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Analysis of Charging Systems for Electric Vehicle

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Abstract- The charging system plays a key factor for the economic breakthrough of electromobility and customer acceptance with charging power, charging times, availability of charging stations, convenience of use. In the state of the art there are three main charging systems (conductive, inductive and automated). In recent years, there are always new requirements from laws, standards, and norms for charging systems. These requirements are important and crucial for the use and further development of the charging systems. With this work three charging systems (conductive, inductive, and automated) are analyzed, evaluated and the requirements from current norms, standard and laws summarized as well as recommendations given. Without analysis and evaluation of the requirements, the further development, implementation of the charging systems and fulfillment of the laws, norms and standards are not possible.

In the literature, there is no comparison of all three major charging systems for different aspects present. With this work, the regulation of the maximum possible charging power of the battery for a charging process is presented and the charging power and efficiency between the conductive and inductive charging systems are compared. All three charging systems are compared in terms of performance, cost, convenience. Here, the impact of different types of charging systems on electrical networks, on smart grids, and the installation and maintenance costs are studied and discussed in detail. Automated charging system brings more opportunity for the future in terms of significant improvement of customer acceptance (secure, convenient, and fast charging).

Keywords Charging, battrey, conductive charging, inductive charging, automated chargin, carging technologies, electric vehicle.

1. Introduction

Electromobility plays an increasingly important role in motorized private transport due to reduction of pollutants such as NOx or CO2 and noise, reduction of dependence on fossil fuels, use of renewable energy, low operating costs, efficient drive performance. This promotes many countries and companies to the further development of electric mobility and electric mobility is gaining more and more importance. For the future of the automotive industry, electromobility is important drivers. Electric vehicles can be fully electric or hybrid. Hybrid vehicles represent a hybrid form with the possibility of switching between classic fuel drive and electric drive. Exit for electromobility will accelerate mainly due to the CO2 fleet limits of the EU as well as the national climate protection commitments in Germany for the year 2030. Due to these initial conditions, the supply of vehicles with electric drives will increase sharply in the coming years to come. In Germany alone, the share of electric vehicles is forecast to rise to 27 percent of new sales by 2025, with around 65 percent of these likely to be pure electric vehicles [1], Fig. 1. In Germany, according to the Federation of German Industries (BDI), nine million electric vehicles are expected to be on German roads in 2030 in order to meet the German government's 2030 climate protection target for the transport sector.

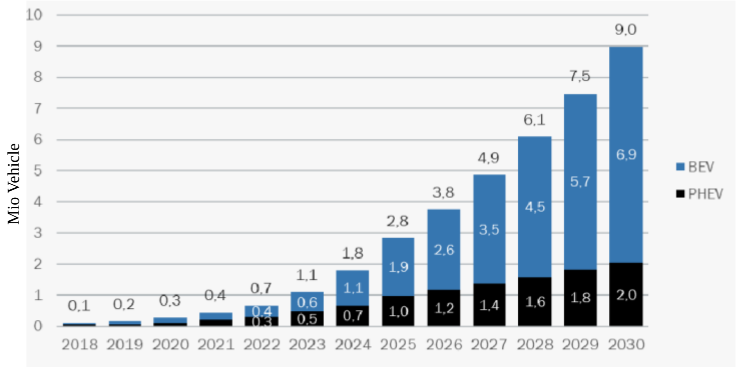


Fig. 1. Number of electric vehicles in Germany by 2025 [1].

Thus, electromobility is not only a key component of a transport turnaround, but also an expression of the fundamental transport turnaround, but also an expression of the fundamental transformation of existing energy systems with the networking of the energy sectors (electricity the interconnection of the energy sectors (electricity, infrastructure and transport) as an important strategic element of the energy transition [2].

For the successful realization of electromobility development, the creation of a charging infrastructure and the expansion of the existing power grid must be driven forward. Since electric vehicles still have a very limited range, new concepts are emerging here to secure the energy supply. This described development of electric mobility until 2030 depends on the availability of a sufficient charging infrastructure. The charging infrastructure for electric vehicles will be the key factor for a smooth transition to electromobility. That is why electric vehicles and charging infrastructure play an important role in the global effort to combat climate change, grow a clean energy economy, and bring innovative technological solutions to market that accelerate the adoption of zero-emission vehicles worldwide.

The increase of more registered electric vehicles leads to the number of required charging stations for electric cars drastically [3]. According to a forecast, the need for publicly accessible charging stations for registered electric vehicles in the European Union is expected to be around 3.6 million in 2030. In 2018, the demand was still around 100,000. The German government wants to push ahead with the expansion of the charging infrastructure. According to the Federal Network Agency, there were around 70,000 charging stations in 2022. Compared to today, the need for publicly accessible charging infrastructure will increase to at least 843,000 charging points in Germany in 2030, Fig. 2.

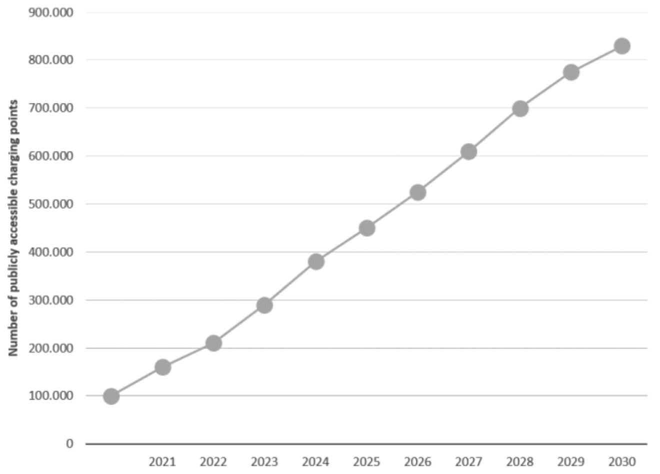


Fig. 2. Prognose for public charging points until 2030 in Germany [4].

The establishment of a simply practical charging infrastructure with sufficient power for short charging durations plays a key factor in the economic breakthrough of electromobility and initially enables a significant improvement in customer acceptance through the totality of cross-technology innovations. Customer acceptance requires even more cost-effective, faster, safe and convenient charging. Technologies will play a significant role in this for electric vehicles. The literature described different charging technologies intelligent charging, vehicle-to-grid (V2G) technology, charging with the help of photovoltaic systems, conductive, inductive and automatic charging systems as well as battery swaps and the charging of electric vehicles on the road.

Previous work in the state of the art for charging technologies has focused on how energy is provided from power sources such as solar or wind [5-8], vehicle-to-grid (V2G) technology [9-11], comparison of efficiencies for energy transfer between the grid and vehicles [12-15], battery swaps [17-19], and comparison of charging technologies with each other [20-25].

Currently, conductive, inductive and automatic charging technologies have been mainly used and developed in the market. There are always new laws, standards and norms for charging systems worldwide. Baseline for these charging systems are the electrical requirements, which are not uniformly presented in the literature. These electrical requirements are important for further development, implementation, and use of charging technologies. Therefore, charging systems must be adapted and further developed according to these requirements.

In the literature, a comparison of all these three charging systems is not available. This comparison is very important and necessary for the selection of the appropriate charging systems.

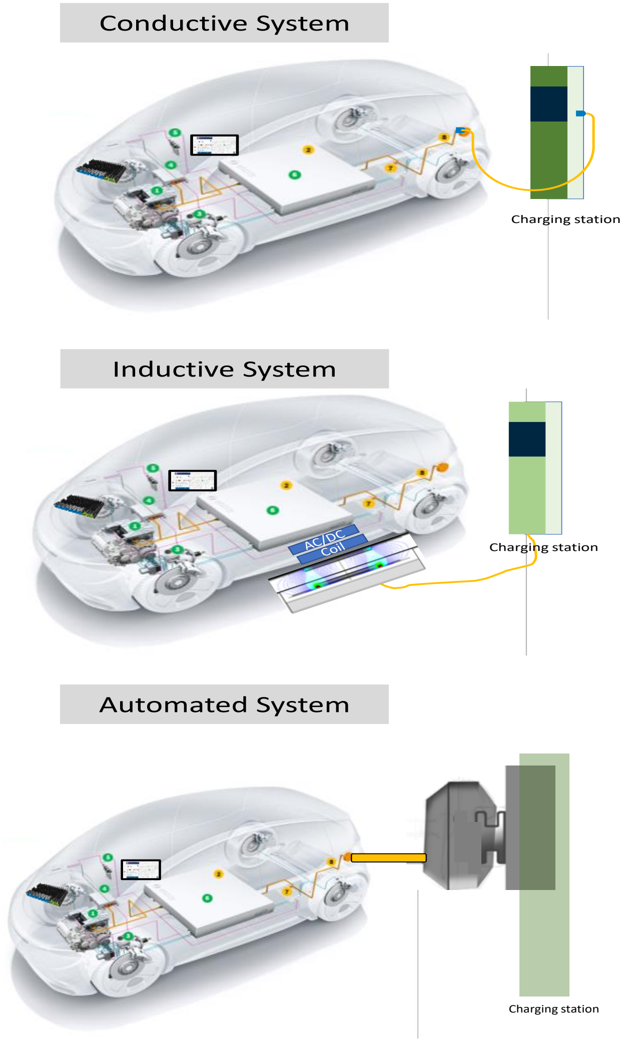


Fig. 3. Charging Systems for the HV Battery Charge.

The aim of this paper is to provide a unified view and evaluation of these three charging systems (Fig. 3) with the current status of the norm and standard and an overview of these three technologies (Fig. 3) in terms of current requirements, implementations and measurements as well as recommendations for the future in Section 2-4. Details are presented for these three technologies in Section 2 for Conductive Charging Systems, in Section 3 for Inductive Charging Systems, in Section 4 for Automated Charging Systems. Section 5 compares the charging performance and efficiency between the Conductive and Inductive Charging systems. The influences of different types of charging systems on electrical grids, on smart grids, and on installation and maintenance costs are studied and explained in detail. At the end, the results are summarized.

2. Requirements for Conductive Charging System

Conductive charging is the term used for cable-based charging. The energy is transferred from a charging station or wallbox to the vehicle battery via a cable and plug-in connection, Fig. 4. For fast charging systems, conventional transfer via charging cable is clearly advantageous, as the required energy can be transferred easily. However, the charging cable proves to be extremely cumbersome. Since the cable is exposed to the elements all year round, it is rapidly aging, leading to costly replacement of the charging cable. Here are the requirements.

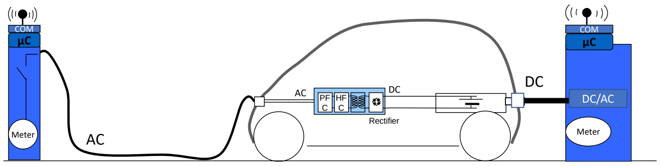


Fig. 4. Eco Systems for conductive charging systems.

2.1 Laws, Standards, Norms and Regulations for Conductive Charging

There are many laws, standards, norms and regulations from different bodies for conductive charging systems worldwide. These are summarized from the most important literature here, Fig. 5. According to this overview, the conductive charging systems must be developed.

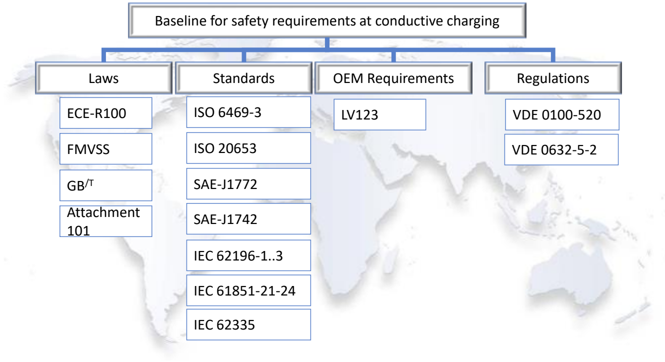
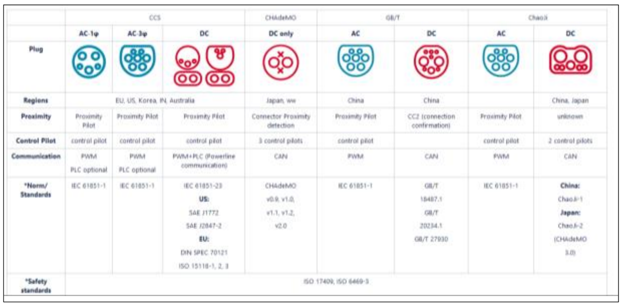


Fig. 5. Laws, standards, and regulations for conductive charging system.

2.2 Charging Plug and Type of Current

Basically, charging of the HV battery was carried out either with the alternating current (AC) or direct current (DC). The main difference between AC and DC charging are power and the place where the alternating current (from the power grid) is converted to direct current (to charge the batteries). In AC charging, the conversion happens in the car itself. Electric cars with on-board charger (OBC), which takes the alternating current and converts it to direct current via several converters, Fig. 4. There are different standards and standards for charging plugs worldwide, depending on the region and type of current, Fig. 6.

To start the charging process (energy transfer, communication) between electric cars and charging station or wallbox, electric cars must be connected to the charging station via a charging plug. The respective plug must be compatible with the charging station. There are currently different plugs. These vary depending on the permissible charging frequency and possible charging power. The higher the charging power, the faster the electric car is charged. Thus, it has a great influence on the duration of the charging process. Currently existing plug types are based on type of power (AC & DC) and regions. To start the charging process between vehicle and charging station, the charging stations and vehicles must be equipped according to this norm and standard, this region and type of electricity. The trend for charging system is about DC fast charging with high power. MCS technology, current developments in standardization work and the importance of national and international activities [26-27]. For the future, Chaoji DC system with power up to 900 kW in Asian [28] and Megawatt Charging System connector (MCS) with power 4.5 MW will be used in NA and EU.



	CCS			CHAdeMO	GB/T		ChaoJi	
	AC-1φ	**AC-3φ**	**DC**	**DC only**	**AC**	**DC**	**AC**	**DC**
Plug								
Regions	EU, US, Korea, IN, Australia			Japan, ww	China	China		China, Japan
Proximity	Proximity Pilot	Proximity Pilot	Proximity Pilot	Connector Proximity detection	Proximity Pilot	CC2 (connection confirmation)	Proximity Pilot	unknown
Control Pilot	control pilot	control pilot	control pilot	3 control pilots	control pilot		control pilot	2 control pilots
Communication	PWM PLC optional	PWM PLC optional	PWM+PLC (Powerline communication)	CAN	PWM	CAN	PWM	CAN
***Norm/ Standards**	IEC 61851-1	IEC 61851-1	IEC 61851-23 **US:** SAE J1772 SAE J2847-2 **EU:** DIN SPEC 70121 ISO 15118-1, 2, 3	CHAdeMO v0.9, v1.0, v1.1, v1.2, v2.0	IEC 61851-1	GB/T 18487.1 GB/T 20234.1 GB/T 27930	IEC 61851-1	**China:** ChaoJi-1 **Japan:** ChaoJi-2 (CHAdeMO 3.0)
***Safety standards**	ISO 17409, ISO 6469-3							

Fig. 6. Overview for the charging plugs and type of current.

2.3 Charging Modes

According to the international standard IEC 61851-1 [29], electric vehicles can be charged in four different charging modes, Fig. 6. The key differences are the charging power, safety (electronically controlled and monitored), plug interlock and communication between the charging point and the vehicle, Fig. 7. The charging mode is determined by the charging device used: this is, for example, the wallbox at home, at work or the charging station on a highway. Therefore, the charging mode does not have to or cannot be selected by the user.

Charging modes 1-3 describes alternating current (AC) charging. When charging, modes 1-3 convert alternating current (AC) in the vehicle to direct current. Mode 4 describes direct current (DC) charging and at the same time the fastest way of charging. In charging mode 4, the conversion from alternating current (AC) to direct current (DC) during charging takes place in the charging station itself and not in the vehicle, so that the DC current is fed directly to the vehicle. The maximum charging current is about 500 A for so-called high power charging (HPC) on a combined charging system basis according to IEC 62196 [30]. For charging mode 4, no cable needs to be selected as it is always connected to the DC charging station. According to this charging mode, the charging process must be designed whether the charges are regulated (electronically controlled and monitored) or unregulated, with alternating current or with direct current.

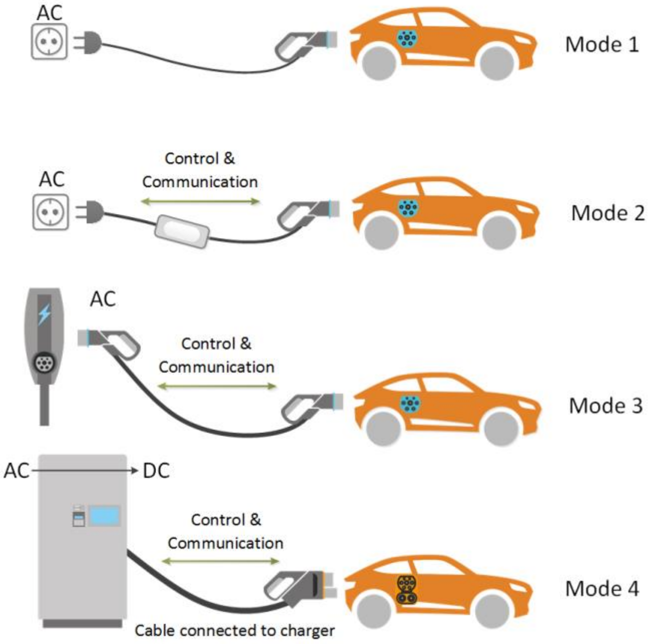


Fig. 7. Modes of charging [31].

2.4 The Necessary Contacts for ac-/dc Charging and Contact Sequencing

There are different contact areas (pins) in AC/DC charging connector to realize power transmission, communication, and safety.

Here are the relevant contacts (pins) in DC/AC charging plug

- Proximity (Control switch) => PP (CS)
- Protective earth => PE
- Neutral contact => N
- Energy transport pins (Phase/x) => AC:(L1, L2, L3 / DC: HV+, HV-
- Control pilot => CP

According to type of storm (AC/DC), power, mode of operation must be selected suitable contact (pins). This plugs, sockets with pins are specified for conductive charging of electric vehicles according to IEC 62196. For high voltage safety reasons (interlock, arc) contact (pins) must be designed and constructed in an AC/DC plug of different length. Thus, a safe contact sequence for the connection and disconnection of the charging plugs for AC / DC connectors is fulfilled, Fig. 8. The contact sequence during the connection process for AC must be such that the contact of the touch or connection switch and the ground contact can be closed and opened simultaneously. When disconnecting the connection, the sequence shall be reversed. Neutral contact N must close before or simultaneously with contacts L1, L2 and L3 and interrupts after or simultaneously with contacts L1, L2 and L3.

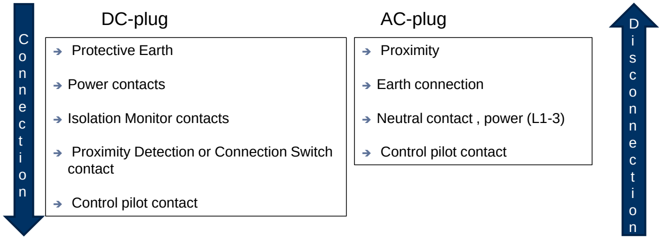


Fig. 8. Contact sequencing for ac/dc-plug.

2.5 Charging Cable

EV charging cables are used to connect electric vehicle charging devices and charging infrastructure to transmit power to electric vehicles and are equipped with a certain amount of signal lines, control lines, power auxiliary lines, etc. to ensure accurate control of the entire charging process and safe operation, Fig. 9. Charging cables are generally used in charging stations [41], parking lots, and other areas. Portable charging cables can be placed in the vehicle. According to the current and power must be selected suitable cable size.

Table 1. Standard for cable

IEC standard	IEC 62893-1/2/3:2017
European standard	EN 50620:2017(less than 35mm2)
Chinese standard	GB/T 33594-2017
US/Canadian Standard	UL2263
Japanese standard	JCS 4522, PSE

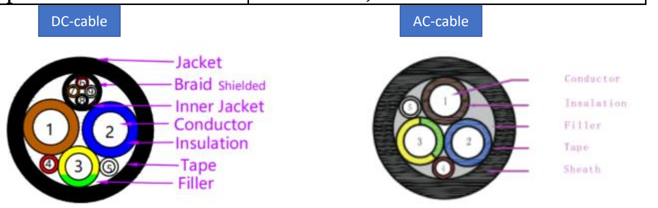


Fig. 9. DC/AC-Charging cable [32].

3. Requirements for Inductive Charging System

Inductive charging allows no user intervention, protection from weather and vandalism safe charging. Typically, the primary coil of the transformer is either embedded in the road surface or formed as a charging plate placed on the ground and is connected to the power grid by means of suitable electronics. The secondary coil of the transformer is typically permanently mounted in the underbody of the vehicle and in turn connected to the vehicle battery by means of suitable electronics, Fig. 10. For power transmission, the primary coil generates a high-frequency alternating magnetic field which penetrates the secondary coil and induces a corresponding current there. Since, on the one hand, the transmissible power scales linearly with the switching frequency and, on the other hand, the switching frequency is limited by the control electronics and losses in the transmission path, the typical frequency range is 20 - 150 kHz [33].

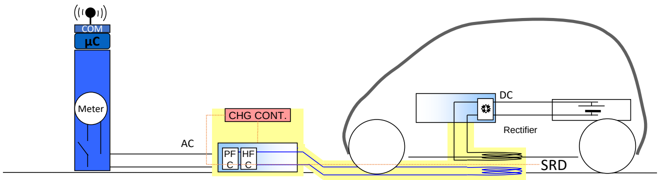
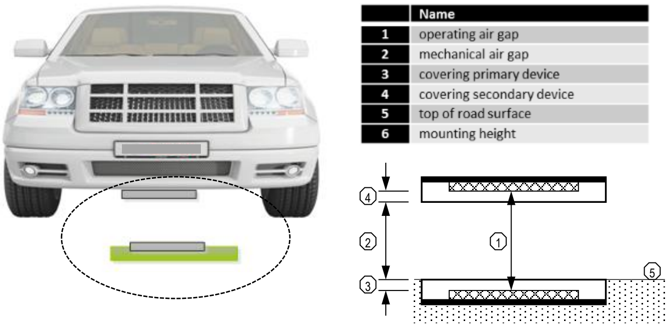


Fig. 10. Eco System for inductive charging system.

However, the inductive charging system requires some measures, such as a device to detect foreign objects in the air gap, in order to protect living creatures as well as the system itself from damage. Likewise, the vehicle must be positioned as precisely as possible above the coil embedded in the ground, as otherwise charging takes place with increasingly poor efficiency and the maximum transmittable power also decreases. Here are the important requirements for the inductive charging system.

3.1 Air Gap Between Vehicle and Charging Station

The air gap between the primary and secondary coils plays an important role for the maximum energy transfer, Fig. 11. For this purpose, the optimum air gap between the coils must be selected. For chassis lowering, decrees of the BMVIT (Federal Ministry for Transport Innovation and Technology) and TÜV data sheet 751 [34]. According to the BMVIT decree, the ground clearance (distance between the lowest point of the body and the road) must be at least 11 cm. It is measured when the vehicle is loaded with 75 kg (equivalent to the standard weight of a driver). The requirement is minimum air gap between the primary and secondary coil to be greater than 11 cm. Higher air gap leads to increase in conduction leakage.



	Name
1	operating air gap
2	mechanical air gap
3	covering primary device
4	covering secondary device
5	top of road surface
6	mounting height

Fig. 11. Air gap between vehicle and charging station.

3.2 Positioning of the Coils

Energy is transferred inductively via the air gap between the coils. To realize the most efficient energy transfer possible, the highest possible coupling between the two coils must be achieved, which is equivalent to minimizing the stray field. With increasing offset between the coils, losses increase, and efficiency is reduced. The requirements are to use optical sensors to enable fine positioning with a maximum transverse and longitudinal offset of ±100 mm and a maximum twist of ±2 ° on a charging station for inductive charging in order to achieve an efficiency of > 90 % during the charging process. (In the application rule [33], a positioning tolerance of (<100 mm) is requested, Fig. 12.

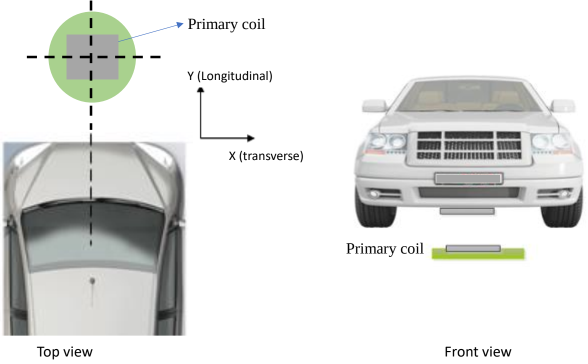


Fig. 12. Positioning of the coils.

3.3 Determination of the Magnetic Field Strength

In order to protect people, farm animals and property from the effects of pulsating electromagnetic fields, various protection goals have been defined according to [33]:

- Protection Goal 1: Protection of persons and animals against the negative effects of electromagnetic fields or waves.
- Protection goal 2: Protection against indirect effects of electromagnetic fields or waves, in particular with regard to or waves, in particular with regard to heating and the risk of burns in the event of direct contact, ignition and fire.

To achieve this protection goal, protection areas are defined to specify areas in and around vehicles that meet uniform protection goals, Fig. 13:

- Protection zone 1: Operating zone (outlines of primary and secondary equipment)
- Protection zone 2: Transition zone (1 to 3)
- Protection zone 3: Public area
- Protection zone 4: Vehicle interior

The requirements is for Maximum allowable limit for public access areas (Zone 3 & Zone 4) ≤ 6.25µT @ 3-150 kHz. This magnetic field strength must be considered when designing electrical coils and power.

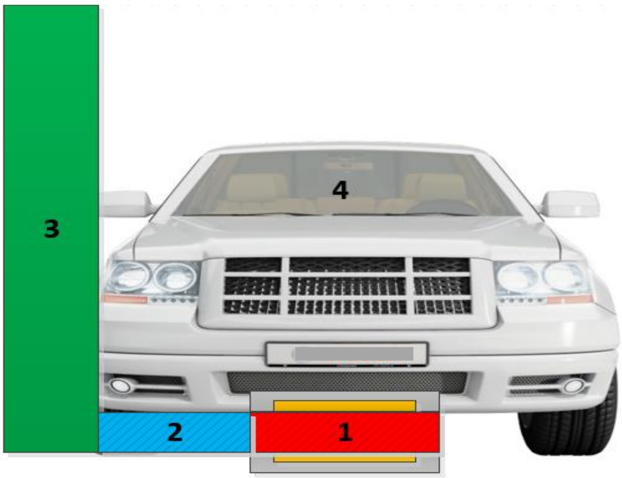


Fig. 13. Safety and personal protection zone for the determination of the magnetic field strength.

4. Requirements for Automated Charging System

To improve user comfort, plugging and unplugging should be automatic (user comfort). In addition, for high power charging (> 50 kW), an automatic plug-in system is useful because the cables and equipment are very heavy (up to 10 kg). Therefore, some drivers, e.g. older drivers, will not be ready to handle such heavy cables.

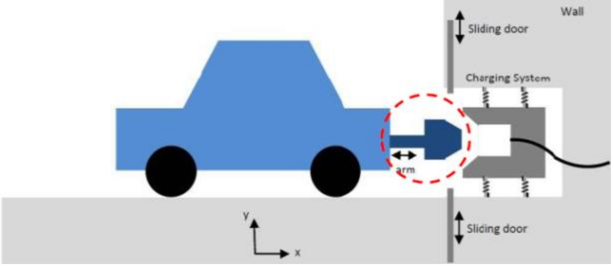


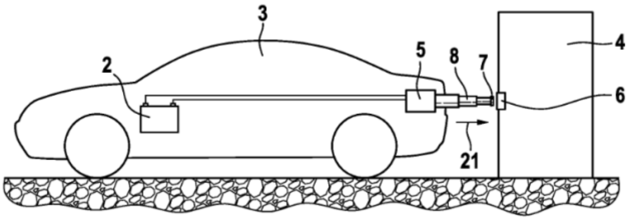
Fig. 14. Eco System for automated charging system.

Most automotive manufacturers would like to offer their vehicle customers with electric drives an automated fast charging option in addition to the conventional charging socket [39] for normal or type 2 plugs. Automated charging is therefore ideally suited to the requirements of the numerous OEMs and customers or users, not only from an economic point of view but also in terms of feasibility.

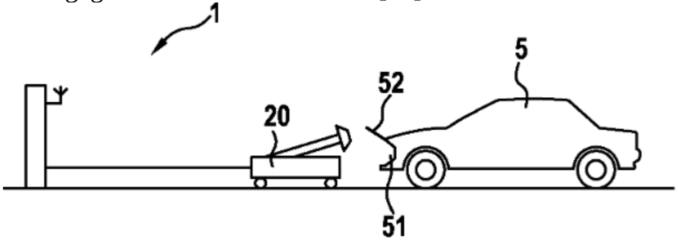
A significant advantage of automated conductive charging is the efficiency, which is close to 98% compared to 90-94% for inductive charging. Furthermore, the placement and dimensioning of the charging unit on the vehicle (front, rear, underbody) is much more variable and independent of the battery position in the vehicle. The installation space required for a conductive docking station and the resulting weight and costs are also expected to be lower on the vehicle side. In addition, ground clearance is not necessarily restricted. The risk of damage is much lower. Moreover, system costs at the charging station can become more favorable due to variability and multivariable charging units. Commercial fleet customers can thus install automatic conductive charging points, so-called docking stations, at their existing loading ramps with relative ease.

4.1 Configuration of Charging Connection

The automated charging system can be built either in the vehicle or in the charging station [35], Fig. 15. It is important for automated charging system where should the connector system be built in the car or in charging station. The answer and requirement of OEM for this is in the charging station due to reduction of cost, weight and integration effort.
To start a safe charging process, the positioning tolerance between plug and socket must be fine-tuned. Sensor based methods can be used for this. The positioning should be functional in different weather and time of day.



a. Engagement from car to station [36]



b. Engagement from station to car [37]
Fig. 15. Configuration of charging connection.

4.2 Charging Plug and Type of Current

Basically, the charging of the HV battery was done either with the alternating current (AC) or direct current (DC). It is requested HPC DC charging with automatic charging systems especially truck from OEM.

Charging plug can be either standard plug type (e.g., Combined Charging System) [38] or individual plug type [39], see Fig. 15.

5. Comparison of the Charging Systems

5.1 Comparison of Charging Process and Charging Power Between Conductive and Inductive

The charging power is decisive for the duration of a charging process. The greater the charging power (P) of the vehicle and the charging station, the faster the electric vehicle charges. The charging power depends on the number of phases, the voltage and amperage of the power connection for the charging station.

Here the charging cable for a conductive charging system is examined [43]. The charging cable is plugged into the vehicle. Low level communication is started between EV and EVSE, lock charging cable, perform insulation test. Then both EV and EVSE must be mutually authenticated. After successful autehtification, will adjust voltage level to HV battery, close pre contactor. EV sends its requests for charging (PowerDelivery) current and voltage demand to EVSE [42]. EVSE turns requested current and voltage (CurrentDemand) to EV and closes the main contactors. Then the power transfer from EVSE to EV is started and the battery voltage increases in the charging mode, Fig. 16. Usually, the current is defined by the charging strategy. This charging current curve (I) can show different current curves. However, in order to prevent excessive charging currents from flowing, which would damage the HV battery and cause it to age more quickly, the charging currents are limited.

These limit values are also set depending on the battery temperature or the battery aging state (SoH) and are specified by the BMS. The maximum charging current is therefore essentially oriented to the limits of the BMS. The charger connected to the EV complies with the limit values and charges the battery with the permitted current. In the SOC range between 20-80%, the charging power increases due to the product of increasing battery voltage and constant charging current. In the SOC range between 80-100% the charging power decreases because the charging current decreases continuously at constant battery voltage (U-Bat). Inductive charging has low efficiency (η) in comparison Conductive charging due to high power dissipation (high air gap, coil positioning), Fig. 17.

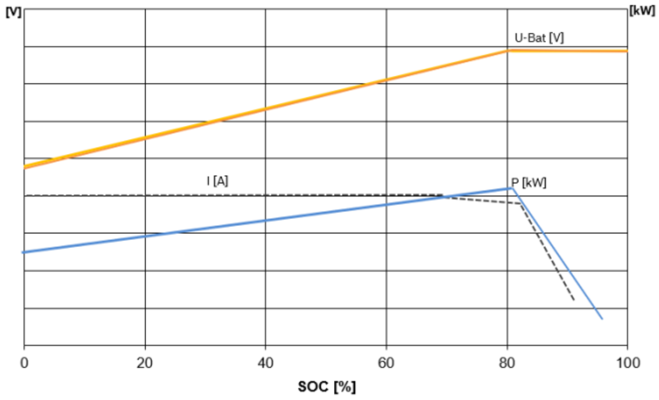


Fig. 16. Maximum possible power consumption of the battery of a charging process for conductive systems

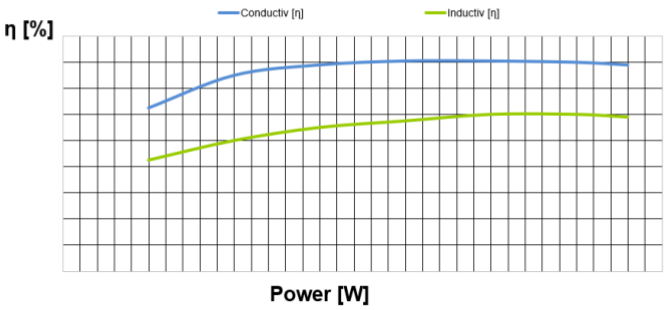


Fig. 17. Comparison of charging power and efficiency between conductive and inductive.

5.2 Comparison of charging process and charging power between conductive and inductive

For the first time is All three charging systems with different criteria, requirements compare, and the results shown in Table 1. Automated Charging System offers more potential with combination Automated driving for the future because of economy, customer convenience.

Automated Charging System leads to considerable convenience and other advantages: There is no need for cumbersome user intervention (e.g., getting the cable out of the trunk, plugging, and unplugging the connector, especially in wet and cold conditions). Thus, the automatic plugging system brings more safety and convenience for end users.

The energy transfer with inductive charging from coils to the battery of the electric vehicle causes energy losses of 8-15 % depending on the distance, geometry, and quality of the coils. If there is a positioning offset between the coils, these losses can increase further. Thus, inductive charging brings in comparison other low efficiency (<92%) and the standardization so far unresolved.

Inductive charging leads to high weight and cost due to additional coils in vehicle. Due to significant additional costs compared to conductive charging, widespread implementation of inductive technology is not expected for the time being from an economic point of view.

Compared to inductive charging, EVs can be charged more quickly using the automatic plug-in system, since only very low transmission losses occur.

Conductive charging without an invoicing system in the private sector is associated with relatively low additional electricity costs of €0.01/kWh since a grid connection with the required power usually already exists at the private parking space [40]. A comparison of the average additional electricity costs between conductive and inductive charging shows that inductive charging is expensive. Inductive charging adds additional electricity costs due to efficiency losses. The difference between inductive and conductive is largest for residential charging. With a difference of 0.19-0.37 €/kWh, the use of inductive charging in the private sector does not seem realistic from an economic point of view. The situation is different in the public sector, where a larger number of vehicles per charging station better distributes the additional costs incurred [40].

The conductive and automatic plug-in system allows more freedom for smart grid due to energy management services and applications [44. 45].

Table 2. Comparison of charging systems

Criterium /requirements	Conductive	Inductive	Automated
Comfort	--	++	++
Efficiency	+ <96%	o <92%	+ <96%
Add. cost (Vehicle side)	++ reference	--	++
Additional weight (vehicle side)	++ reference	--	++
Installation and maintenance	+ reference	-	++

costs (charging station side)			
Standardization	+ (CCS, GB)	o	o
Charging duration	++ reference	-	++
Charging cost at home use case	++ reference	--	++
Charging cost at industrial use case	++ reference	--	++
Smart grid	++ reference	+	++

5. Conclusions

The future of electric mobility depends on charging systems, as charging systems determine charging performance and charging times of electric vehicles and safety, comfort, and costs for end users. The development and implementation of the charging systems depends on the requirements.

This paper analyzes, evaluates, and summarizes the requirements from current norms, standards, and laws for three charging systems (conductive, inductive and automated) and provides recommendations.

The paper compares the regulation of the maximum possible battery charging power for a charging process and the charging performance and efficiency between conductive and inductive charging systems. Conductive charging has high efficiency compared to inductive charging because of few powers' dissipation.

All three-charging system are compared with each other in terms of performance, cost, convenience. Inductive charging brings few advantages due to significant extra cost, few efficiencies and safety due to electromagnetic fields and positioning of coil compared to conductive charging and Automated Charging System.

For the first time, the impact of the three charging systems on electrical grids, smart grids and installation and maintenance costs as well as different use cases (home charging or public charging) is studied and discussed in detail. Automated charging system brings more opportunity for the future in terms of significant improvement of customer acceptance (secure, convenient, and fast charging) and economic efficiency as well as combination with automated driving.

Thus, this paper provides a unified view and evaluation of three charging systems considering the current norms, standards, and an overview of the required parameters as well as the current status and future forecast for electric vehicle and charging stations.

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