A REVIEW ON ELECTRICAL VEHICLE, ENERGY STORAGE SYSTEM, EV CHARGING STATIONS AND THEIR IMPACT ON GRID

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ABSTRACT

Electric vehicles (EVs) are becoming more prevalent in the transportation sector every day, but traditional internal combustion engine (ICE) vehicles still dominate. To promote the adoption of electric vehicles and achieve sustainable transportation, impediments must be removed, which include high-cost EVs, range anxiety, a lack of EV charging infrastructure, and grid pollution caused by EV chargers. The high cost of EVs is due to costly energy storage systems (ESS) with high energy density. This paper presents a detailed overview of EV technology, focusing on electric vehicle supply equipment (EVSE), energy storage systems (ESS), and electric car chargers. This paper focuses on the negative effects of EV chargers as well as possible solutions. In the final section of this paper, the international standards established by various institutions and universally adopted are discussed, and finally, the approaching advancements in EV technology are discussed.

1. INTRODUCTION

The country's economic and social development depends mainly on the existing transportation sector in the country [1]. Internal combustion engine (ICE)-powered vehicles currently hold the majority of the market share. The tailpipe emissions and exhaust from these have a direct impact on the climate, and the pollutants potentially reduce air quality, which has negative consequences for human health and the environment [2], [3]. The transportation sector is responsible for about 23% of the total CO2 that results from the combustion of fossil fuels [4].

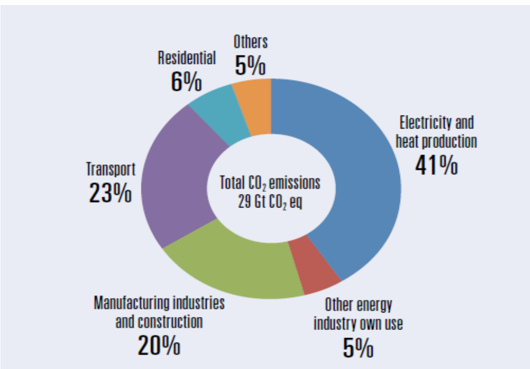

Fig 1: Sector-wise C02 emission from fuel combustion

Fig 1 shows the sector-wise emission of CO2 from the combustion of fuel and is likely to increase with urbanization, industrialization, and with an increase in the number of vehicles in the coming future [5]. There is a need to find a transit option to alleviate the aforementioned difficulties.

The inclusion of electric vehicles (EVs) in the transportation sector is the best option for reducing tailpipe emissions that can improve the air quality and therefore reduce the adverse effects of ICE-based vehicles [1]. Moreover, EVs are comparatively efficient, have better performance, and have a lower cost per mile as compared to ICE-based vehicles.

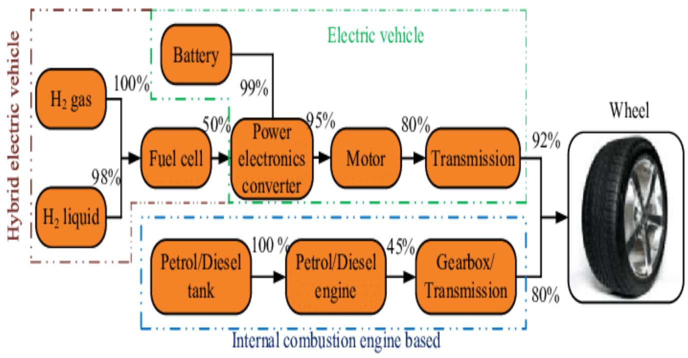

Fig 2: Efficiencies of different vehicles.

The electric motor that drives EVs utilizes 80-85% of the total energy that is supplied through the batteries compared to 12-30% that the ICE-based vehicles utilize [6].Fig 2 shows that EVs have a higher tank-to-wheel efficiency than ICE-powered vehicles.

On December 5th, 2015, 195 countries participated in the Paris Climate Conference and adopted the first ever universally and legally adopted agreement on climate change [7]. At the conference, growing concerns about climate change were addressed, and governmental policies to endorse the use of electricity in the transportation sector were proposed. The transportation sector currently accounts for 23% of all CO2 emissions by mankind, and this figure is expected to rise at an alarming rate as urbanization and industrialization develop [4].

Shifting from petroleum or fossil fuel-based transportation to an electricity-based transportation system has evolved an idea of EVs that are powered through an on-board energy storage system (ESS), with the latter being powered by electricity. The battery storage must be able to meet the EV's energy requirements. Recent research and technological breakthroughs in the last few years have proposed the use of Li-ion batteries in electric vehicles [8], [9]. Despite improvements in Li-ion batteries, the energy density is 200–300 Wh/kg, which is much lower in comparison to petroleum (13,000 Wh/kg). Due to this, the driving range of an EV is limited to one complete charge of the battery and there is always "range anxiety," i.e., a fear of having no charge and also being unable to charge at the desired moment [6].

Another impediment to widespread EV adoption is the lack of adequate EV charging infrastructure that can compete with and replace existing charging stations [10], [11]. Furthermore, the charging infrastructure deployed must minimize harmful harmonic impacts on the electric utility distribution system [12] and [13]. As a result, developing EV charging infrastructure, including other refueling stations with little impact on the existing electric utility distribution system, is critical, especially in areas where extended travel is required (highways). Furthermore, the proposed EV charging infrastructure must take into account industry standards, current technology, and government policies [14].

The EV charging infrastructure is mainly categorized into two categories: (a) inductive power transfer (IPT) or wireless power transfer (WPT) and (b) conductive power transfer. Both have advantages and disadvantages compared to one another. These are further separated into on-board and off-board facilities for charging [15], [16]. On-board EV charging infrastructure means the EV charger circuitry is placed inside the EV along with the ESS, while off-board EV charging infrastructure means the charging circuitry is not an integral part of the EV.

The main idea of this paper is to develop the off-board charging infrastructure that can be deployed similar to the refueling stations and can elevate the bottleneck in the vast adoption of EVs due to the lack of availability of proper EV charging infrastructure. Furthermore, the designed EV charging infrastructure is reliable, resilient, flexible, cost-effective, and meets IEEE 519-2014 power quality (PQ) criteria.

This study also examines the technology underlying the ESS and introduces numerous kinds of commercially available electric vehicles. The in-depth review on the electric vehicle supply equipment (EVSE) which includes mainly EV charging cords, residential and public charging stands, plugs, power outlets with different recommended power levels by the society of automotive engineers (SAE) is presented. Finally, a detailed state-of-theart evaluation of the various topologies for EV charging stations, as well as their negative effects on the electric utility distribution system, is presented.

2. EV CLASSIFICATION

Based on the combination of electrical and fuel energy that drives them EVs are broadly classified into three main categories.

BATTERY ELECTRIC VEHICLE (BEV)

A battery electric vehicle (BEV) is based only on an electric motor and ESS and does not need the support of traditional ICE. They are plugged into an electrical supply to recharge their ESS (batteries) when they are exhausted. BEVs can also recharge their batteries through the regenerative braking process, which uses the vehicle's electric motor to assist in slowing down the vehicle and to recover the energy which is usually converted to heat energy by the brakes [17]. Some commercially available BEVs are Tesla Model S, Nissan Leaf, BMW i3, Mitsubishi iMiEV, Smart EV, Ford Focus EV, etc. The main advantages of BEVs are:

- Fast and smooth acceleration.
- It is simple to charge at home.
- Zero tailpipe emissions.
- Not necessary to refuel with gas or oil.
- Overall low cost of operation.

Apart from the benefits, there are some drawbacks

- Shorter drive range as compared to ICE-based vehicles.
- Expensive than ICE-based vehicles, however, the payback period from fuel savings is only about 2-3 years.

PLUG-IN HYBRID ELECTRIC VEHICLE (PHEV)

The plug-in hybrid electric vehicle (PHEV) uses an electric motor and ESS along with the ICE. The feature of having ICE in PHEV makes it a more suitable and promising option for long-distance journeys. The operation of PHEV is divided mainly into two modes; namely, charge depleting (CD) mode and charge sustaining (CS) mode.

The advantages of PHEVs are:

- Long driving range.
- Low fuel consumption than conventional ICE-based vehicles.
- Low emission of pollutants in the environment.

Some disadvantages of PHEVs are:

- Environmental pollution is not eliminated.
- Expensive to operate as compared to BEVs.

HYBRID ELECTRIC VEHICLE (HEV)

Both, ICE and the electric motor drive the vehicle at the same time.

However, HEVs do not have the facility of charging from the utility grid, all their driving energy comes from the fuel and the regenerative braking process in the vehicle [18], [19]. Some commonly available HEVs are Audi Q5 Hybrid, Acura ILX Hybrid, Cadillac Escalade Hybrid, BMWActive Hybrid 3, BMWActive Hybrid 5, BMWActive Hybrid 7, Honda Civic Hybrid, Honda CR-Z Hybrid. Some advantages of HEVs are:

- Zero tailpipe emission is not achieved.
- The mechanism of operation is complex.
- Expensive to operate as compared to BEVs.
- Cheaper compared to ICE-based vehicles.
- Lower fuel consumption compared to ICE-based vehicles.

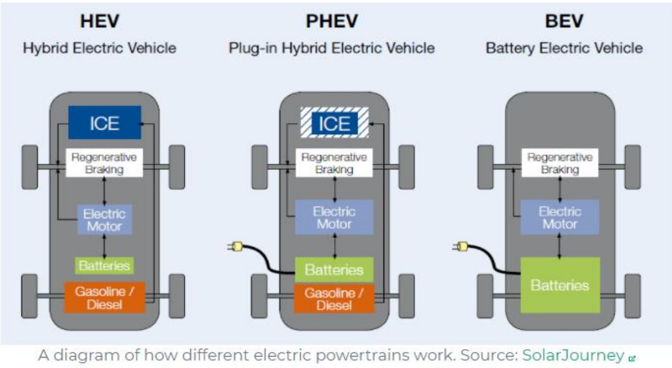

Fig 3: Architecture of (a) HEVs. (b) PHEVs. (c)BEVs.

Fig 3 depicts the architecture of BEVs, PHEVs, and HEVs, which explains how they work.

3. ENERGY STORAGE SYSTEM (ESS)

To make EVs acceptable for long journey, the ESS (batteries) in the EVs must meet high energy density parameters in order to improve the driving range of the EVs. High power density for the fast acceleration of EVs; a large number of life cycles; wide range of temperature in which they can operate and low maintenance, the capability of accepting high power repetitive charges from regenerative braking operation [20].

The internal DC resistance (DCR) of each cell determines the rate at which a battery is charged. Batteries used in EV applications require more safety precautions because frequent fast charge and discharge operations in the EV battery lead to the generation of excessive heat. There are different types of commercially available batteries that are now employed in various electric vehicles [21]. The various chemistries used in EV batteries are listed below.

- NICKEL-METAL HYDRIDE (NiMH) BATTERIES
- NICKEL-CADMIUM (NiCD) BATTERIES
- LITHIUM-ION (LI-ION) BATTERIES

Charging of ESS depends on the rate of transfer of energy, Fast charging solutions at high power levels are useful for EV owners who want to charge their batteries faster. The chemistry involved in a battery determines the power level at which it can be charged [22]. Furthermore, the charging methods/techniques adopted are also responsible for the fast charging of EVs. Several charging techniques are listed below

- CONSTANT CURRENT-CONSTANT VOLTAGE (CC-CV) MODE
- MULTISTAGE CONSTANT CURRENT-CONSTANT VOLTAGE (CC-CV) MODE

4. EV SUPPLY EQUIPMENT

The electric vehicle supply equipment (EVSE) supplies electricity to charge an electric car's battery. EVSE is commonly known as EV charging stations or EV charging points. EVSE includes the electrical power conductors, related equipment, software, and communications protocols that deliver the electrical energy efficiently and safely from the electric utility distribution system to the ESS of the EVs. The block diagram of a charging pool with EV charging station is shown in Fig 5.

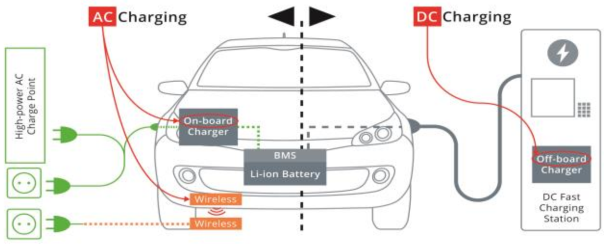

Fig 4: EV Charging station

A charging pool consists of single/multiple charging stations and the parking bays. The charging pool is operated by one charge point operator (CPO) and a global positioning system (GPS) coordinates at a location. The charging pool is related to ``cartographic view'', guiding tools, and the features that represent a charging infrastructure on a map.

A Charging Station is a physical structure having one or more charging points that share a common user identification interface (UII). Some charging stations have radio-frequency identification (RFID) readers, displays, and LEDs, while others are only `Plug & Charge', and do not have buttons, displays, etc.

The electric energy is delivered to the EV through the charging point. A charging point has one or many connectors to accommodate different types of connectors (discussed latter). As shown in Fig 5, only one connector is used at a time.

Fig 5: Photograph of charging pool

The connector is a physical interface between EV and its charging station that provides electricity for the charging purpose, as shown in Fig 5. Different types of connectors are discussed and explained in the latter part of this paper.

5. CLASSIFICATION EV CHARGERS

Single-phase or three-phase chargers with unidirectional or bidirectional power flow capability are required for EV charging [16], [23] [24]. Conductive and inductive chargers are the two types of electric vehicle chargers. Conductive charging technology is well developed while inductive charging technology remains the hot topic for researchers.

CONDUCTIVE CHARGING

To transfer power, conductive charging uses direct metal-to-metal contact between the utility grid and the EV. This charging method has been found to be both efficient and reliable. On-board and off-board charging infrastructures are two types of conductive chargers. The power level of these chargers is limited due to weight, space, size, and cost constraints. On the other hand, off-board EV chargers have no constraints on their size, weight, and space since they are not an integral part of the EV and are installed in public parking bays like those of hospitals, shopping malls, and universities. Fig 6 represents the photograph of conductive charging. On-board chargers are generally used for slow charging purposes, while off-board chargers are intended for fast charging.

Fig 6: Conductive charging for EV's

INDUCTIVE CHARGING

Inductive or wireless chargers work on the principle of IPT, i.e. mutual induction to transfer power from the utility grid to the EV. There is no physical interaction between the power grid and the electric vehicle. Furthermore, they may or may not require isolation transformers for safety reasons, resulting in a smaller size than conductive chargers [25]. However, inductive chargers are comparatively less efficient due to misalignment between the power transferring coils. Inductive chargers are classified into three categories, a) static inductive chargers, b) dynamic inductive chargers, and c) quasi-dynamic inductive chargers. The schematic of static and roadbed inductive chargers for charging electric vehicles wirelessly is shown in Figure 7.

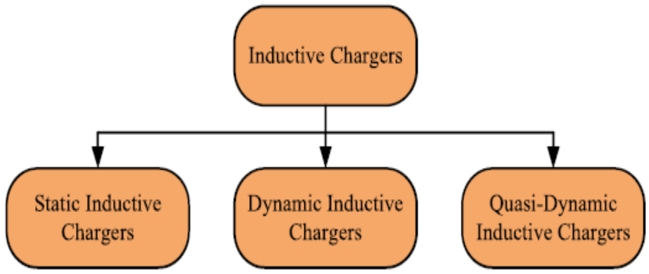

Fig 7: Classification of Inductive charger

UNIDIRECTIONAL & BIDIRECTIONAL CHARGERS

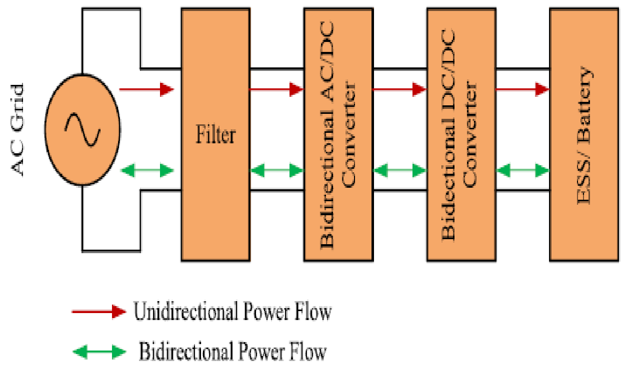

Fig 8: **Unidirectional & Bidirectional charging topology**

Figure 8 consists two alternative power flows between the EV and the utility grid. Unidirectional chargers charge the vehicle but do not feed the energy back into the utility grid. Unidirectional chargers appear to be a promising approach to achieve most utility requirements while avoiding the cost, safety, and performance constraints associated with bidirectional chargers [28], [29].

On the other hand, a bidirectional charger has two power stages; one is an active grid-connected bidirectional ac to dc converter that endorses unity power factor (PF), and the second is a bidirectional dc-dc converter that regulates the charging current [26], [27].

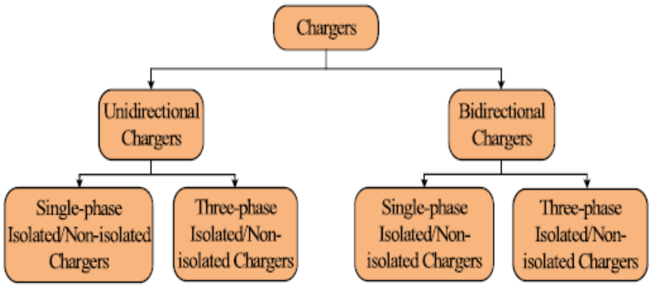

Fig 9: Classification of unidirectional and bidirectional chargers.

Figure 9 shows the classification of unidirectional and bidirectional chargers. Among these single-phase chargers are used for slow charging purposes while three-phase chargers are utilized in fast charging of EVs. Isolated chargers include diode bridge rectifiers (DBR) along with Fly back/ Forward/ Push-pull/ SEPIC/ CUK/ Multilevel circuit configurations, while non-isolated chargers include DBR along with Buck/ Boost/ Buck-Boost circuit configurations.

6. EV CHARGER IMPACT ON UTILITY

The rapid deployment of electric vehicle chargers puts extra pressure on utilities. This problem is magnified in poorly maintained utilities. This section examines the impact of electric vehicle chargers on various aspects of the utility grid, as well as measures to mitigate them.

IMPACT ON GRID STABILITY

The EV load on the grid may raise the problems of stability in grid utility. Many distribution systems work on the verge of instability even without the EV load, thus stability analysis is a must before connecting EV chargers as load. Stability analysis on IEEE 3-bus test system is performed for determining the stability of the grid, with and without the EV charger load [30]. The study confirmed that the EV charger load reduces the stability of the grid.

IMPACT ON SUPPLY-DEMAND BALANCE OF GRID

A study in the city of the United Kingdom showed that increased penetration of EV charging load by 10% caused an 18% hike in the demand from utility grid [32], [33]. To meet the supply-demand balance it is necessary to integrate the RES in the charging station and utilize the smart charging techniques that include coordinated charging [34]_36].

IMPACT ON GRID VOLTAGE

The EV load on the grid may raise the problems of stability in grid utility. Many distribution systems work on the verge of instability even without the EV load, thus stability analysis is a must before connecting EV chargers as load. Stability analysis on IEEE 3-bus test system is performed for determining the stability of the grid, with and without the EV charger load [30].

IMPACT ON SUPPLY-DEMAND BALANCE OF GRID

Study in the city of Australia was carried out to evaluate the effect of uncontrolled EV charging. For this, all EVs in the city were considered and results from the study proved that uncontrolled EV charging increases the load on the grid and this can lead to total blackout if uncontrolled charging is carried out during peak load periods [35], [31]. Thus, the idea of coordinated charging was proposed to avoid blackouts during peak load periods on the grid.

IMPACT ON GRID CURRENT HARMONICS

The non-linear power electronics involved in the EV chargers are responsible for injecting the current harmonics into the grid. The amount of THD in the line current drawn by the EV charger depends directly on the circuit topology of the charger [37]. To reduce the current harmonics, EV chargers involve high-frequency PWM or modified PWM techniques, also matrix converters are involved for multi-phase EV chargers. These high-frequency converters reduce THD in current but increase the charger circuit complexity [38], [39].

IMPACT ON GRID LOSSES

The losses in the grid due to EV chargers are because of increased RMS current which in turn increases the *I* 2*R* losses, where *I* is the RMS value of current drawn and *R* is the equivalent resistance of the grid [31]_[33]. The increased losses in the grid are also responsible for deteriorating the life span of grid components. These losses are increased by 40% during the off-peak charging period, while 62% during the peak period. To reduce these losses the EV charger must draw the input line current with lower harmonic content and at a high power factor.

7. INTERNATIONAL STANDARDS

The international standards are developed by a team of experts and are adopted universally. Various international standards have been developed and published to ensure the successful deployment of EV chargers. These are well-developed to address the EV industry's safety, reliability, and interoperability challenges. Various industries that utilize these standards include EV manufacturers, ESS manufacturers, utility companies, and EV charger manufacturers, code of cials, EV charger safety equipment manufacturers, and insurance companies.

The following are some of the different EV charging standards [40][41] that have been used in the literature:

a. **SOCIETY FOR AUTOMOBILE ENGINEERS (SAE)**

- J1772: EV conductive connector/charging method.
- J2894: Issues of power quality.
- J2836/2847/2931: Communication purposes.
- J1773: Inductive coupled charging.
- J2293: For energy transfer systems to find the requirements for EVs.

b. **NATIONAL FIRE PROTECTION ASSOCIATION (NFPA)**

- NFPA 70: Safety management.
- NEC 625/626: Charging systems for EVs.

- NFPA 70E: For safety.
- NFPA 70B: Maintenance of electrical equipment.

c. INSTITUTE OF ELECTRICAL AND ELECTRONICS (IEEE)

- IEEE 2030.1.1: Quick DC charging for EVs.
- IEEE P2690: Charging network management, Vehicle
- Authorization.
- IEEE P1809: Electric transportation guide.
- IEEE 1547: Interconnecting electric system with distributed resources/Tie Grid.
- IEEE 1901: Provide data rate while vehicles are charged overnight.
- IEEE P2030: Interoperability of smart grid.
- IEEE 519-2014: Power quality standards

d. INTERNATIONAL ELECTROMECHANICAL COMMISSION (IEC)

- IEC-1000-3-6: Issues of power quality.
- EC TC 69: Regarding infrastructure of charging and safety requirements.
- IEC TC 64: Electrical installation, electric shock protection.
- IEC TC 21: Regarding battery management.

e. UNDERWRITERS LABORATORIES (UL) INC

- UL 2231: Safety Purposes.
- UL 2594/2251, 2201: EVSE

f. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION

- ISO 6469-1:2009: Used for on-board rechargeable energy storage systems.
- ISO/CD 6469-3.3: Safety specifications.

g. JAPAN ELECTRIC VEHICLE ASSOCIATION

- JEVS C601: EVs charging plugs.
- JEVS D701: Batteries.
- JEVS G101-109: Fast Charging.

h. ISOLATION AND TECHNICAL SAFETY STANDARDS

- SAE J-2929: This standard is related to the safety of the propulsion battery system.
- SAE J-2910: This standard deals with the electrical safety of buses and test for hybrid electric trucks.
- SAE J-2344: Defines rules for EV's safety.
- SAE J-2464: Standard defines the safety rules for recharge energy storage systems (RESS).
- ISO 6469-1:2009 (IEC): Standard is related to electrically road vehicles, on-board RESS, inside and outside protection of a person.
- ISO 6469-2:2009 (IEC): Safe operation of EVs, protect against inside failure.

8. FUTURE ADVANCEMENT

Since EVs are supposed to take the place of conventional vehicles, the development in technology is growing every day. At present, there are lots of EV charger manufacturers and these are being even deployed in most of the developed and developing countries. However, research is going on towards further improvement and currently, researchers are more focused towards:

- Development of robust and cost-effective off-board and on-board EV chargers with improved power quality at grid and EV side.
- Development of high-voltage (1100 V DC) off-board chargers to reduce the overall footprint of the charging station.
- Development of on-board charger with the minimum requirement of additional PEI.
- New and optimized design of power pads for efficient WPT.
- Optimized planning of EV charging such that the grid stability is improved and the EV owner can earn by selling its extra energy either to utility (V2G operation) or to other EV owners (V2V operation).
- Usage of wide band-gap power semiconductor devices such as silicon carbide (SiC) and gallium nitride (GaN). Key features of these devices are high efficiency, high power density, and low thermal stress.
- Development of ESS with high energy density, low cost, volume, and weight.

CONCLUSION

This paper explains why electric vehicles are needed in the transportation sector and gives an overview of the many components of EV technology. EVSE is mentioned along with the different ESS for EVs. There is a detailed classification of EVs, which includes BEVs, PHEVs, and BEVs. With low-/high-frequency transformers in the front-stage and end stage, several on-board and off-board chargers are addressed. The different charging standards, GB/T, and CCS are discussed along with their specifications and connectors. The IPT concept for charging an electric vehicle while moving is explained. In addition, the negative effects of EV chargers on the grid are discussed, as well as possible solutions. Various international standards for EV technology are described, all of which must be committed to in order for EVs to be adopted successfully in the transportation industry. Finally, future trends and research areas that need to be addressed have been identified.

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