE 62704-2:2017 establishes the concepts, techniques, validation procedures, uncertainties and limitations of the finite difference time domain technique (FDTD) when used for determining the peak spatial-average and whole-body average specific absorption rate (SAR) in a standardized human anatomical model exposed to the electromagnetic field emitted by vehicle mounted antennas in the frequency range from 30 MHz to 1 GHz, which covers typical high power mobile radio products and applications.
Underwriters Laboratories Inc.(UL) International Organization for Standardization (ISO)	ISO 15118-1 (ISO 15118-1:2019, 2019)	Road vehicles - Vehicle to grid communication interface - Part 1: General information and use case definition / ISO 15118-1:2019 This document, as a basis for the other parts of the ISO 15118 series, specifies terms and definitions, general requirements and use cases for conductive and wireless HLC between the EVCC and the SECC.
Underwriters Laboratories Inc.(UL) International Organization for Standardization (ISO)	ISO 15118-8 (ISO 15118-8:2020, 2020)	Road vehicles - Vehicle to grid communication interface - Part 8: Physical layer and data link layer requirements for wireless communication / This document specifies the requirements of the physical and data link layer of a wireless High Level Communication (HLC) between Electric Vehicles (EV) and the Electric Vehicle Supply Equipment (EVSE).
Underwriters Laboratories Inc.(UL) International Organization for Standardization (ISO)	ISO 15118-9 (ISO 15118-9:2022, 2022)	Road vehicles - Vehicle to grid communication interface - Part 9: Physical and data link layer conformance test for wireless communication / ISO 15118-9:2022 This document specifies conformance tests in the form of an abstract test suite (ATS) for a system under test (SUT) implementing an electric-vehicle or supply-equipment communication controller (EVCC or SECC) with support for WLAN-based high-level communication (HLC) according to ISO 15118-8 and against the background of ISO 15118-1.
Underwriters Laboratories Inc.(UL) International Organization for Standardization (ISO)	ISO 15118-20 (ISO 15118-20:2022, 2022)	Road vehicles - Vehicle to grid communication interface - Part 20: Network and application protocol requirements / ISO 15118-20:2022 This document specifies the communication between the electric vehicle (EV), including battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV), and the electric vehicle supply equipment (EVSE). The application layer messages defined in this document are designed to support the electricity power transfer between an EV and an EVSE.
Society for Automobile Engineers (SAE)	J2954-202010 (SAE J2954-202010, 2020)	Wireless Power Transfer for Light-Duty Plug-In EVs and Alignment Methodology / The SAE J2954 standard establishes an industry-wide specification that defines acceptable criteria for interoperability, electromagnetic compatibility, EMF, minimum performance, safety, and testing for wireless power transfer (WPT) of light-duty plug-in electric vehicles.
Japan Electric Vehicle Association JEVS	G106 (JEVS G106-2000, 2000)	EV inductive charging system: General requirements
Institute of Electrical and Electronic Engineers (IEEE)	IEEE C95.1-2019 (IEEE C95.1-2019, 2019)	IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz

The choice and application of the standard are contingent upon the specific country mandating it and the particular segment of the charging infrastructure it pertains to, encompassing communication protocols, dispenser specifications, cable standards, power electronic equipment guidelines, as well as fire and security protocols.

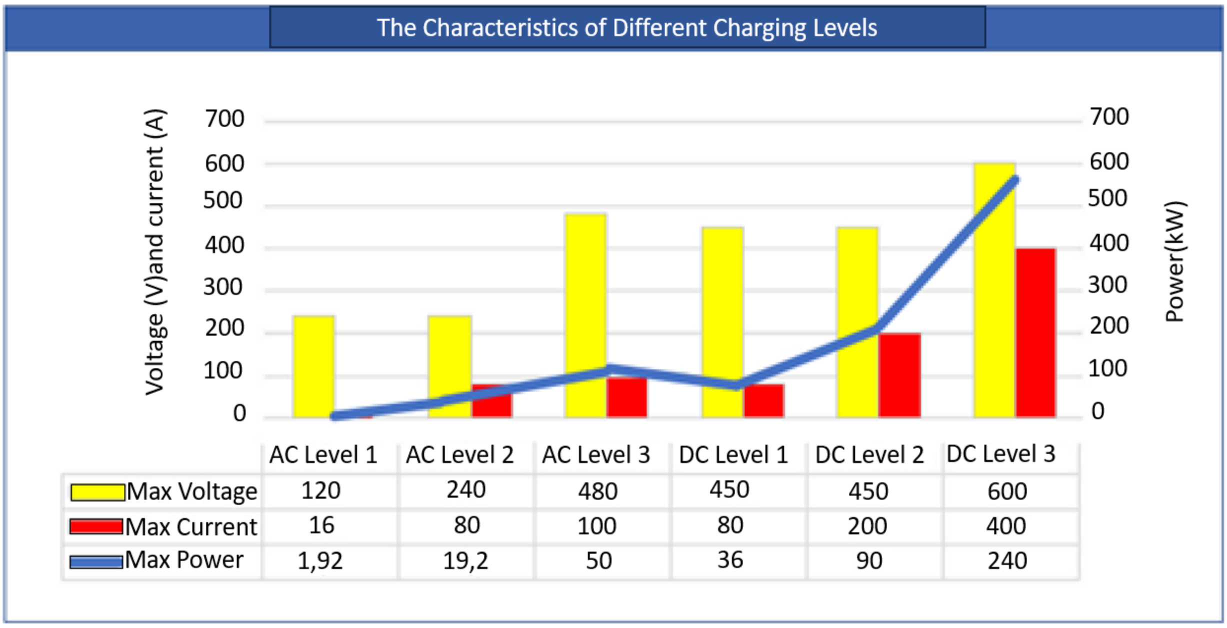
3. Wired Charging System

In a wired charging system, energy from the grid is transported through cables, and compatible connector structures connect the charging device to the electric vehicle. Through this connection, the energy from the charging device charges the electric vehicle battery. Wired charging structure is used in plug-in hybrid vehicles and fully electric vehicles. Wired charging applications can be implemented in public spaces such as homes, parking lots, and charging stations.

Two compatible connectors are required for the charging process in wired charging applications. The needed power is obtained from a standard electrical outlet or a public charging station and transferred to the electric vehicle via a cable. The most significant disadvantage of this application is that the user has to carry and plug in the cable. Any disconnection or malfunction in the cable can lead to undesired consequences (Unal et al., 2018). Furthermore, increasing current level increases wire cross sectional area. After certain level, it becomes heavier than human can carry. So, it needs liquid cooling system to reduce cross sectional area that increases cost and volume of the system.

Wired charging is essentially divided into two modes: Alternating Current Charging Mode and Direct Current Charging Mode. Each mode is further divided into different levels. Figure 9 displays a table and graph illustrating the characteristics of some different charging levels specified by the SAE standard (Ahmad et al., 2017).

With the introduction of heavy vehicle charging systems, today's charging level has exceeded megawatts and some of them directly connected to the medium voltage grid. Recently, up to 1250V, 1000A megawatt charging systems (MCSs) are introduced. Standards for such systems are still under development.



	AC Level 1	AC Level 2	AC Level 3	DC Level 1	DC Level 2	DC Level 3
🟨 Max Voltage	120	240	480	450	450	600
🟥 Max Current	16	80	100	80	200	400
🟦 Max Power	1,92	19,2	50	36	90	240

Figure 9. The characteristic of different charging levels (Ahmad et al., 2017)

3.1. *Charging Modes*

According to the IEC 62196 standard, four different charging modes have been determined for both electric vehicles and charging equipment. These modes differ in terms of parameters such as control, protection, communication capabilities, charging application environments, and charging speeds. Table 4 shows the characteristics of these 4 modes. Figure-10 illustrates a visual representation of these four modes which is seen in Table 4.

Table 4. Charging modes

Charging Mode	AC/DC	Voltage /Ampere	Proprietary Socket	Control, communication and protection system	Environment
1	AC	250V (Single phase) 480V (Three phase) Max 16 amps.	No	No	Can be used at home environment
2	AC	250V (Single phase) 480V(Three phase) Max 32 amps.	No	Yes	Can be used at home environment
3	AC	3.7 kVA (16A, Single-phase 230V AC)/ 7.4 kVA (32A, Single Phase – 230V AC)/ 11 kVA (16A, Three-phase – 400V AC)/ 22 kVA (32 A, Three-phase – 400V AC)	Yes	Yes	Needs to special infrastructures
4	DC	400 A ~200kW/~240kW	Yes	Yes	Needs to special infrastructures

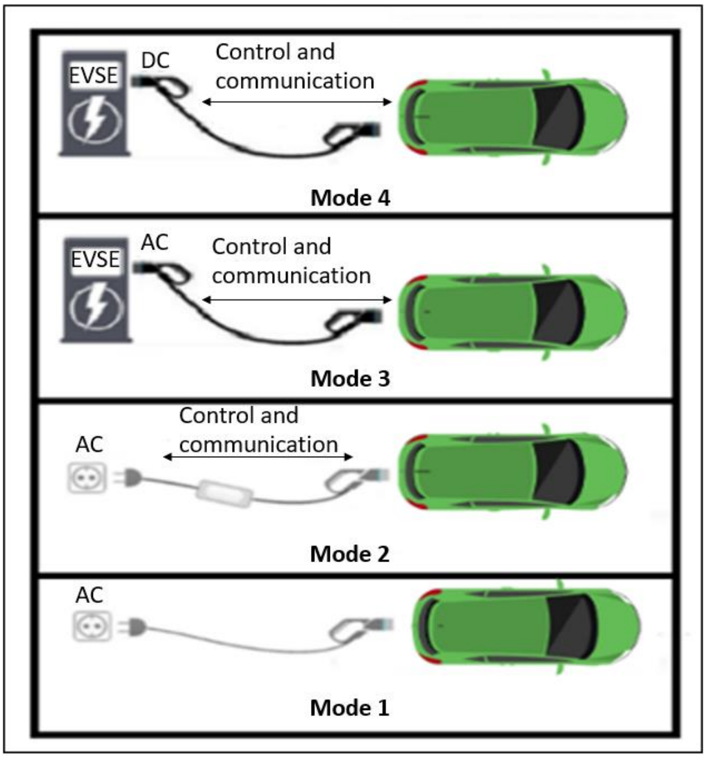


Figure 10. Visual representation of these four modes

While AC system for low power level, DC system has more power and it still increasing. Although MV megawatt class standard has not been introduced yet, the highest power shown in Table 4 not limited with 240kW.

3.1.1. Mode 1

This charging mode can be applied in home environments. For Mode 1, the electrical capabilities vary depending on the country, with current values ranging from 8 A to 16 A, and voltage values at 480 V for three phases and 240 V for single phase (Acharige et al., 2023). This mode uses a standard power socket cable. This cable does not have control and protection structures. Therefore, the use of this mode can be hazardous, and its use is prohibited in many countries (Triviño et al., 2021).

3.1.2. Mode 2

In Mode 2, the charging cable includes an in-cable control and protection device (IC-CPD), and it can be applied in home environments similar to Mode 1. Thanks to the control and protection structure, Mode 2 provides significantly more control and protection compared to Mode 1, albeit at a limited level. However, due to its electrical capacity, it can provide a restricted amount of power transfer (Triviño et al., 2021). This mode can provide a maximum power flow of 32 A / 15,3 kW in AC. In Mode 2, a voltage of 240 V can be applied in single-phase, and in three phases, a voltage of 480 V can be applied (BS EN IEC 61851-1:2019, 2019).

3.1.3. Mode 3

Mode 3, which offers much more advanced control, protection, and a higher level of power transfer compared to Mode 1 and Mode 2, is used with AC charging stations. Due to its power transfer capacity and control and protection structures, it is widely used worldwide (Triviño et al., 2021). While performing power transfer on the station side, Mode 3 charging mode actively utilizes continuous control, communication, and protection structures. Special structures integrated into the station are required for the effective use of these features in Mode 3 charging mode.

In Mode 3 charging mode, the energy obtained from the AC charging station is transferred to the electric vehicle through specially designed cables, connectors, and sockets. This AC energy is converted to DC on the electric vehicle side and charges the electric vehicle battery under the control of the battery management system. In three phases, depending on the infrastructure and energy levels, it enables power transfer of 11 kW (400V /16A), 22 kW (400V /32A), and 43 kW (400V /63A) (BS EN IEC 61851-1:2019).

3.1.4. Mode 4

Mode 4 is a mode used for fast charging systems in fixed charging stations. It directly delivers energy to the vehicle as DC. This process eliminates the need for AC-DC conversion by the built-in charger on the vehicle, reducing charging times. Similar to Mode 3, Mode 4 also utilizes advanced control, communication, and protection structures. Therefore, a special infrastructure integrated into the station is required for Mode 4 (Kersten et al., 2021).

The DC charging option used to be added to vehicles as an optional feature due to its high cost by manufacturers until recently. However, this situation has started to become standard in recently. In addition, for DC charging to be possible, the DC charging mode must be installed and operational on the station side. In Mode 4 DC charging, the energy from the grid is converted from AC to DC on the station side. The external charging unit used for this conversion is called the external charger, and as a result, the built-in charger on the electric vehicle is not used for this process (Triviño et al., 2021). The energy converted to DC is transferred to the electric vehicle through specially designed cables, connectors, and sockets. Control, protection, and communication structures actively operate from the charging preparation process to the completion process. Charging occurs under the control of the battery management system on the electric vehicle side.

Depending on the infrastructure used in Mode 4 and the capabilities of the receiving side, energy up to 1000 V (DC) voltage and 400 A current, providing 400 kW, can be delivered (BS EN IEC 61851-1:2019). Recently, megawatt class charging system introduced their voltage end current level exceed the 1000 A @1250VDC.

3.2. *Wired Charging Standards*

Ideally, having a single standard connection and charging structure for all electric vehicles and charging stations worldwide could provide convenience. However, on a global scale, different manufacturers or groups of manufacturers in different regions have developed their own unique charging structures, following standards set by relevant authorities such as SAE, IEC, IEE, GB/T. These structures may vary from model to model. In general, these structures affect aspects such as how the connector and socket structure will be for charging electric vehicles, which method will be used for communication protocols, and what the power capacities will be. The developed structures are shown in Table 5 (GB/T 20234.2-2015, 2015).

Table 5. Wired charging standards

Standard	**IEC 62196-2**	**SAE J1772**	**GB/T AC 202034.2**	**CCS Combo 1 & SAE 1772 & IEC 62196-3**	**CCS Combo 2&SAE J1772 & IEC 62196-3**	**CHAdeMO &IEC 62196-4**	Tesla	GB/T DC&GB/T 202034.3	Chaoji
Region	EU	North America/ US/Japan	China	North America/ US	EU	Japan	US	China	Japan/China
Max Power	~33 kW	~166 kW	~48 kW	200 kW	350 kW	400 kW	250 kW	250 kW	900 kW
Start Date	2009	2009	2015	2014	2013	2009	2012	2013	2020
Power Type	AC	AC	AC	DC	DC	DC	AC/DC	DC	DC

In addition to these standards, there are many different standard groups determined by authorities for wired charging, including SAE, IEC, ISO, and GB/T. These standards provide instructions and information on the electrical characteristics, connection structures, communication standards, and many other features for charging structures on both the electric vehicle and charging station sides. Some of these standards are shown in Table 6 (Acharige et al., 2023; Ahmad et al., 2017; Rachid et al., 2022).

Which standard will be used and how it will be used depends on which country the standard is required for and which part of the charging system it is related to, such as communication, dispenser, cable, power electronic equipment, fire and security. Factors such as communication protocols determine how charging stations interact with vehicles and network systems, while dispatcher functionality standards enable efficient and user-friendly charging experiences. While cable specifications and power electronic equipment standards govern the efficiency and reliability of power transmission, fire and safety regulations are crucial to ensuring public safety and protecting against potential hazards. The selection and implementation of standards for electric vehicle charging infrastructure varies depending on the specific needs and priorities of each country and the functions of each component within the system. The standards that are generally accepted worldwide are the standards set by the European Union and the USA. Although the standards groups led by both countries are not exactly the same, they contain high similarities. However, there are countries that use their own standards, including China and Japan.

Table 6. Wired charging standards specified by authorities

Standard	Standard Description
IEC 6185123	Electric Vehicle (EV) conductive charging system part 23: DC EV charging station.
IEC 621961	Vehicle Connectors, Socket Outlets, Plugs, and Vehicle Inlets Conductive Charging of EVs Part 1: General Requirements.
IEC 621962	Vehicle Connectors, Socket Outlets, Plugs, and Vehicle Inlets Conductive Charging of EVs Part 2: Contact Tube Accessories.
IEC 621963	Vehicle Connectors, Socket Outlets, Plugs, and Vehicle Inlets Conductive Charging of EVs Part 3: Contact tube Vehicle Couplers and Dimensional Compatibility & Interchangeability Requirements for DC Pin.
IEC 60038	Standards for the voltage for charging applications.
IEC 60664-1	Installation coordination for charging equipment in low-voltage supply.
IEC 62752	Standards for cable control and protection devices.
ISO 15118	Standards for V2G communication protocols and interfaces.
ISO 17409	Specifications for the connection of EV with an external energy source.
SAE J 1772	Conductive charge coupler for EV and PHEV.
SAE J2344	Guidelines for EV safety.
SAE J2953	Standards for interoperability of EV and charger.
SAE J2847/1	Communication between EV and the grid.
SAE J3068	EV power transfer system using a three-phase AC capable coupling.
GB/T 18487.1	Part 1: Details of general requirements for EV conductive charging system.
GB/T 18487.2	EVs requirements for conductive connection to an AC/DC supply.
GB/T 18487.3	EV conductive charging system AC/DC EV charging station.
GB/T 20234.1	Part 1: General Requirements for Connection Set for Conductive Charging of EVs.
GB/T 20234.2	Part 2: AC charging coupler for Connection Set for Conductive Charging of EVs.
GB/T 20234.3	Part 3: DC charging coupler for Connection set for charging conductive charging of EVs.
GB/T QC/T 895	Detail of EVs On-board Conductive Charger

3.2.1. CCS

Combined Charging System (CCS) is a charging standard developed according to the SAE J1772 standard, used by many automotive manufacturers such as Audi, Porsche, Honda, Kia, Fiat, Hyundai, Volvo, Smart, MINI, General Motors, Ford, Chrysler, Dodge, Jeep, BMW, Mercedes, Volkswagen, Jaguar, Land Rover, Bentley, Rolls Royce in Europe and North America. Tesla produces the European model of Model-3 with a compatible CCS connection structure and also provides a separate CCS converter for its other models (Ekici et al., 2021).

According to the CCS charging standard, both AC charging mode and DC fast charging mode can be implemented (National Academies of Sciences, 2021). For the DC charging mode, there are two pins at the bottom of the connector. The CCS charging standard uses CCS-Combo-1 structures in America and CCS-Combo-2 structures in Europe for the DC charging mode. For the AC charging mode, CCS-Type-1 structures are used in America, and CCS-Type-2 structures are used in Europe. Connector structures for CCS are shared in Table 7 (Rachid et al., 2022).

Table 7. CCS connector structure

CCS Combo Connector Definition	CCS Combo Connector Structure	Region	Function
Type 1		North America	Single-phase AC charging with Type 1 EV plug
Combo 1		North America	DC fast charging via dedicated pins with CCS Combo 1 EV plug
Type 2		Europe	AC charging with Type 2 EV plug
Combo 2		Europe	DC fast charging via dedicated pins with CCS Combo 2 EV plug

3.2.2. CHAdeMO

CHAdeMO (Charge de Move) is a charging standard used by manufacturers such as Mitsubishi and Nissan in Japan. It is developed based on the GB/T 20234 and IEC 62196-4 standards (INL, 2010). When charging with J1772 compliant charging stations, an intermediate cable is required.

Currently, CHAdeMO provides fast DC charging capabilities ranging from 6 kW to 400 kW. CHAdeMO does not have an alternative current charging mode, so in Japan, SAE J1772 Type-1 is used for AC charging mode. Connector structures for CHAdeMO are shown in Figure 11(Rachid et al., 2022).

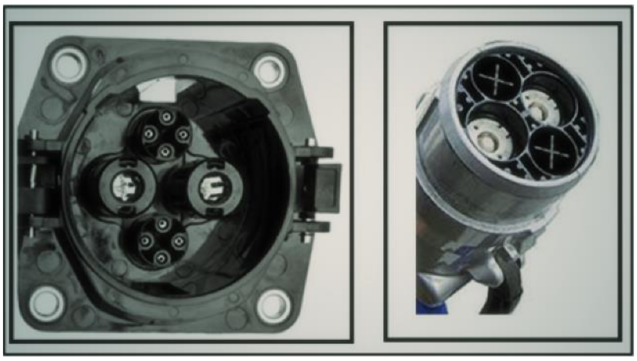


Figure 11. CHAdeMO connector structure (Rachid et al., 2022)

3.2.3. GB/T

GB/T 20234-2015 charging standard is used for both AC charging mode and DC fast charging mode in China (GB/T 20234.1-2015, 2015). GB/T 202034.2 standard specifies the AC charging mode, while GB/T 202034.3 specifies the DC charging mode.

The GB/T charging standard provides a maximum of 8 kW energy in the AC single-phase charging mode with 250 V voltage and 10/16/32 A current. In the AC three-phase charging mode, it offers a maximum of 48 kW energy with 440 V voltage and 16/32/63 A current. In the DC charging mode, it provides a maximum of 250 kW energy with 700/1000 V voltage and 80/125/200/250 A current (GB/T 20234.3-2015, 2015). In Figure 12, the GB/T 202034.2 AC charging connector structure and GB/T 202034.3 DC charging connector structure are illustrated (Rachid et al., 2022).

Figure 12. GB/T connector structure (Rachid et al., 2022)

3.2.4. Tesla

Tesla manufactures the EV charging connector structure based on the region where the vehicle is sold. Accordingly, the U.S. version is also sold in Canada, Mexico, Japan, and Taiwan, equipped with a special Tesla inlet as shown in Figure 13a. In contrast, Figure-13b illustrates the addition of a dual inlet for the Tesla vehicle in China. One of these inlets is for AC GB/T charging mode connection, and the other is for DC GB/T charging mode connection. Finally, it is shown in Figure-13c that the Tesla vehicle sold in Europe uses the CCS-Type-2 connection structure for AC charging mode, and in Figure-13d, it uses the CCS-Combo-2 connection structure for DC charging mode (Herron, 2019).

Tesla provides different connection structures for both AC and DC charging modes at all charging levels. Tesla Supercharger stations offer high-speed charging through their own charging infrastructure, and the connectors can transfer electric power at 72 kW, 150 kW, or 250 kW.

Figure 13. Tesla inlet structure by regions: (a) U.S.; (b) China; (c) Europe and (d) Europe (Rachid et al., 2022)

3.3. *Communication Protocols for Wired Charging*

In wired charging systems, communication between the electric vehicle battery system and the charging station is generally achieved using CAN-Bus and Power Line Communication (PLC) protocols. Table 8 illustrates which communication protocols are used by wired charging standards worldwide.

Table 8. Communication protocols of wired charging standards

Standard	IEC 62196-2	SAE J1772	GB/T AC 20203 4.2	CCS Combo 1 & SAE1772 & IEC 62196-3	CCS Combo2&SAE J1772 & IEC 62196-3	CHAdeMO&IEC 62196-4	Tesla	GB/T DC&GB/T 202034.3	Chaoji
Protocol	PLC	PLC	CAN Bus	PLC	PLC	CAN Bus	CAN Bus	CAN Bus	CAN Bus

3.3.1. CAN-Bus

The Controller Area Network protocol (CAN or CAN-Bus) is a differential two-wire, bidirectional serial communication method that enables electronic subsystems to be interconnected within a network and interact with each other on the same network (Typhoon HIL, 2023).

In the early 1980s, with the increasing use of electronic control units in vehicles, the amount of cables used inside vehicles also increased. This, in turn, added extra weight to vehicles and reduced fuel efficiency. As a result, companies like Germany's Robert Bosch began searching for a new data transmission system that would facilitate communication between multiple electronic control units (ECUs) and vehicle systems, while eliminating the need for additional communication control cables. However, they did not achieve the desired results. Therefore, Bosch, Mercedes-Benz, Intel®, and several German universities collaborated to develop the CAN-Bus protocol. In 1986, Bosch introduced the CAN standard at the SAE Congress in Detroit. A year later, Intel® began shipping the first CAN controller chips. This innovation replaced the heavy cables used for communication control in vehicles with a two-wire CAN-Bus, significantly reducing the cable load in vehicles. This marked a significant change in the automotive industry.

The CAN-Bus communication protocol is widely used in the automotive sector. In addition to automobiles, it is also employed in other applications such as aircraft, marine vessels, factory production lines, medical devices, and household appliances like washing machines.

3.3.1.1. Operating Principle of CAN-Bus

The CAN-Bus communication protocol, along with its data transmission principles, is defined by the International Organization for Standardization (ISO) in the ISO-11898:2003 standard (Corrigan, 2016). Communication between devices connected to a network in the physical environment is defined by the physical layer of the model. The seven-layer model defined according to the ISO 11898 architecture is shown in Figure 14.

The CAN-Bus communication protocol consists of interconnected nodes on a network. Each of these nodes is connected in the physical layer via differential CAN lines. Each node represents a point where these structures are connected to the network to communicate with an Electronic Control Unit (ECU) or similar structures.

CAN communication protocol is a protocol with Carrier Sense, Multiple Access, Collision Detection, Message Arbitration, and Collision Resolution on Message Priority (CD+AMP/CSMA) features. CSMA ensures that each node remains passive before sending data. CD+AMP means that collisions are resolved through bit-level detection based on pre-programmed priority for each message in the message identifier field. Access priority on the bus is always provided for a higher-priority message (Corrigan, 2016).

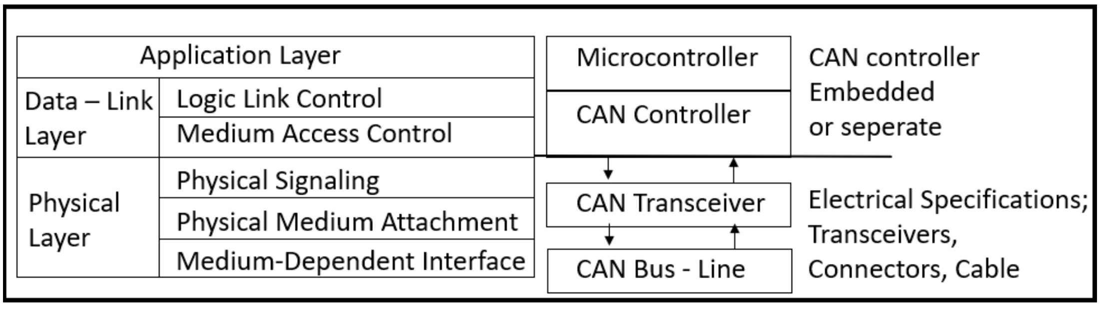


Figure 14. Architecture of CAN-Bus standard according to ISO 11988 (Corrigan, 2016)

CAN communication standard is divided into three groups: Standard CAN-Bus, Extended CAN-Bus, and CAN-Bus FD. The general differences between these three groups are shown in Table 9 (Corrigan, 2016).

Table 9. CAN-Bus communication groups

Order	STANDARD CAN-BUS	EXTENDED CAN-BUS	CAN-Bus FD
1	Initially developed for automotive applications,		It is an enhanced version of the classical CAN-Bus protocol, providing the capability to upgrade all features of CAN-Bus.
2	The DATA length is fixed at 8 bytes (DLC - Data Length Code).		The DATA length is flexible and can be set to 0, 8, 12, 16, 20, 24, 32, 48, or 64 bytes (DLC - Data Length Code).
3	It is an ideal option for applications with a large number of ECUs and where the bandwidth requirement is low.		It provides enhanced functionality for applications with advanced data exchange and bandwidth requirements due to flexible signal transmission.
4	The maximum communication speed is 1 Mbps.		It provides communication speeds ranging from 2.5 to 8 Mbps.
5	It is not compatible with higher-level protocols like CAN-Bus FD		It is compatible with lower-level protocols, similar to Classical CAN-Bus.
6	The message identifier field is 11 bits.	The message identifier field is 29 bits.	Message identifier field can be set as 11 bits or 29 bits.

3.3.1.2. Standard CAN-Bus

The message structure of Standard CAN-Bus communication is shown in Table 10 (Corrigan, 2016).

Table 10. Message structure of standard CAN-Bus :11-bit identifier

Bit No	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Content	SOF	11- bit Identifier	RTR	IDE	r0	DLC	0…..8 Bytes Data	CRC	ACK	EOF	IFS	IDLE

The bit-wise meanings of the expressions given in Table 10 are explained below, respectively:

1. The Start of Frame (SOF) bit field in the message structure contains information about the beginning of the message. This field is also used to ensure synchronization between nodes on the bus after the waiting time.
2. The 11-bit Identifier bit field determines the message priority. When two messages are compared, the message with a higher value in this bit field is considered more prioritized.
3. RTR (Remote Transmission Request) bit is active when information is requested from a different node. All nodes receive this information request, but the identifier determines which node will transmit the information. Similarly, the sent response is transmitted to all nodes. Any node interested in this information can use it. This way, all data used in the system remains in the same format. The main purpose of this bit is to indicate that a remote data request is made. When a remote data request is made, this bit is sent as 1. In a regular data transmission, this bit is sent as 0.

4. IDE (Identifier Extension) bit indicates whether standard CAN-Bus communication is used, implying that the extended mode is not employed.
5. r0 bit is a reserved bit for future use, to be utilized if needed.
6. DLC (Data Length Code) bit field determines how many bytes the transmitted data will be.
7. In Standard CAN-Bus communication, data transmission can be up to 64 bits (8 byte).
8. CRC (Cyclic Redundancy Check) bit field is used for error detection purposes by employing a checksum.
9. ACK (Acknowledgment) bit field conveys information to the transmitting node about whether the message has reached its destination correctly by manipulating these bits. If information about the message being received incorrectly is conveyed, the transmitting node repeats its response.
10. EOF (End of Frame) bit signals the end of the message.
11. IFS (Inter frame Space) bit field is used to adjust the time required by the controller to move a correctly received message to the appropriate location in the buffer area.
12. IDLE state is used to ensure the synchronized transfer of a message from the transmitter to the receiver during message transmission. No CAN message is transmitted in the IDLE state. Instead, 8 bits of a recessive message are transmitted to the connected nodes.

3.3.1.3. Extended CAN-Bus

The message structure of Extended CAN-Bus communication is illustrated in Table 11 (Corrigan, 2016).

Table 11. Message structure of extended CAN-Bus: 29-bit identifier

IDLE	SOF	11- bit Identifier	SRR	IDE-A	18-bit Identifier	r1	r0	DLC	0….. 8 Bytes Data	CRC	ACK	EOF	IFS	IDLE

In the Extended CAN-Bus message structure, there are additional 18-bit identifier bits, an SRR (Substitute Remote Request) bit, an additional IDE-A bit, and an additional r1 bit, which differ from the standard CAN-Bus message structure (Corrigan, 2016). The SRR bit takes the place of the RTR bit. While the additional IDE-A bit indicates the usage of the 18-bit identifier extension, the r1 bit has been added to the Extended CAN-Bus message structure in addition to r0 for later usage.

3.3.1.4. CAN-Bus FD (Flexible Data)

The message structure of CAN-Bus FD communication is illustrated in Table 12 (Lennartson, 2015).

Table 12. Message structure of CAN-Bus FD

IDLE	SOF	11- bit / 29 – bit Identifier	RRS	IDE	EDL	FDF	BRS	ESI	DLC	0….. 64 Bytes Data	CRC	ACK	ACKD	EOF	IFS	IDLE

The CAN-Bus FD (Flexible Data rate) protocol has been developed as an enhanced communication protocol with advanced and higher communication capabilities through additions to classic CAN-Bus communication. This development comes as a response to the classic CAN-Bus communication falling behind in adapting to technological advancements. The CAN-Bus FD protocol is defined in the ISO 11898-1:2024 standard (ISO 11898-1:2024, 2024). CAN-Bus FD offers a cost-effective communication protocol with increased bandwidth for the automotive and other industries. Additionally, almost every feature of classic CAN-Bus in CAN-Bus FD has been elevated to a higher level, with added capabilities for wider data transfer and broader communication bandwidth. Furthermore, CAN-Bus FD supports legacy structures used in classic CAN-Bus.

Structures in the message format of CAN-Bus FD that differ from classic CAN-Bus include:

1. The RRS (Remote Request Substitution) bit is always transmitted as 0, unlike in classic CAN-Bus. This is because CAN-Bus FD does not support remote data requests. The name has been changed to RRS due to the difference in usage.
2. The FDF (Flexible Data Rate) Format bit indicates the use of the FD format for communication and is always transmitted as 1.
3. The EDL (Extended Data Length) bit is used to manage larger data and facilitate faster communication. It is always transmitted as 1.
4. The BRS (Bit Rate Switch) bit field determines the bit rate of the message:
    a. When bit is set as 0, it indicates communication at up to 1Mbit/sec.
    b. When bit is set as 1, it indicates communication at up to 5Mbit/sec for CAN-Bus FD.
5. The ESI (Error State Indicator) bit indicates the error state:
    a. When bit is set as 0, it indicates that the error state is active.
    b. When bit is set as 1, it indicates that the error state is passive.

3.3.2. Power Line Communication (PLC)

Power Line Communication (PLC) refers to the transmission of data over existing low, medium, and high-voltage power infrastructure (Koch, 2015).

While the experimentation and development of PLC protocols date back to the early 1900s, the widespread adoption of its applications is relatively more recent compared to CAN-Bus. It was developed with the purpose of enabling communication over power lines to eliminate the need for additional cables in wired systems. PLC finds a wide range of applications, including smart grids, home automation, internet access, remote monitoring and control, energy management, automotive applications, electric vehicle charging stations, smart cities, and industrial automation (Lampe et al., 2016).

The specifications for the PLC protocol are outlined in standards such as IEEE 1901, ISO 15118-3:2015, and others. While the IEEE 1901 standard provides a general and broad framework for the PLC protocol, the ISO 15118-3:2015 standard specifies structures tailored for its use in the automotive domain (IEEE 1901-2020, 2020; ISO 15118-3:2015, 2015).

The configuration structure of a typical distributed control system PLC module is shown in Figure 15 (Lita and Visan, 2012). The fundamental operating principle of PLC is based on the modulation of data by the transmitter and the demodulation of received data by the receiver. In the PLC protocol, a user can control all structures connected to the same power line.

PLC has four different types: 'In-house networking,' 'Broadband over Power Line,' 'Narrowband in-house applications,' and 'Narrowband outdoor applications.' Descriptions for these types are provided in Table 13 (Ferreira et al., 2011).

Table 13. Types of Power Line Communication

Types of PLC	Explanation
In -house networking	It provides high-speed data communication over the household's main power grid.
Broadband over Power Line(BPL)	BPL (Broadband over Power Line) is a type of PLC (Power Line Communication) technology that provides internet access using data transmission over electrical power lines.
Narrowband in-house applications	It allows low-speed data transfer over the household's main power grid for home automation and intra-home connections.
Narrowband outdoor applications	It enables the use of power lines for communication in surveillance systems, measurement systems, or Electric Vehicles (EVs) for battery charging station communication.

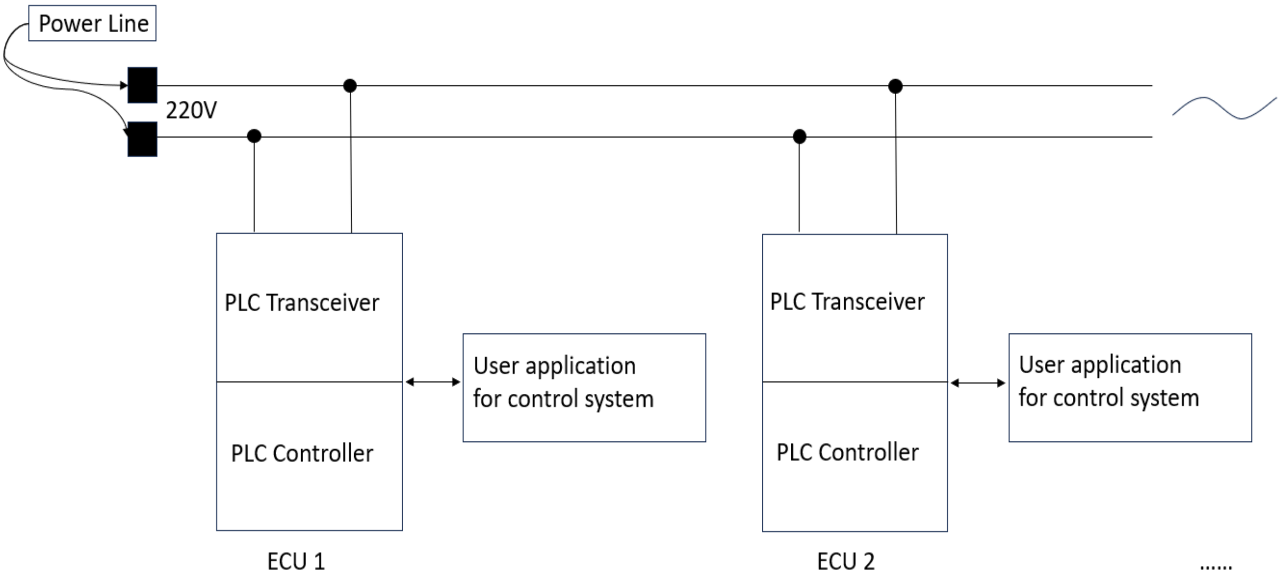


Figure 15. The configuration structure of a typical distributed control system's Power Line Communication module (Lita & Visan, 2012).

4. Future of EV Charging Technology

Electric vehicle technology continues to be developed and improved in various ways today. The battery and charging system, among the most critical components for electric vehicles, play a significant role in increasing the range, extending battery life, and reducing charging times. Therefore, these components in electric vehicles are constantly evolving.

Over the years, various types of batteries, battery management systems, charging stations, and charging systems have been developed, varying from region to region and manufacturer to manufacturer. This diversity can unfortunately lead to compatibility issues in charging electric vehicles in different regions. Hence, efforts are ongoing worldwide to unify the electric vehicle charging infrastructure under a common standard.

Japan and China are actively working on developing a shared charging infrastructure standard in their regions through the Chaoji standard. Organizations such as CHAdeMO in Japan and the China Electricity Council (CEC) in China collaborate on the international development of high-speed DC charging standards. Their joint efforts aim to establish a standardized approach for charging electric vehicles globally (Liu Yong Dong, 2020). The Chaoji standard is aimed at being compatible with the older versions of CHAdeMO and GB/T standards (Boyd, 2019). The information regarding the Chaoji standard is provided in Table 5, and prototype images for the connection structure of the Chaoji standard are shared in Figure 16.

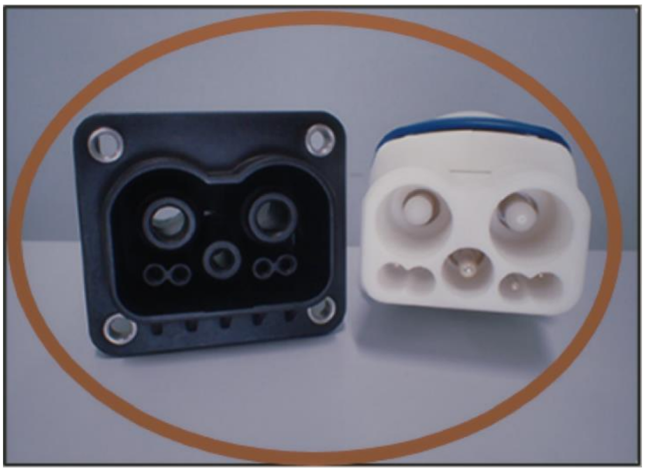


Figure 16. Inlet-socket prototype of the Chaoji standard

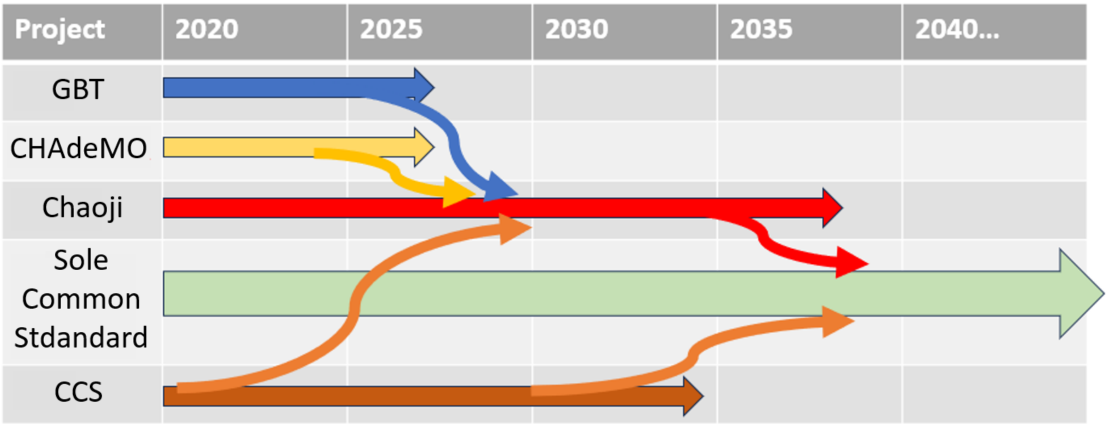


Figure 17. The table forecasting the process of converging charging into a single common standard

The Chaoji standard can be considered a pioneering effort towards developing a universal standard for all electric vehicles worldwide. In line with the progress of technology, transitioning to such a standard is planned in the coming years. Figure 17 illustrates the anticipated outcome in the literature, where a single standard that is compatible with all electric vehicles is expected to emerge as a result of these efforts (NI Feng, 2023).

5. Discussion

The history of electric vehicle technology, although dating back to the past, can be considered a more innovative and adaptable technology in today's structure. Additionally, the increasing prevalence of electric vehicle usage compels continuous development in battery technology, electric motor technology, charging systems, and communication protocols to offer more environmentally friendly, efficient, and effective solutions.

Due to lifespan, range, charging time and similar factors, battery system performance has a critical importance for electric vehicles. The strength and reliability of battery performance are not solely dependent on the type and design of the battery system but are also influenced by the charging system, which is another crucial factor affecting the battery system.

This article provides a general overview of the literature and practical methods, standards, and capabilities applied to both wired and wireless charging systems for electric vehicles. It delves into the CAN-Bus and PLC standards facilitating communication between the vehicle's battery system and the charging station in wired charging systems. The study covers various structures used by different manufacturers for electric vehicles.

The development of improvements for both wired and wireless systems is expected to continue, with dynamic and semi-dynamic charging systems holding significant potential for the future of wireless charging. Integrating these systems into cities and roads is shown to contribute significantly to meeting charging needs quickly and efficiently, thereby increasing the range of electric vehicles. However, the integration of these structures into cities and roads requires comprehensive and costly infrastructure work.

In this context, the study also provides an insight into various wireless power transfer techniques, such as Microwave Wireless Power Transfer, Laser Optical Wireless Power Transfer, Resonant Inductive Wireless Power Transfer, Magnetic Gear Wireless Power Transfer, Inductive Wireless Power Transfer, and Capacitive Wireless Power Transfer.

Regarding wired charging, the article explores the presence of various charging structures. It explains the capabilities of charging modes, Mod 1, Mod 2, Mod 3, and Mod 4. Widely used global charging standards, including CCS, CHAdeMO, GB/T, and TESLA, are examined. It is indicated that CHAdeMO and GB/T are expected to merge under a single standard called Chaoji in the future. The article also highlights ongoing efforts for a single global standard for wired charging systems.

The study delves into the protocols facilitating communication between the battery system and the charging station in wired charging systems. It reveals the use of Power Line Communication in the CCS charging system and the CAN-Bus communication protocol in CHAdeMO, GB/T, and TESLA systems. The general topologies of PLC and CAN-Bus protocols are explained.

6. Conclusion

The development of battery and charging systems is crucial for the advancement of electric vehicles. The progress of these technologies will make electric vehicle usage more widespread and reliable. Therefore, developments in this field are continuously relevant. It is anticipated that, in the future, wired and wireless charging systems will converge into a single common standard accessible for any electric vehicle worldwide. The power of electric vehicles is experiencing continuous growth, with a notable surge in electrification observed in electric buses and trucks. The integration of diverse devices like mine machines, ships, trains, and trolleybuses into the system has introduced gaps, both in the structure and characteristics of chargers, as well as in the standards governing them. This research delves into the study and comparison of international standards employed in the charging systems of electric vehicles. The prevalent charging standards are categorized into three segments: wired, wireless, and battery replacement. These standards are further analyzed based on criteria such as maximum power output, connector type, and communication protocols. Consequently, the study presents an overview of the overarching characteristics of electric vehicle charging standards, encompassing their electrical capabilities, connection types, communication protocol structures, and the general framework of these communication standards. The study shows that international standards currently fall short in adapting to the evolving landscape of new systems, particularly megawatt charging systems. Presently, there is no unified structure for socket and charging systems, whether for low or medium power. Furthermore, there is a dearth of accepted standards and equipment, encompassing sockets and charging systems, specifically designed for megawatt-scale applications.

Conflict of Interest

The authors declare that they have no conflict of interest.

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