Workshop-PEDSTC 2022

Title:

Charging Infrastructures of Electric Vehicles (EVs): Types, Charger Topologies, and Standards

Presented by:

Dr. Alireza Khoshsaadat

Table of Contents

1. Electric Vehicle (EV): introduction and development trend

1.1. EV introduction

❑ **An Electric Vehicle (EV)** is a vehicle that is powered or propulsed, at least in part, by electricity.

❑ **Main merits of EV:**

✓ Contribution in reducing Green House Gas (GHG): in 2009, the transportation sector emitted 25% of the GHGs produced by energy related sectors;
✓ Quiet operation (reducing noise pollution urban);
✓ Provides the total torque from startup (high instant torque);
✓ Does not require trips to the gas station;
✓ Various onboard energy storage devices (batteries, Ultra-Capacitors (UCs), Fuel Cells (FCs));
✓ Does not use any stored energy or cause any emission while idling;
✓ Regenerative braking to recover the kinetic energy of the vehicle;

❑ **Main limitations of EV:**

✓ High costs (Due to high price of battery pack);
✓ Battery volume and weight;
✓ Short drive range per charge;
✓ Long charging time;
✓ Loading a high demand on power grid.

1.2. EV history

- By the 1900s, EVs had captured a notable share of the leisure car market. Among the 4200 automobiles sold in the United States in 1900, **38% were electric** and only **22% were gasoline**, while another **40% were still steam driven**. Why ICE conquered the market and EVs got lost into oblivion?

- ✓ Very low oil price;
- ✓ Simple operation of Vehicle starter;
- ✓ Problems in battery technology (low energy density cause to Short driving range; and low life cycle);
- ✓ Weak chargers technology;

A few decades stagnation of EVs

- EV resurrection began with **General Motors EV1** production in 1996 and quickly became very popular. Other carmakers, **Ford**, **Toyota**, and **Honda** presented their own EVs as well. **Toyota Prius**, was the first commercial Hybrid Electric Vehicle (HEV), launched in Japan in 1997, with **18,000** units sold in the first year of production.
- Nowadays, the market is dominated by **Nissan Leaf**, **Chevrolet Volt**, and **Tesla Model S**, and **BYD** (mostly in Chinese market).

Nissan Leaf

Tesla Model S

BYD Tang

General Motors EV1

1.3. Statistic of EV trend in the world;

- Some of most **famous EV manufacturers** are: Nissan, Mitsubishi, Chevrolet, Tesla, BYD.

Table 1. Some of first mass produced highway-Capable and Light Utility. EVs.

Model	Market Launch	Global Sales	Sales Through
Nissan Leaf	December 2010	83,000	September 2013
Mitsubishi i-MiEV family	July 2009	>26,000	September 2013
Tesla Model S	June 2012	18,200	September 2013
Renault Kangoo Z.E.	October 2011	11,069	September 2013
Chery QQ3 EV	March 2010	9512	October 2013
Renault Zoe	December 2012	6605	September 2013
Mitsubishi Minicab MiEV	December 2011	4972	September 2013
BYD e6	May 2010	3220	October 2013
Tesla Roadster	March 2008	~2500	December 2012
Bolloré Bluecar	December 2011	2300	September 2013
Ford Focus Electric	December 2011	2167	September 2013

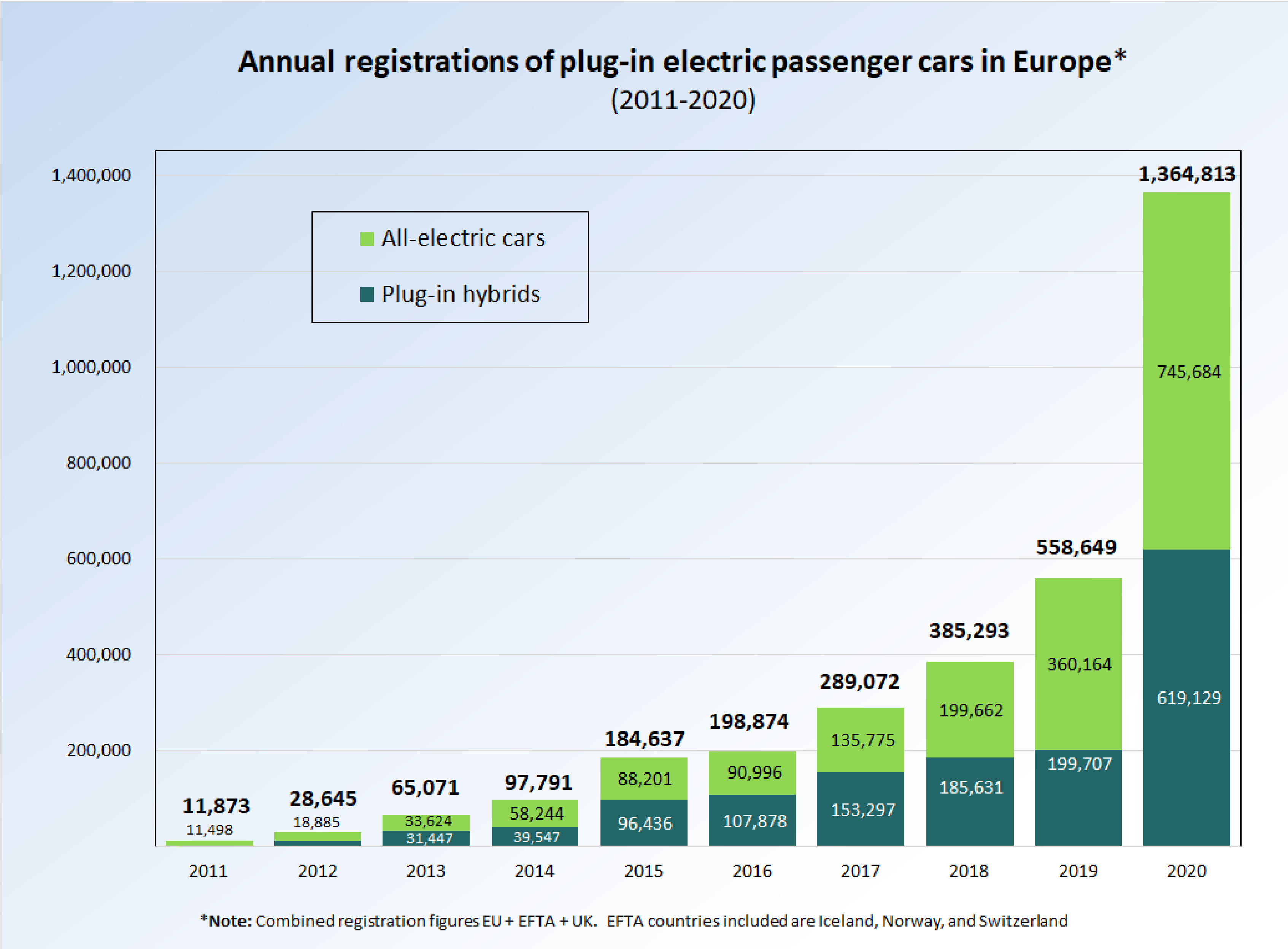


Fig. 1. Annual registration statistics of plug-in passenger EVs in Europe from 2011 to 2020.

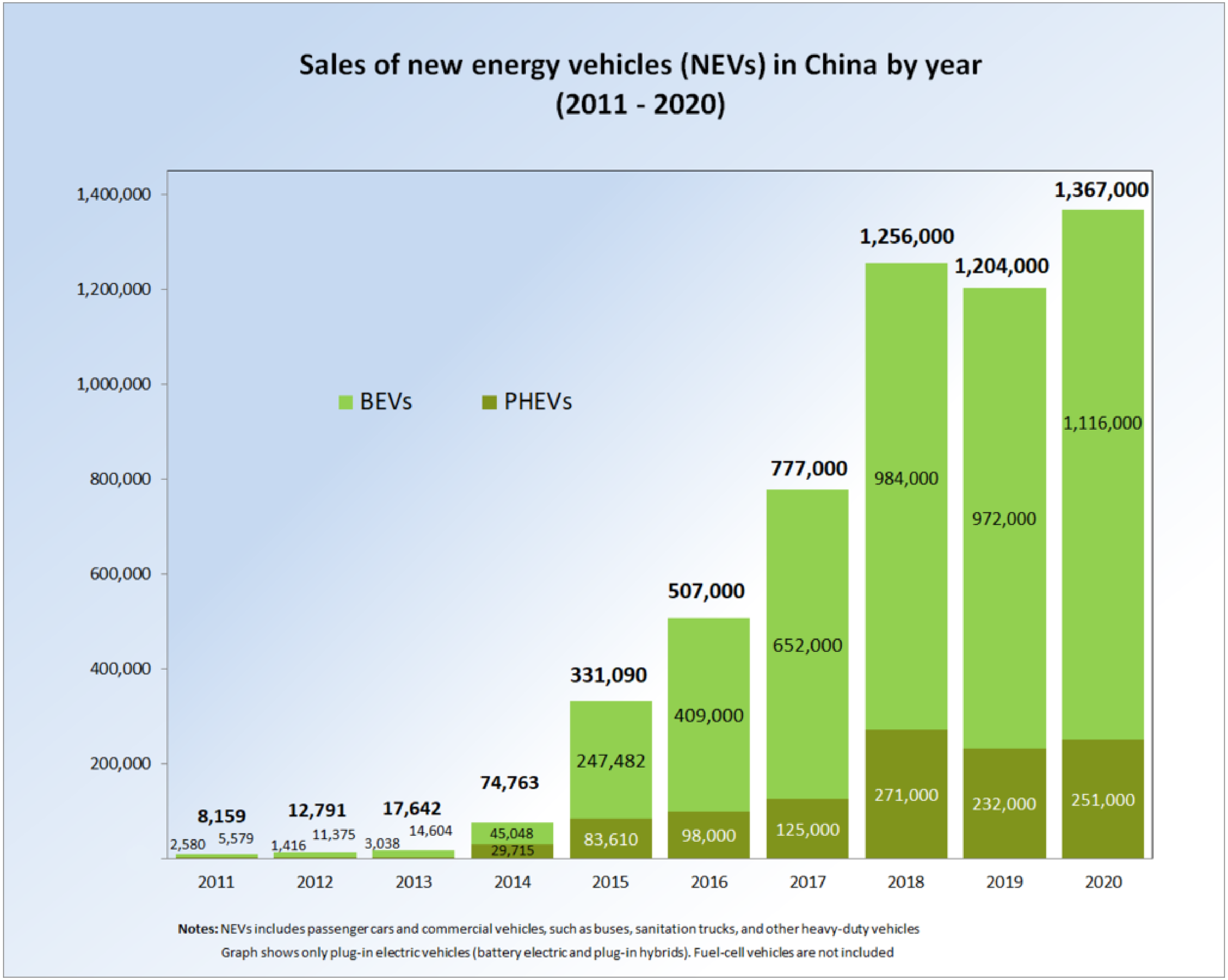


Fig. 2. Annual sales statistics of EVs in China from 2011 to 2020.

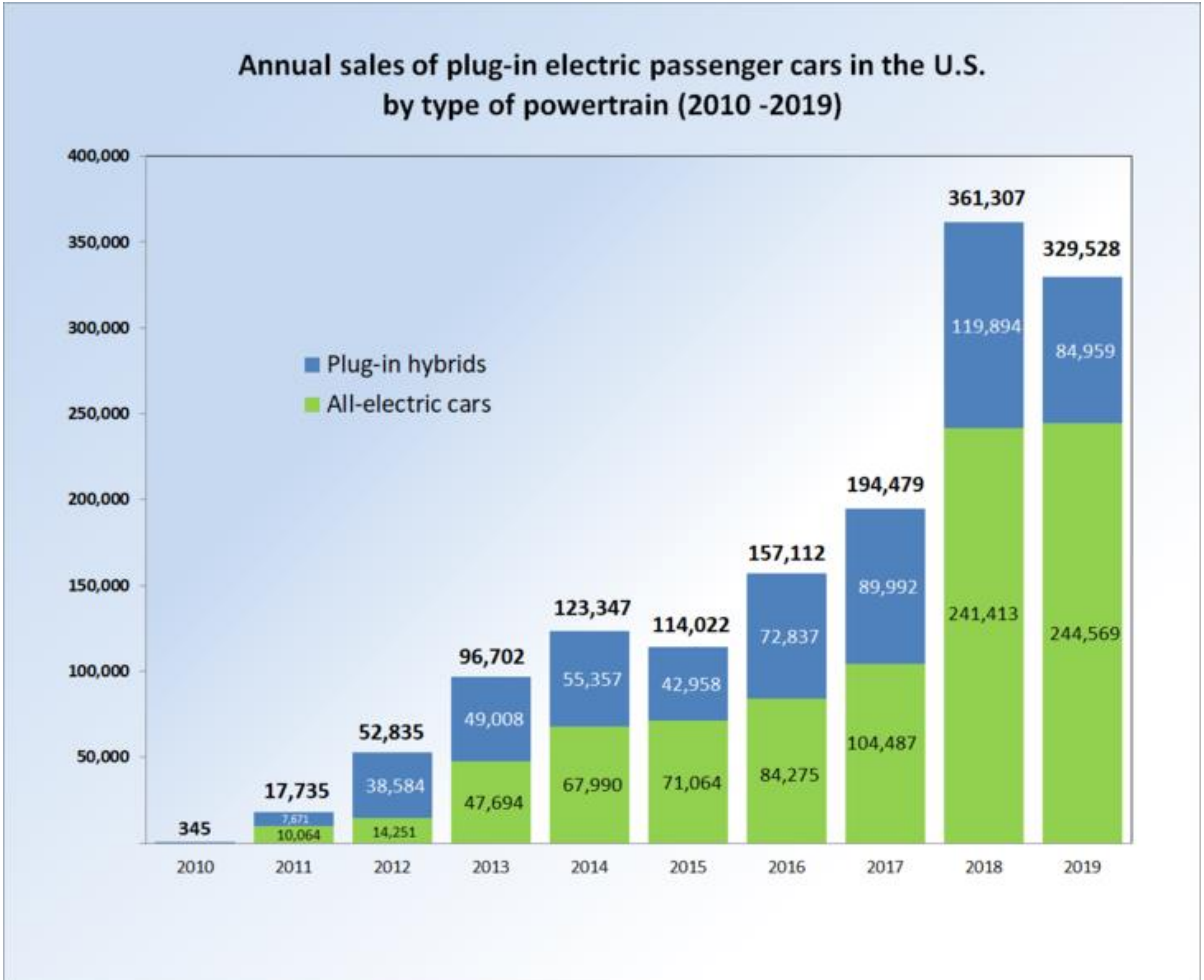


Fig. 3. Annual sales statistics of EVs in the U.S. from 2011 to 2019.

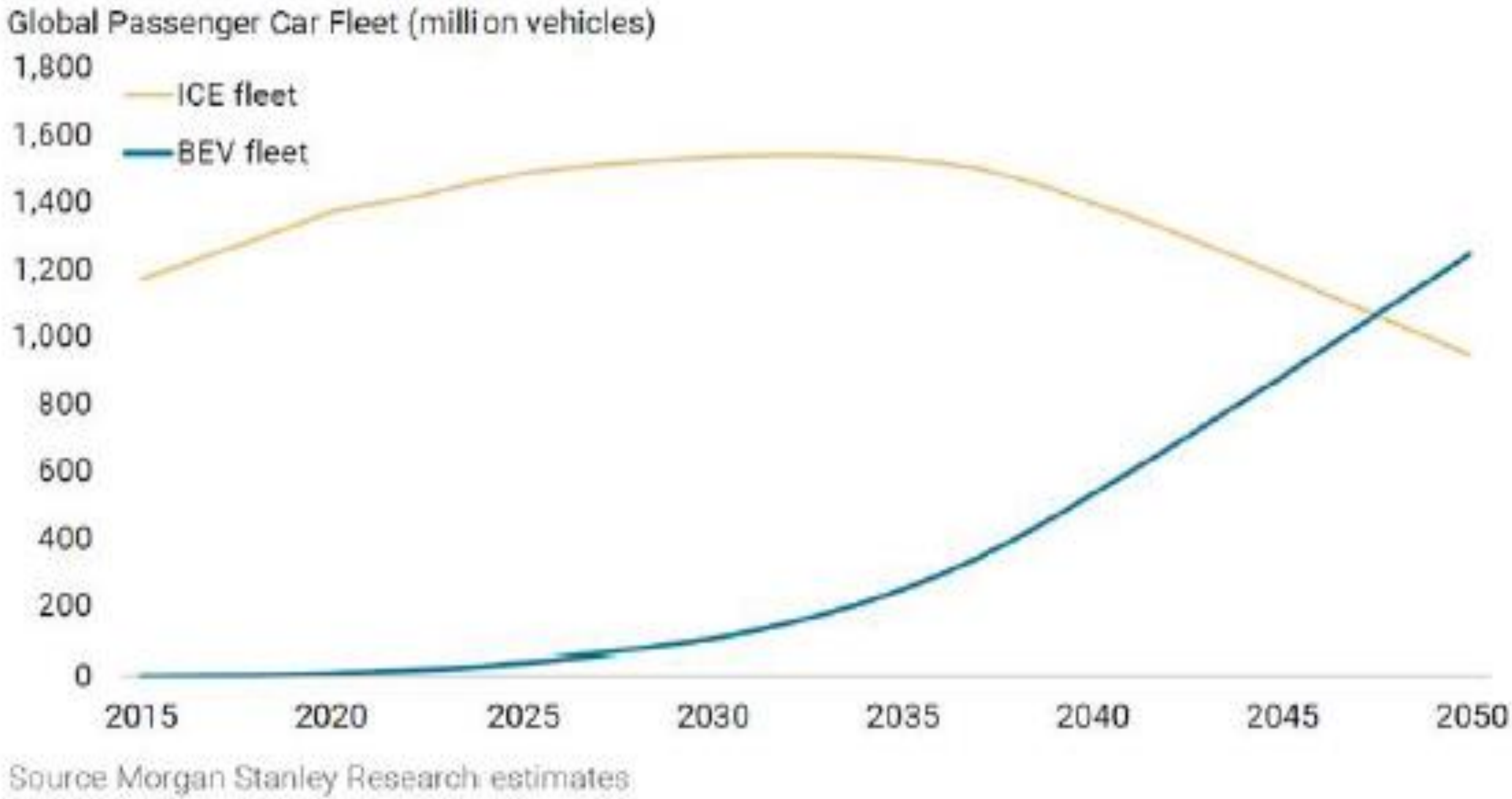
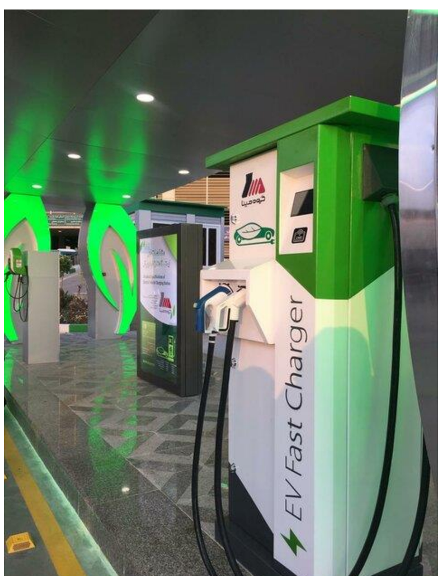


Fig. 4. Number of EVs and ICE Vehicles in a trend to 2050.

2. General features and infrastructure of EV chargers

❑ Important issues that must be considered for an EV charger:

1) **Safety:** The battery charger system must minimize the risk of electrical **shock, insulation, fire**, and **injury** to the end user for a wide range of operating and fault conditions. The principal safety standards are from **Underwriters Laboratories (UL)** in the US and **VDE** in Germany.
2) **Reliability:** The automotive environment is **very harsh**. The same performance is expected whether a car is driven in a **dry heat, a freezing cold, or a humid condition.** The car is exposed to **significant shock** and **vibration** in addition to corrosive solvents, salt, water, and mud. A charger for the EV must have a **long service life** with daily operation. The electrical connector must be designed to withstand over **10,000 insertions** and withdrawals in these harsh conditions and still remains safe for the consumer for the many fault scenarios.



3) **User-friendliness:** Present method of fueling an ICE vehicle is **simple and straightforward.** EV charging must also be simple and should pose minimal challenge to EV users. The basic reason for this, is that **the EV may require daily charging**, whereas the gasoline-powered car may only be fueled once a week or less.

4) **Power levels and charging times:** For EVs to gain widespread acceptance, the charging power levels should be maximized in order to reduce the charging times. However, in practice the power levels can be limited by the **household electrical wiring**, **electrical grid impacts**, **battery chemistries and degradation** due to high charging levels, and, of course, **size** and **cost**.

5) **Standardization:** Market acceptance of a new product can be accelerated by creating a product standard. **A market standard can reduce the cost** by ensuring a larger market with access to more charging points and ease of communication. **An advantage of a commonly agreed standard is that the automotive companies do not have to compete on the charging** but can focus on the vehicle.

6) **Communication:** At a basic level, the plug and cable assembly must not only transmit power, but must also **provide a communications path between the charger and the vehicle in order to ensure a safe and optimized power flow.** Communication has taken on a greater role in society in the twenty-first century as smartphones and the Internet are part of the overall communications and control interfaces. Simple messages relating to **availability, maximum power output, charging time, and problem or fault reporting** are also critical communications.

7) **Compliance (Compatibility):** An electrical equipment (especially a charger) must comply with standards to **limit electrical noise emissions (EMI)**, to protect other electrical devices, for example, cardiac pacemakers, and also **to increase immunity to unwanted emissions from other equipment** or from events, such as lightning strikes.

- The most important infrastructure to have a charging station is the electrical energy source to fed to the charger input. Then, charger converts the input AC power to the compatible DC level to fed to the EVs.

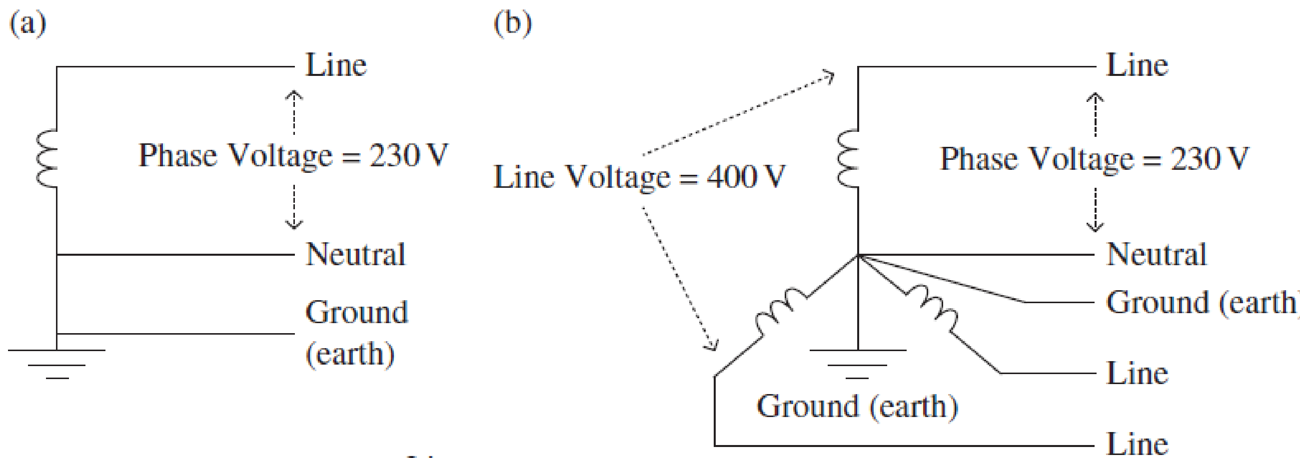


Fig. 5. Basic 230V wiring system. (a) Single phase, (b) three phase.

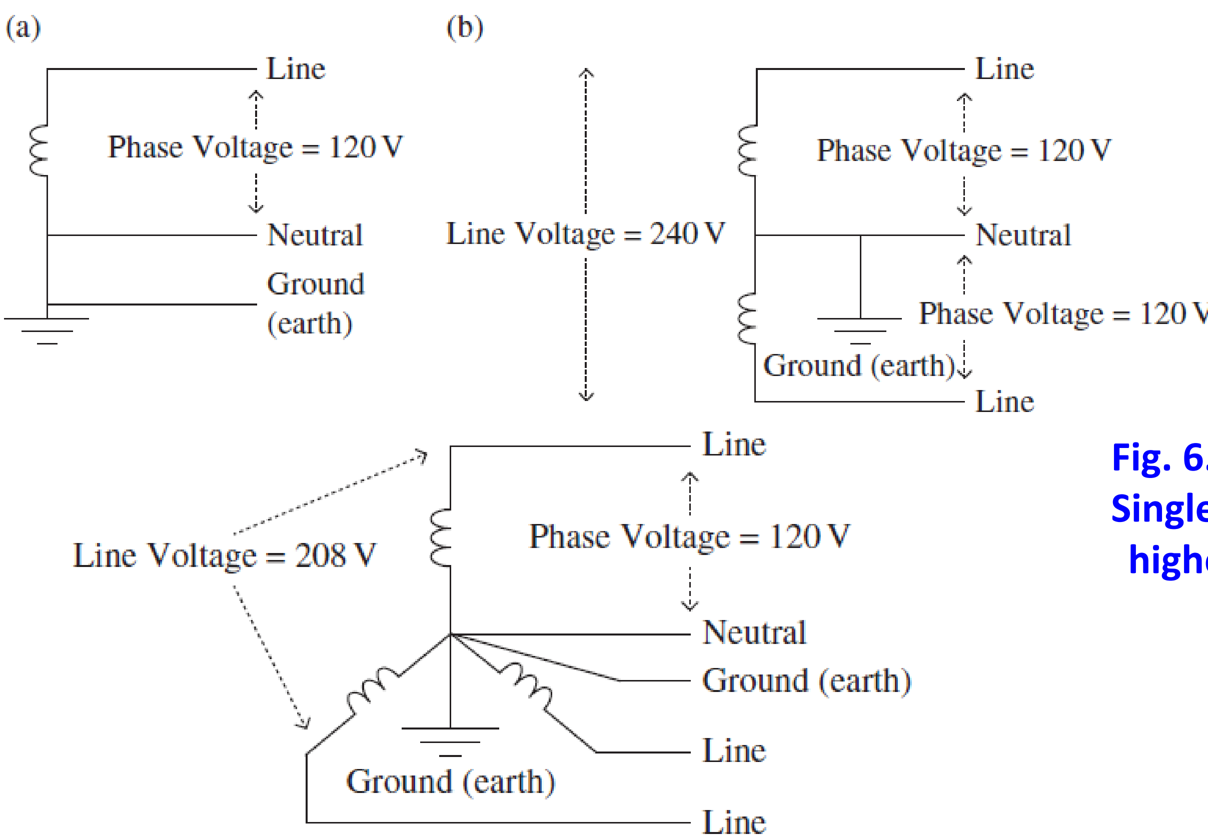


Fig. 6. Basic 100/120V wiring system. (a) Single phase, (b) single phase to achieve higher voltage (240V), (c) three phase.

3. General structure and classification of EV chargers

❑ Basic structure for all of the EV chargers contains two major parts for power converting as:

1) **AC/DC converter with PFC;**
2) **DC/DC converter;**

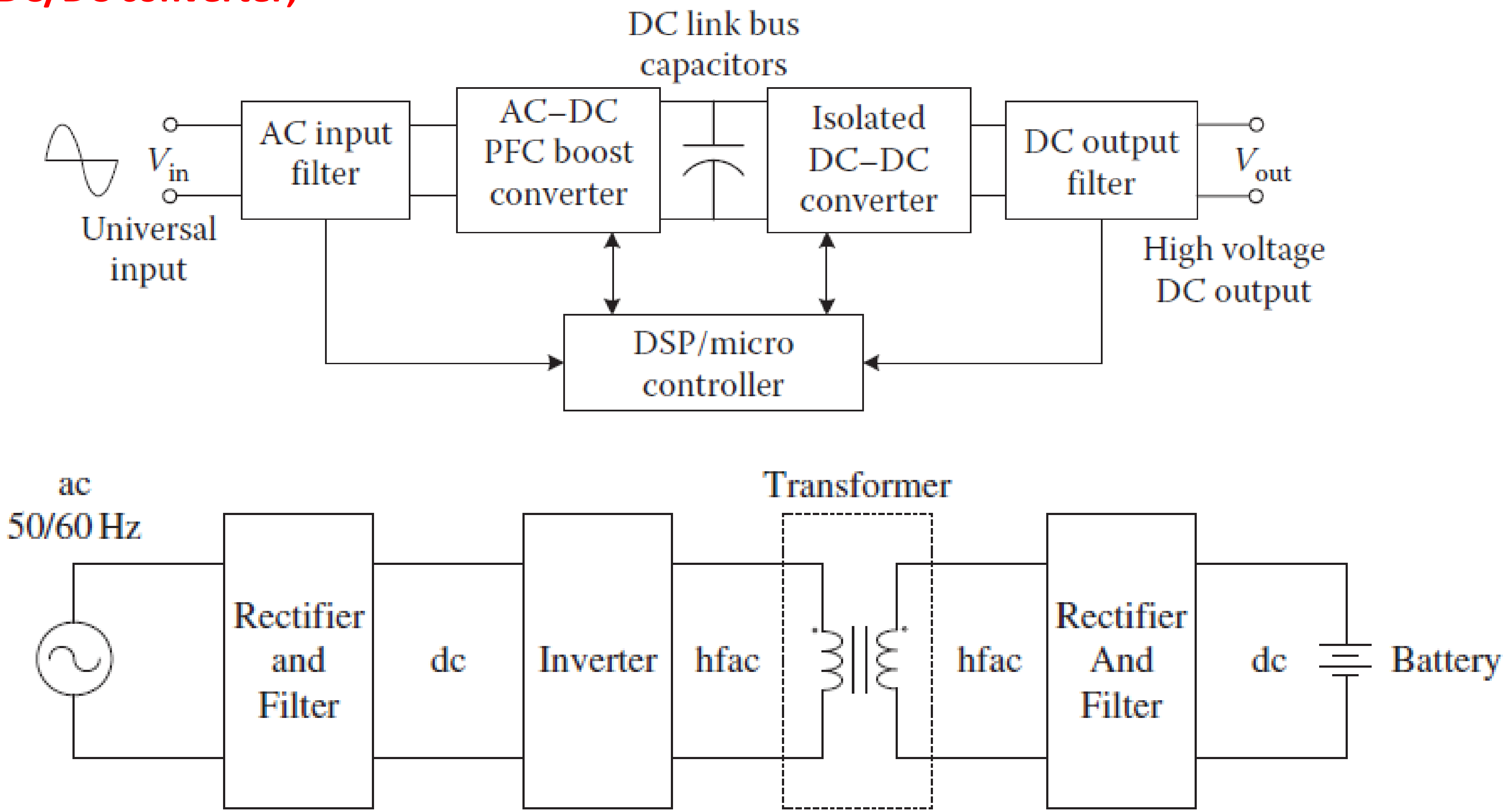


Fig. 7. Basic block diagram of a battery charger in two presentation aspects.

- ❑ Based on the **power level** of the chargers and also **location of the AC/DC/DC power conversion unit** (internal/external of the EV) , they can be in two categories as:

1) **On-board charger:** AC/DC/DC power conversion take place in the EV with relative lower power (generally: 6.6kW);
2) **Off-board charger:** AC/DC/DC power conversion take place out of the EV with relative higher power (up to multi-hundred kW);
3) **Wireless charging:** some part of AC/DC/DC power conversion take place out of the EV and some take place in the EV, with relative lower power;**;**

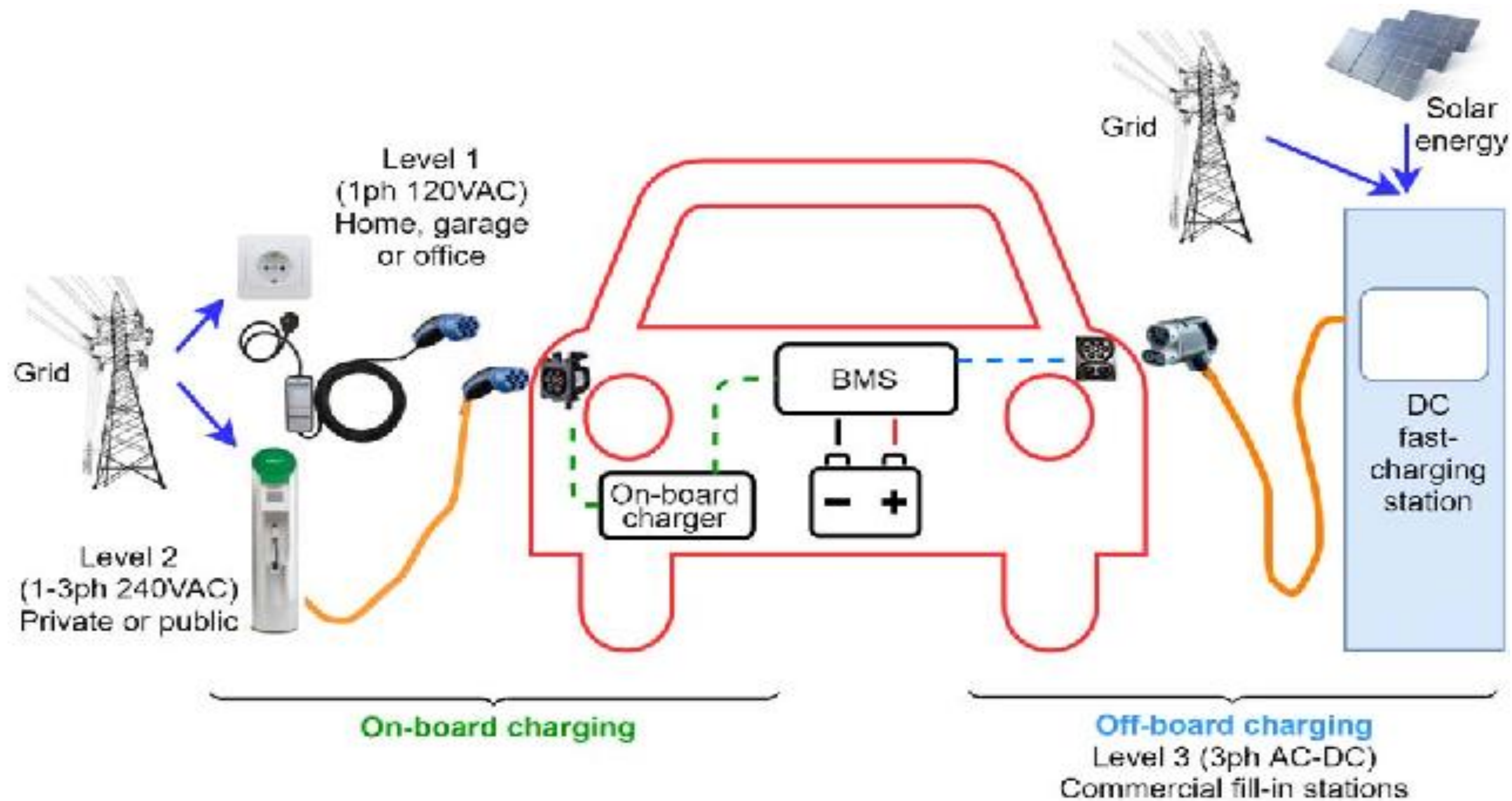


Fig. 8. AC charging versus DC charging (on-board versus off-board charging).

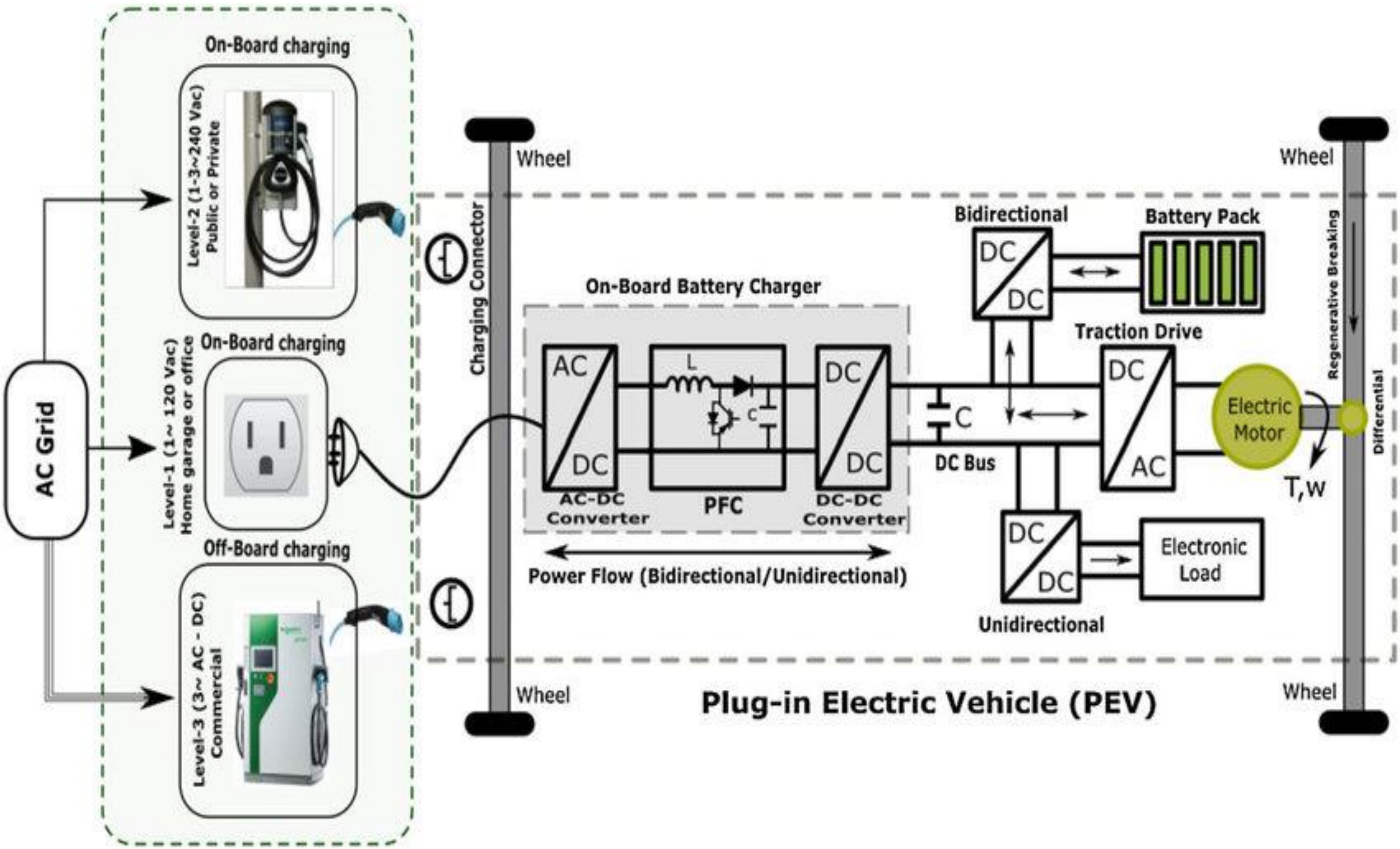


Fig. 9. Conceptual presentation of the conductive charging systems for EVs: on-board and off-board.

3.1. AC charging

- **AC charging:** system provides **an AC supply** that is **converted into DC** to charge the batteries. This system needs an **AC\DC\DC converter**. According to the standard Society of Automotive Engineers **(SAE)** AC Charging Power Levels are as:
- ✓ **Level 1**: The maximum voltage is **120 V**, the current can be **12 A or 16 A** depending on the circuit rating. Also, this can be used with standard **110 V** household outlets without requiring any special arrangement, using **on-board chargers**. Charging a small EV with this arrangement can take **multi hours**. this system is suitable for **overnight charging.**
- ✓ **Level 2**: uses a direct connection to the grid through an Electric Vehicle Service Equipment **(EVSE)**, using **on-board chargers**. Maximum system ratings are **240 V, 80 A** and **19.2 kW**. This system is used as a **primary charging method** for EVs. **6.6kW on-board charger** are more applicable in light EVs.
- ✓ **Level 3:** uses a **permanently wired supply** dedicated for EV charging, with power ratings **greater than 19.2 kW**.

Table 2. AC charging characteristics according to Society of Automotive Engineers (SAE).

Type	Level	Supplied Voltage Range (V)	Maximum Current (A)	Output Power Level (kW)	Estimated Charge Time (hours)
AC charging (on-board chargers)	Level 1	120 Vac (1-phase)	up to 16 A	up to 1.92 kW	7–17 hours
	Level 2	208–240 Vac (1-phase)	up to 80 A	up to 19.2 kW	0.4–7 hours
	Level 3	208–240 Vac (1 and 3-phase)	up to 400 A	up to 96 kW	Less than 0.5 hours

- There are different current and voltage configurations for AC charging (**levels**). The **time required for a full charge** depends on the level being employed. **AC charging is used in lower level comparing to DC charging.**

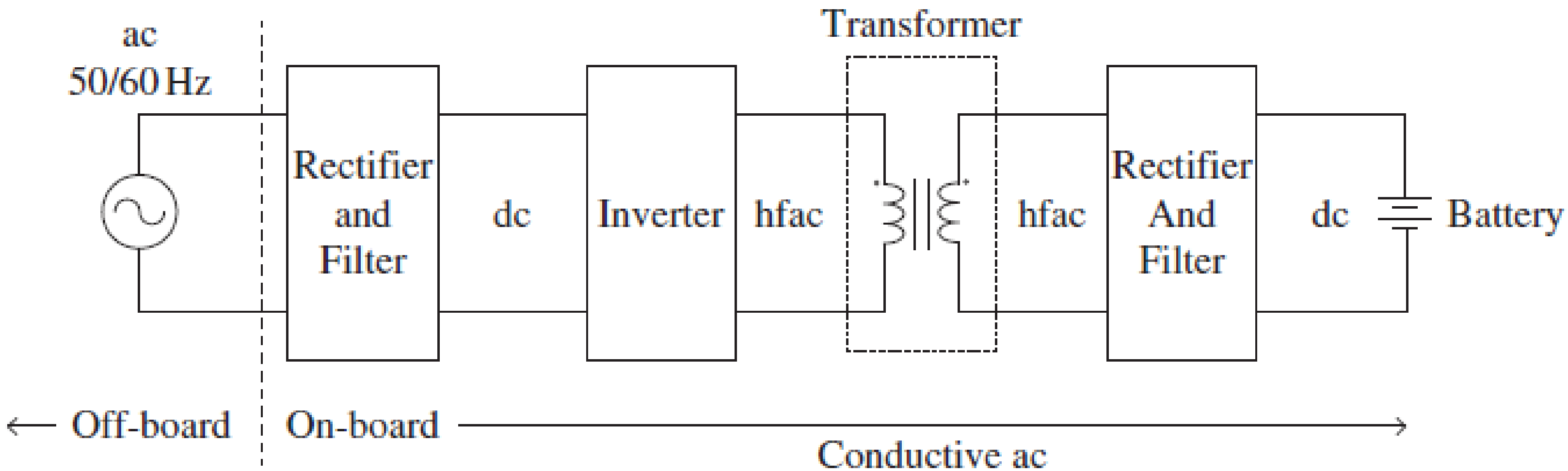


Fig. 10. Conductive AC charger block diagram and a sample.

3.2. DC charging

- **DC charging** systems require **dedicated wiring and installations** and can be mounted at garages or charging stations. They have **more power than the AC systems** and can **charge EVs faster**. As the output is DC, **the voltage has to be changed for different vehicles** to suit the battery packs. Modern stations have the capability to do it **automatically**. All DC charging systems has a permanently connected EVSE that incorporates the charger. Their classification is as below:
- ✓ **Level 1**: The rated voltage is **450 V** with **80 A** of current. The system is capable of providing power **up to 36 kW**.
- ✓ **Level 2**: It has the same voltage rating as the level 1 system; the current rating is increased to **200 A** and the power **to 90 kW**.
- ✓ **Level 3**: Voltage in this system is rated **to 600 V**. Maximum current is **400 A** with a power rating of **240 kW**.

- The main existing standards/protocols for DC chargers are:
- ✓ **Combined Charging System (CCS):** applied for European EVs;
- ✓ **CHAdeMO:** applied for Japanese EVs;
- ✓ **GB/T:** applied for Chinese EVs;
- ✓ **Supercharger:** only for Tesla EVs;

Table 3. DC charging characteristics according to SAE.

Type	Level	Supplied Voltage Range (V)	Maximum Current (A)	Output Power Level (kW)	Estimated Charge Time (hours)
DC charging (off-board chargers)	Level 1	200–450 VDC	up to 80 A	up to 36 kW	0.4–1.2 hours
	Level 2	200–450 VDC	up to 200 A	up to 90 kW	0.2–0.4 hours
	Level 3	200–600 VDC	up to 400 A	up to 240 kW	0.1–0.2 hours

- **DC charging** is used for higher power to charge EV in a less time. It can be in the range of 30kW to more that 300kW for light vehicles.

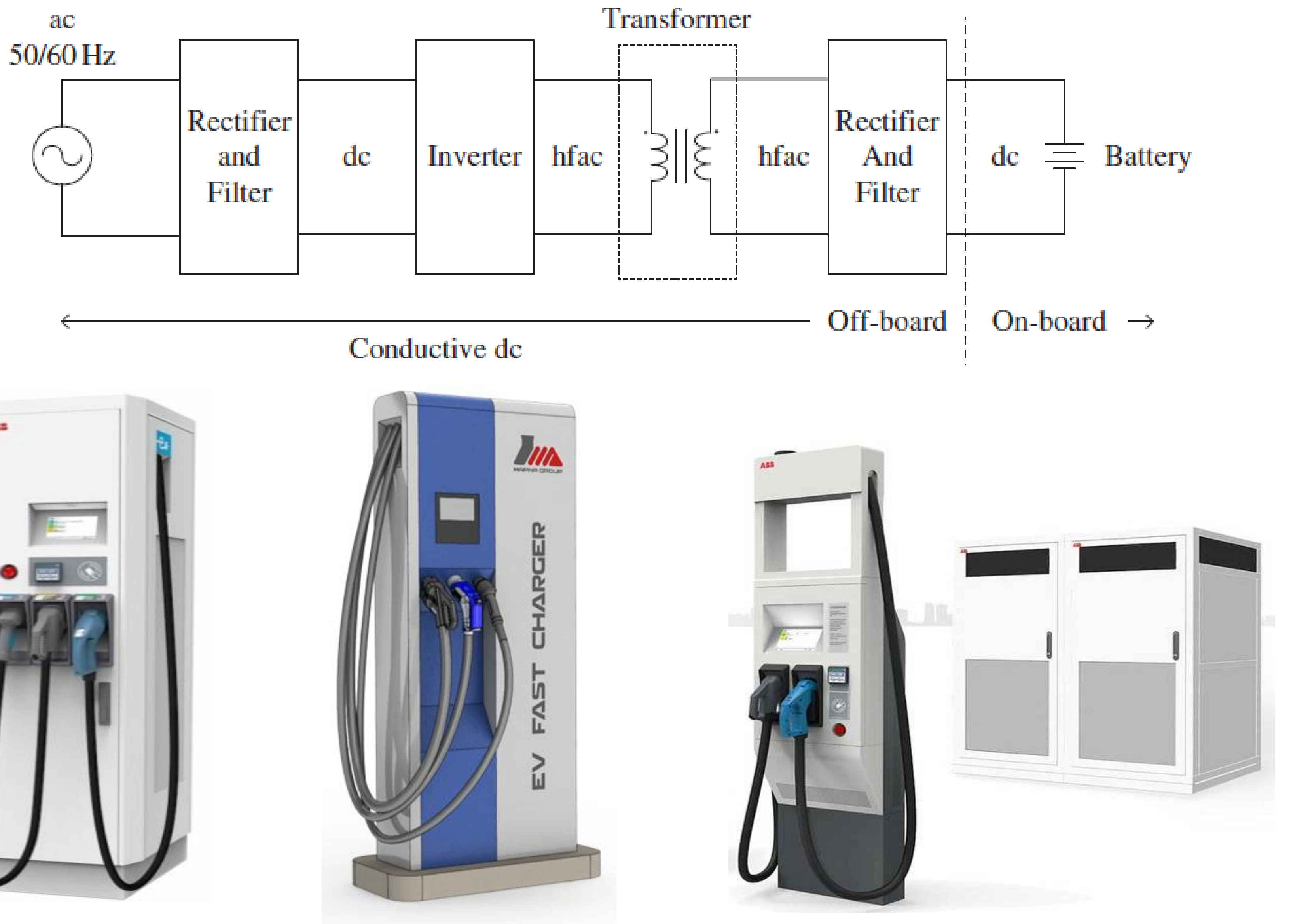


Fig. 11. Conductive DC charger block diagram and three samples.

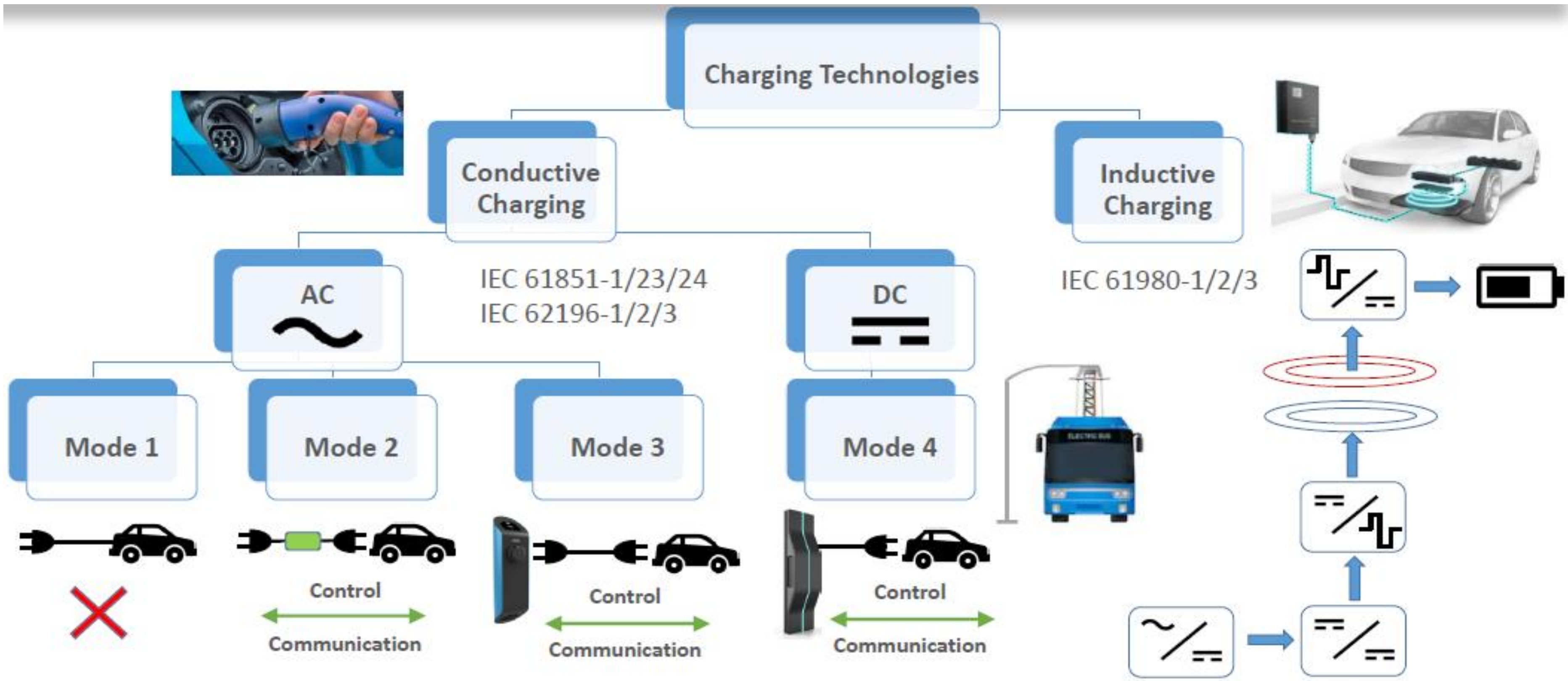


Fig. 12. Conductive charging modes based on IEC 61851.

❑ In summary for AC charging systems:

- ✓ AC chargers are commonly on-board the vehicle;
- ✓ AC is supplied to the vehicle;
- ✓ Charger supplies DC to the battery;
- ✓ Must be automotive-grade components;
- ✓ Considerations for reliability, thermal cycling, vibration, lifetime/warranty, and so on;
- ✓ High cost to produce and low proit margins for suppliers;
- ✓ AC levels 1 and 2 are the dominant technologies in production today;
- ✓ Usually AC systems have price lower that 1000-3000;

❑ In summary for DC charging systems:

- ✓ DC chargers are off-board (not in the vehicle);
- ✓ AC supplied to a charging box;
- ✓ Charger supplies DC to the vehicle;
- ✓ Consumer-grade components;
- ✓ Considerations for reliability, thermal cycling, vibration, and so on not as demanding;
- ✓ Lower cost to produce and potentially increased proit margins;
- ✓ Price of a typical 24kW DC chargers is 10000$ and a 150kW has 80000$ price;

3.3. Wireless charging;

- In **wireless charging of Wireless Power Transfer (WPT)**, the power transfer is performed without any direct contact between the EV and the charger. Power level in WPT usually is lower that 10kW right now due to technological problems.

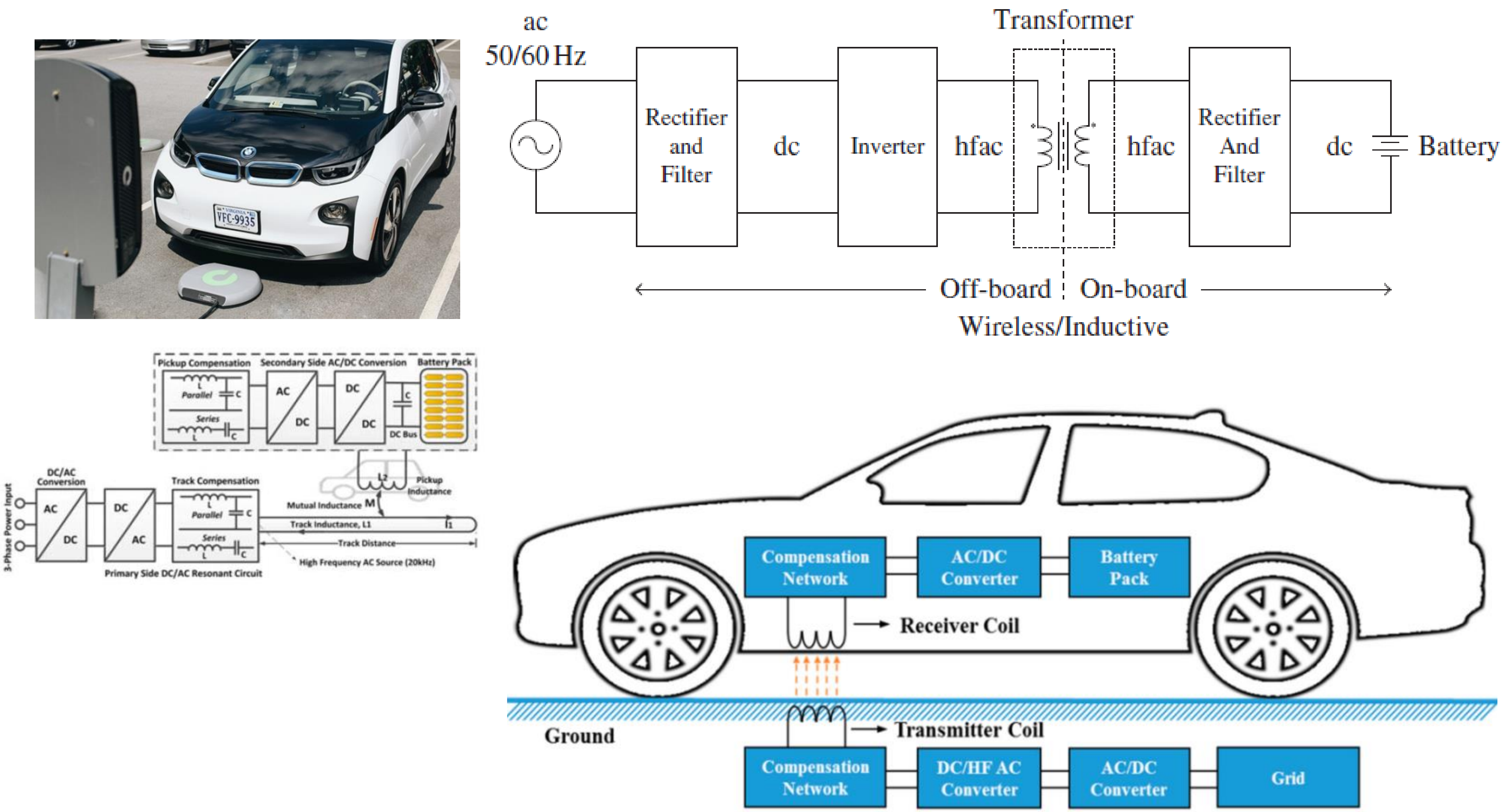
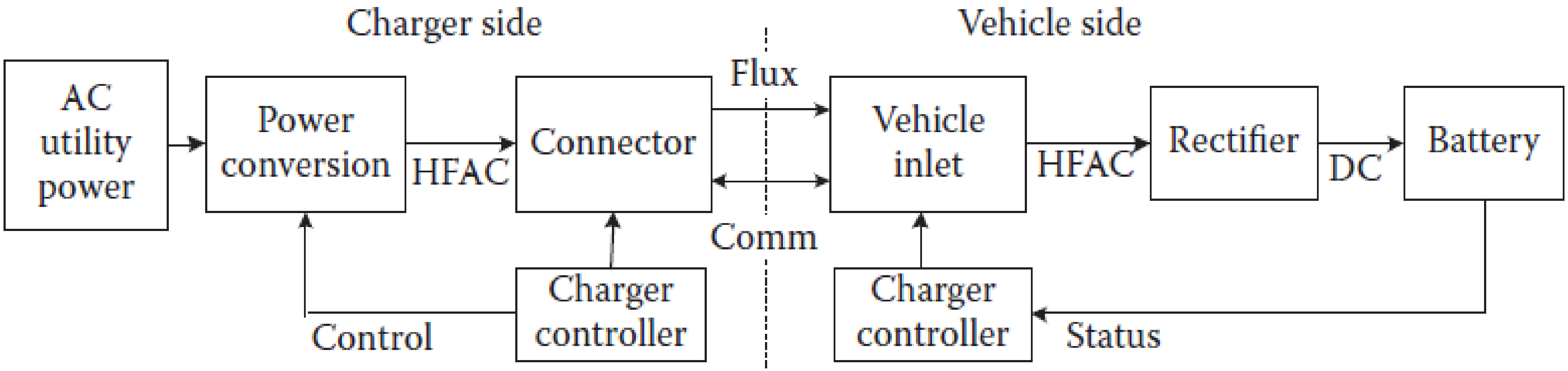


Fig. 13. Wireless charging conceptual block diagrams and a sample.



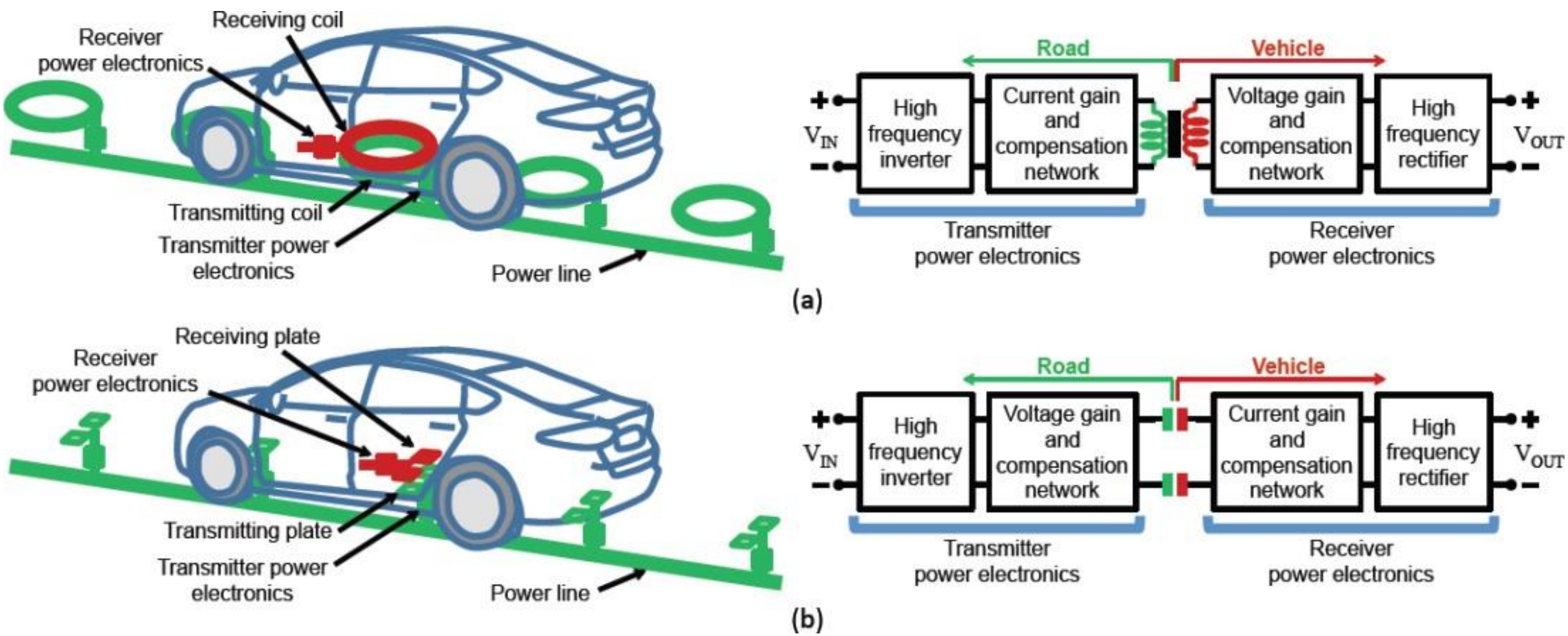


Fig. 14. Two main scenario for wireless power transferring in EV charging: inductive power transfer (high), capacitive power transfer (low)

4. Structure and subsystems of an EV charger

- There are two main power conversion steps in any EV charger:

1) **AC/DC stage** to rectifying the input AC power;
2) **DC/DC stage** to create a proper DC level to fed to the battery pack;

4.1. AC/DC stage topologies

- Rectifying (AC/DC) with **Power Factor Correction** (**PFC**) for any chargers is a must to acquire **high power density,** have a **sinusoidal input current**, and **high efficiency**.
- **Two types of PFC techniques are:**
  - ✓ **single-stage**: has higher rated components, lower efficiency (due to the high current and voltage stress), simpler structure and controller (suits for low-power and charge only lead-acid batteries because of high low frequency ripple).
  - ✓ **two-stage:** has lower rated components, higher efficiency, more complicated structure and controller (suits for high power applications).

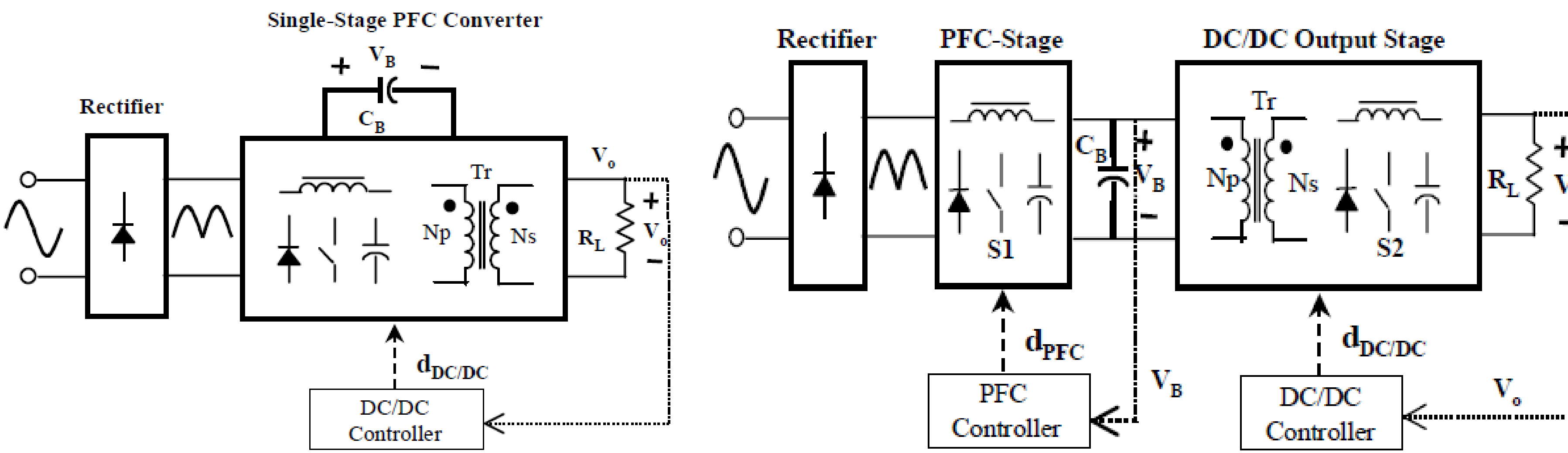
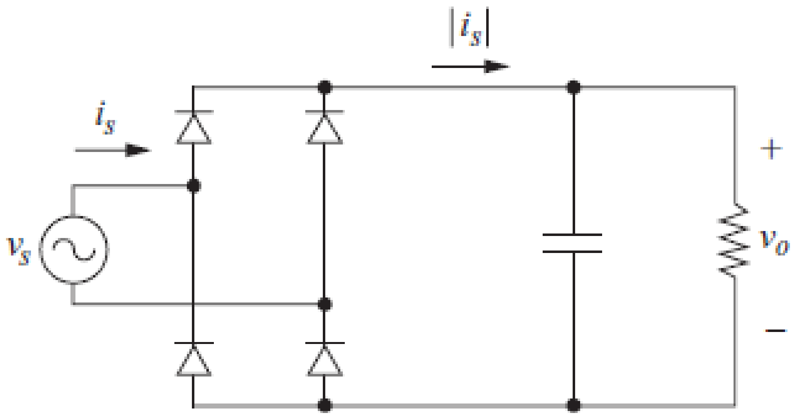
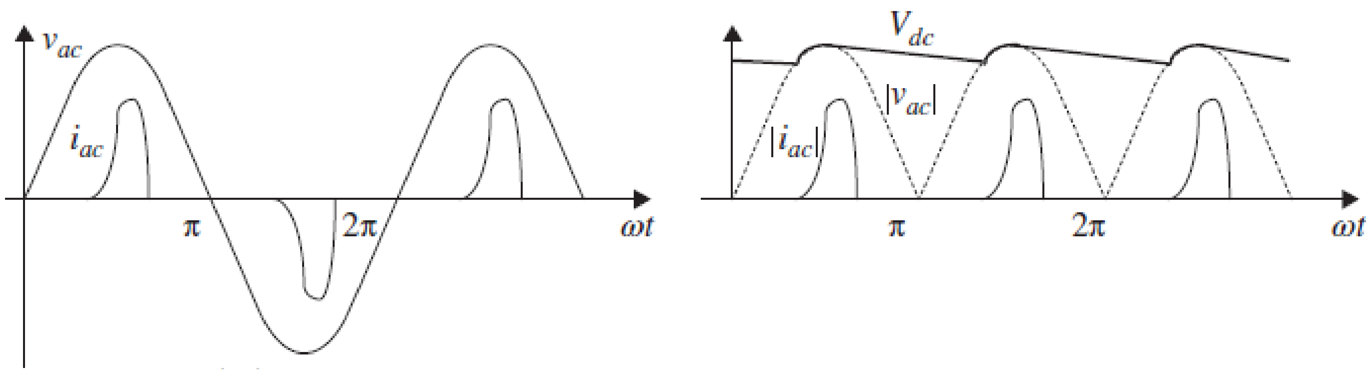


Fig. 15. Conceptual structures of the single-stage (left) and two-stage (right) PFCs.



$$\text{Power factor (PF)} = \frac{\text{Real power (W)}}{\text{Apparent power (VA)}}$$



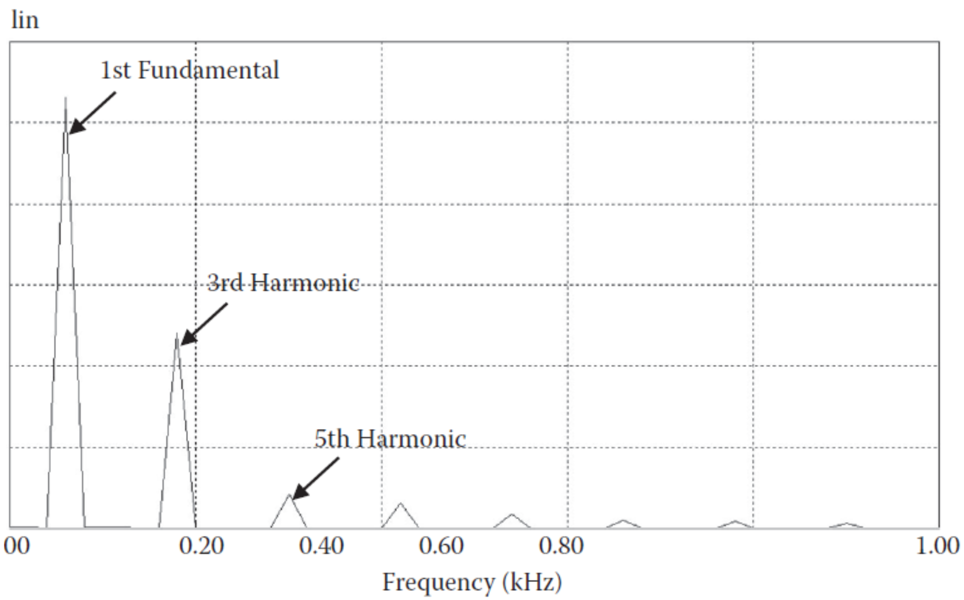
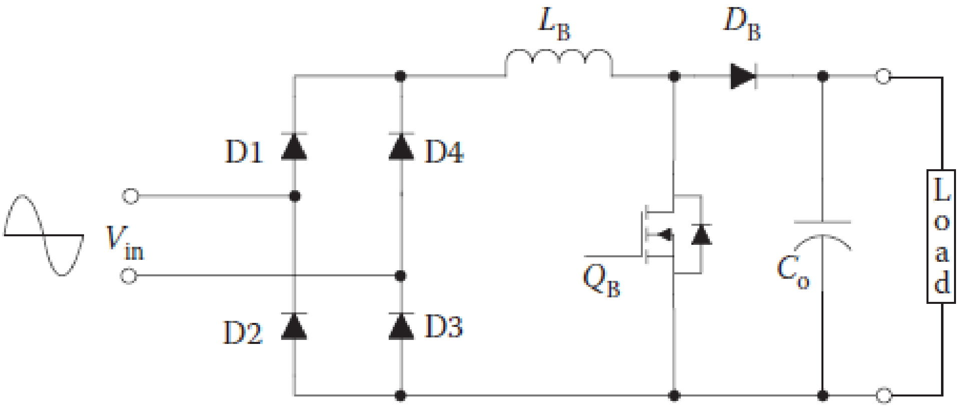


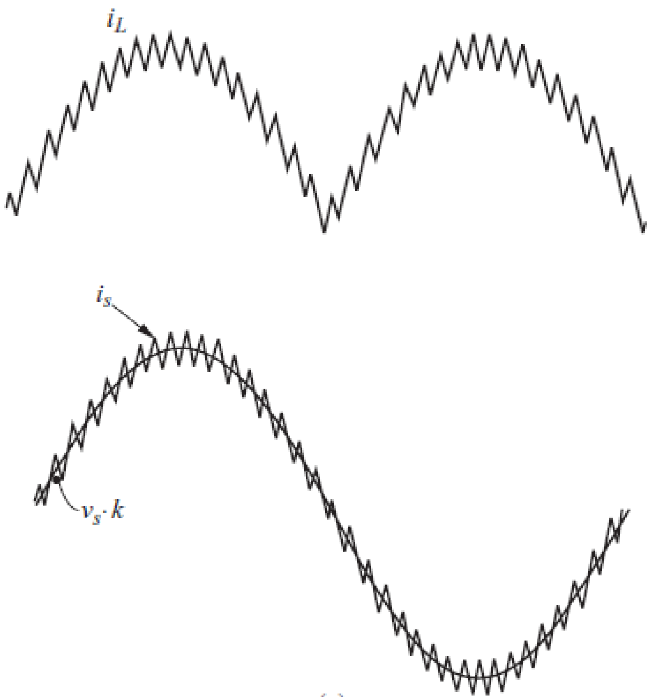
Fig. 16. A single-phase rectifier without PFC capability (upper). Input and output waveforms without the PFC circuit (middle). Harmonic spectrum without the PFC circuit (Lower).



Conventional PFC boost converter

❑ **Main Features are:**

- ✓ High ripple of the capacitor current;
- ✓ Low efficiency due to the diode bridge especially in high power;
- ✓ High inductor volume at high powers;
- ✓ Power rating limitation for current sense resistors at high power;



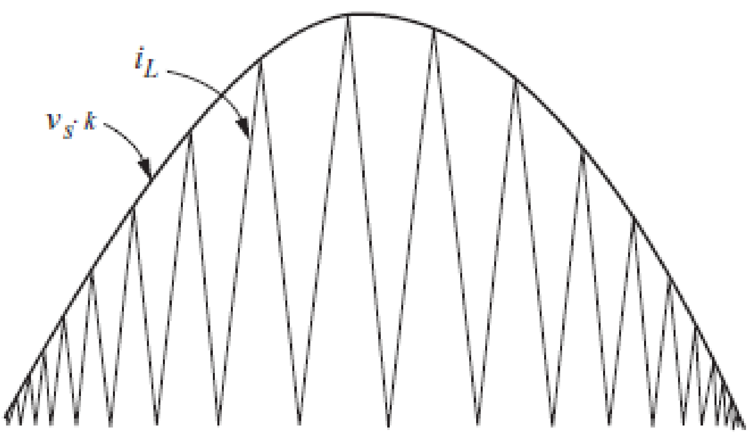
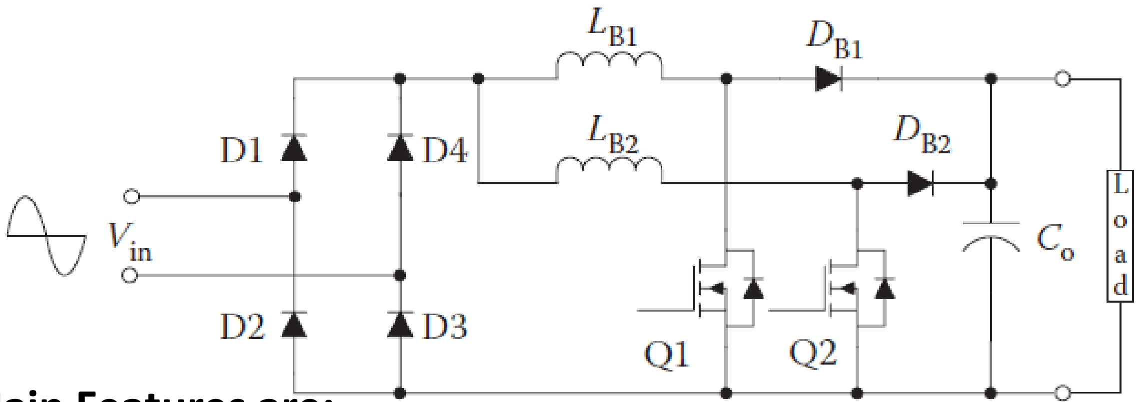


Fig. 17. A single-phase rectifier stage with PFC capability (upper). Input and output waveforms with the PFC circuit (lower) for continues and discontinues modes.

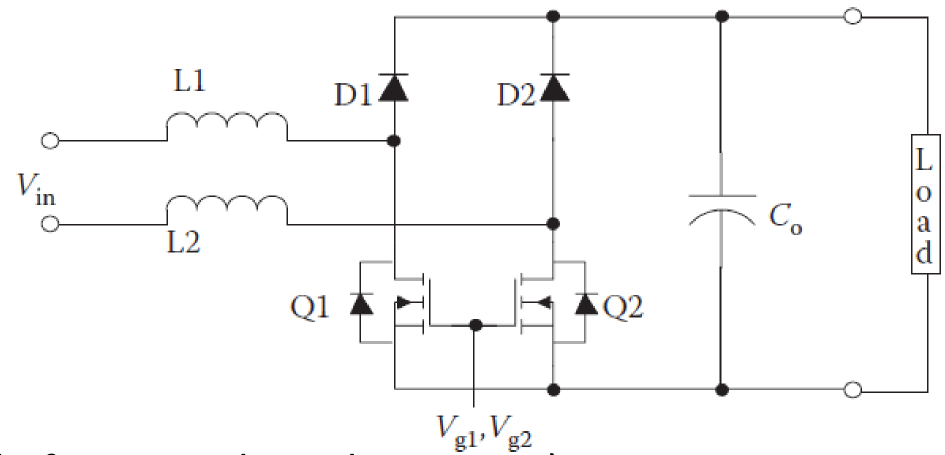


Interleaved PFC boost converter

❑ **Main Features are:**

- ✓ Lower ripple of the input current due to out of phase input inductors current;
- ✓ Smaller input EMI filter due to twice frequency of the input ripple current;
- ✓ Lower stress on the output capacitor due to ripple cancelation at the output;

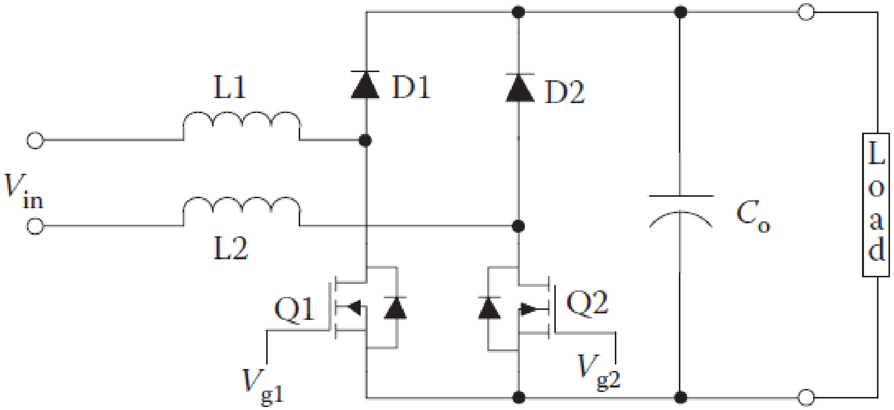
Bridgeless PFC boost topology



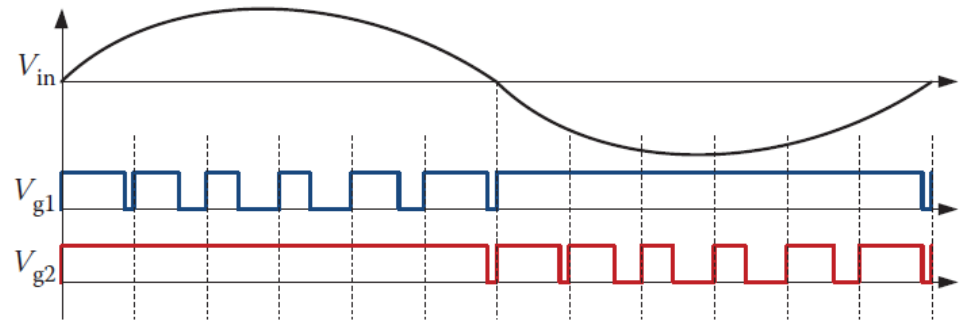
❑ **Main Features are:**

- ✓ MOSFET gates are not made decoupled;
- ✓ Rectifier input bridge is not needed.
- ✓ High efficiency and power density (suitable for more than 1kW power);
- ✓ High EMI especially Common-Mode noise (Since the amplitude of the noise source applied to stray capacitor from high-voltage DC bus and power ground is a lot higher;
- ✓ Float input; thus input voltage sensing cannot be done without low-frequency transformer or optocoupler;

Fig. 18. Some of other introduced single-phase rectifiers with PFC capability: Interleaved PFC boost converter, and bridgeless PFC boost topology. (Con.)



Dual-boost PFC topology

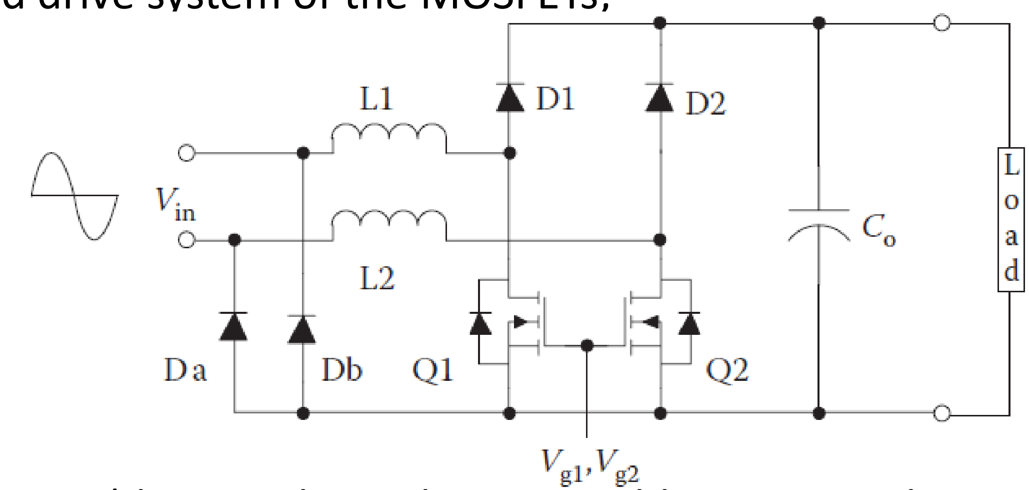


half-line cycle synchronous rectification for the dual-boost PFC .

❑ Main Features are:

- ✓ High efficiency in light load due to low conductive losses and also low gate losses (the MOSFET gates are decoupled, enabling one of the switches to remain on and operate as a synchronous MOSFET for half-line cycle);
- ✓ Complicated controller and separated drive system of the MOSFETs;

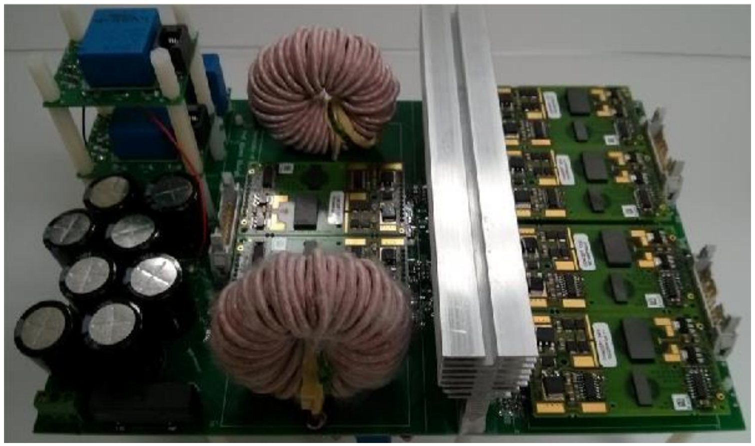
Semi-bridgeless PFC boost topology

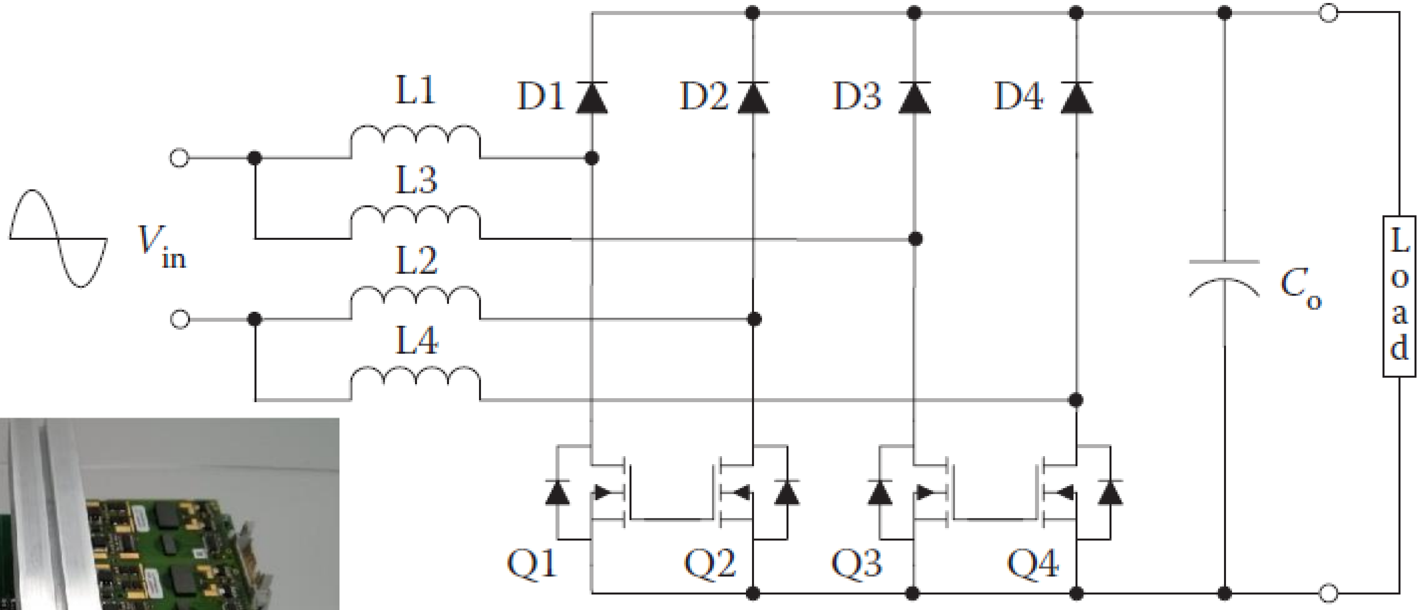


❑ Main Features are:

- ✓ Low EMI (By two slow diodes);
- ✓ Solving the float input voltage sensing (the topology change enables input voltage sensing using a string of simple voltage dividers);

Fig. 18. Some of other introduced single-phase rectifiers with PFC capability: dual-boost PFC topology, and Semi-bridgeless PFC boost topology (Con.).





Bridgeless interleaved PFC boost converter

❑ **Main Features are:**

✓ The gating signals have a phase difference of 180^o;

✓ Suitable option for high power single phase (more that 3.5 kW);

✓ Interleaving two bridgeless PFC reduces the EMI;

✓ Since the proposed topology shows high input power factor, high eficiency over the entire load range, and low input current harmonics, it is a potential option for single-phase PFC in high-power level 2 battery charging applications.

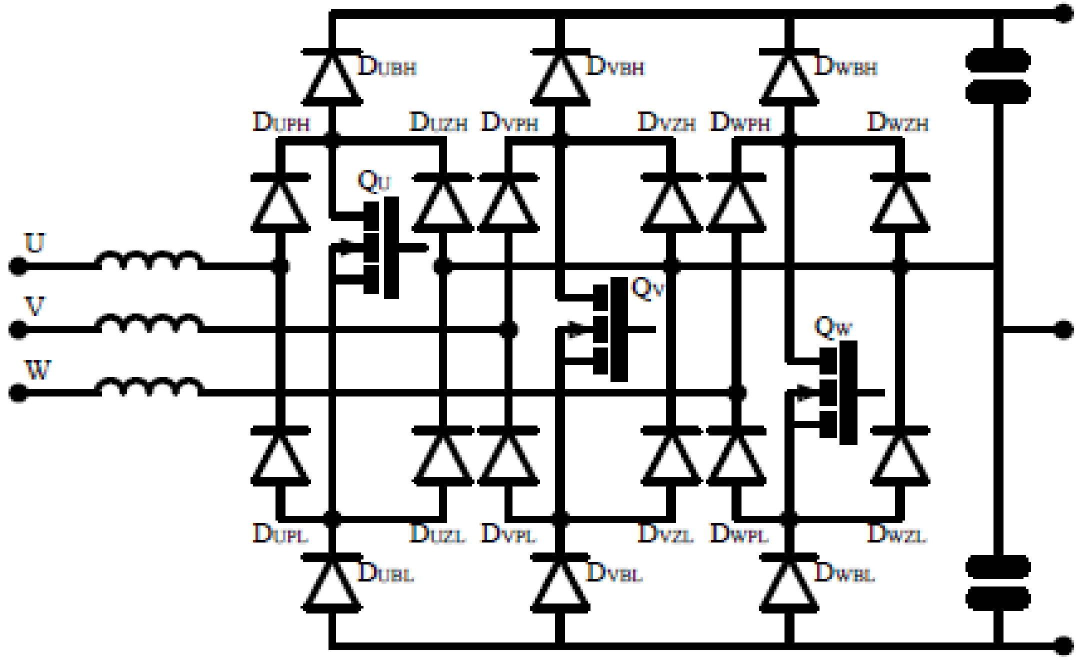
Fig. 18. Some of other introduced single-phase rectifiers with PFC capability: bridgeless interleaved PFC boost converter.

- **Advantages of three-phase systems:**
  - ✓ Achieving higher power systems with higher power density;
  - ✓ Reducing required wiring, size or weight per watt compared to single-phase configurations;
  - ✓ Delivering a constant power output, while single-phase systems have a variable output power and normally require a large low-frequency filter to power the loads.

- **Note:** Another driver for the spread of three-phase PFC topologies is the advent of silicon carbide (SiC) power semiconductors. Their **higher breakdown voltages and lower switching losses** allow high efficiencies at what are considered high frequencies for silicon-based switches, and therefore devices deliver well-rounded solutions in terms of size, cost and performance. In other words, **SiC MOSFETs and diodes are enabling higher power and higher voltage applications** for power electronics, including three-phase PFC systems.

- **PFC application advantage in three-phase systems:**
  - ✓ Three-phase-connected linear and equal loads are automatically balanced and no PFC is needed. However, this is not true with non-linear loads like a power supply. This leads to an unbalanced three-phase system. Without a neutral wire the voltage middle point is unbalanced and not equal to zero, **leading to unequal voltage amplitudes in each line and possibly overvoltage or undervoltage faults.**
  - ✓ To optimize the power delivered to the load, the current needs to have the same shape as the voltage to maximize the power factor and bring it as close to 1 as possible. **The line voltage from the ac grid is a sinewave, so the current should be.**

- **Main Features are:**
  - ✓ PWM rectifier with controlled output voltage;
  - ✓ Boost system (continuous input current);
  - ✓ Unidirectional power flow;
  - ✓ High power density;
  - ✓ Simple control to stabilize the neutral point potential;
  - ✓ Low complexity, low realization effort;
  - ✓ Low switching losses;
  - ✓ Reliable behavior under heavily unbalanced mains voltages and in case of mains failure.

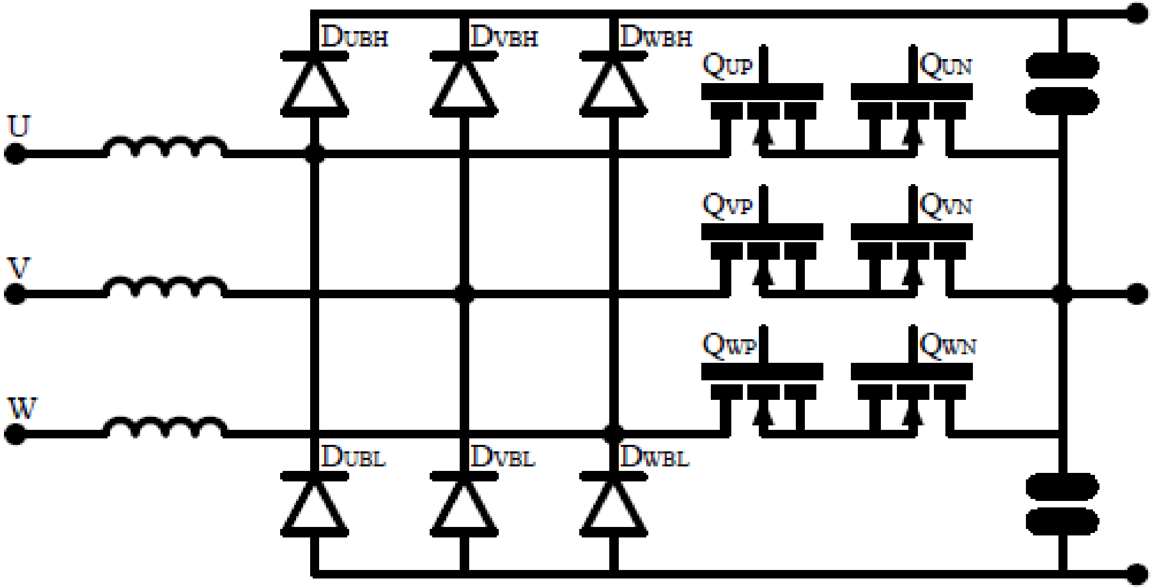


Vienna PFC converter (three-switches boost)

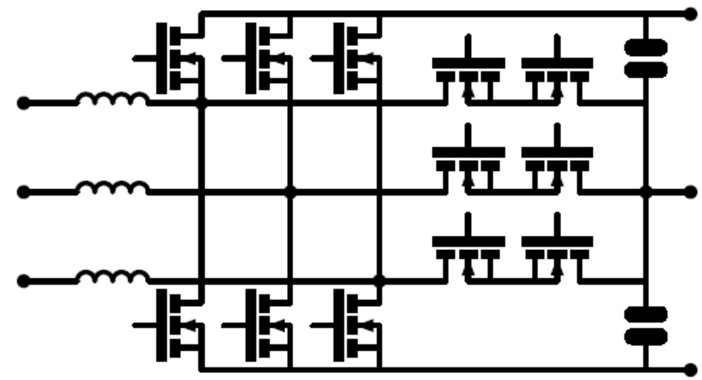
✓ The major advantage of this topology is its use of a **single switch per phase.** It makes the control easier even if the schematic seems more complex with the number of diodes involved. **The topology is also low cost** because there is a very small number of switches.

✓ A major disadvantage of this topology is **the large number of diodes.** There are always two diodes in the current path, which impacts the efficiency. **All drivers are floating** and need a specific floating power supply.

Fig. 19. Main introduced three-phase active rectifiers with PFC capability: Vienna rectifier (Con.).



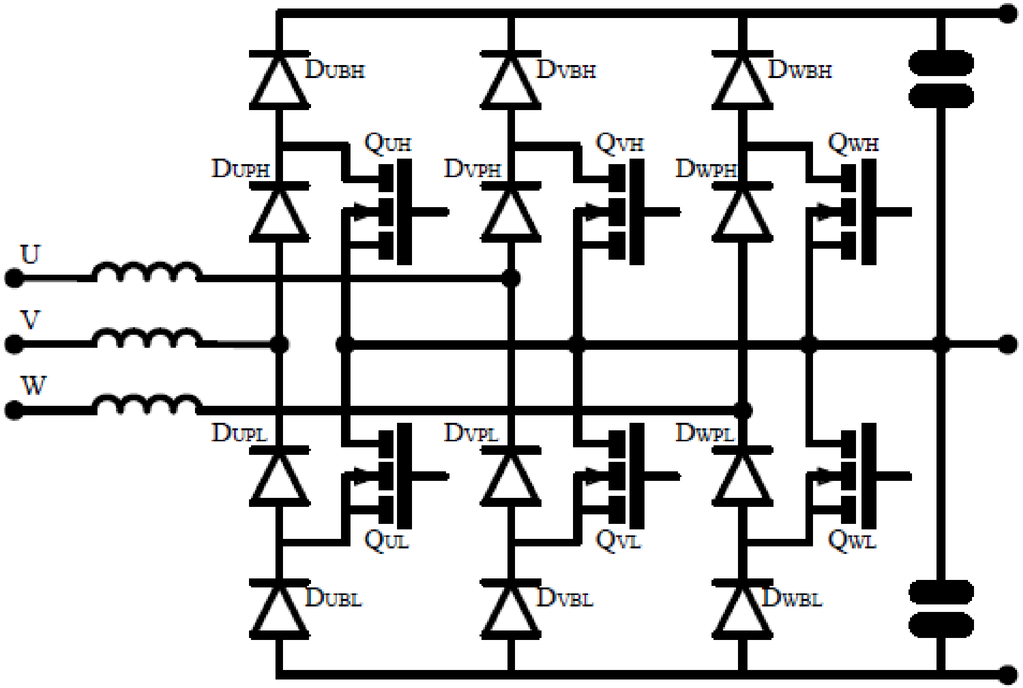
T-NPC PFC converter



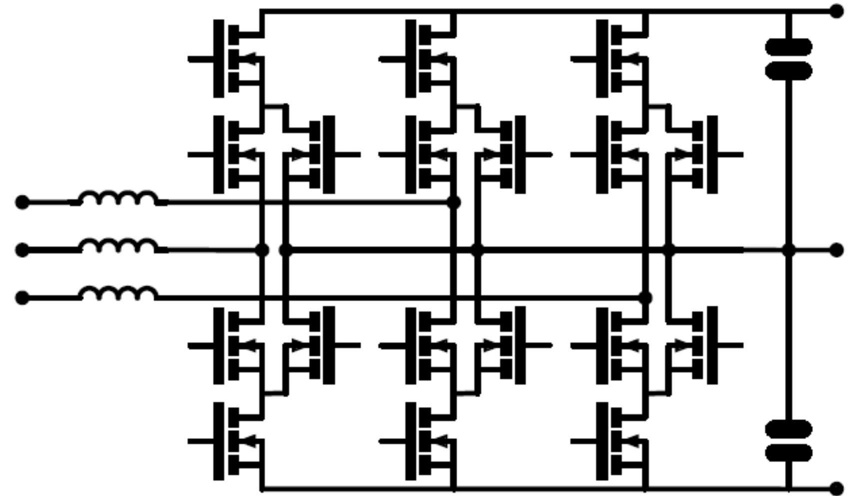
Bidirectional T-NPC PFC converter

- ❑ **Main Features are:**
- ✓ Instead of using a rectifier bridge to convert a unidirectional switch to a bidirectional switch, the T-NPC uses a configuration of back-to-back switches;
- ✓ The **number of components is much lower** than that of the original Vienna PFC;
- ✓ The **conduction losses are also much lower** because only one diode at a time is in series in the current flow;
- ✓ As the boost diodes are 1200-V devices, **the switching losses are a little bit bigger** than they would be with 600-V diodes; But as there are fewer diodes, it is difficult to predict which topology will have the best efficiency;
- ✓ The T-NPC structure is also used as an inverter. In this case, the boost diodes are replaced by switches;

Fig. 19. Main introduced three-phase active rectifiers with PFC capability: T-NPC rectifier (Con.).



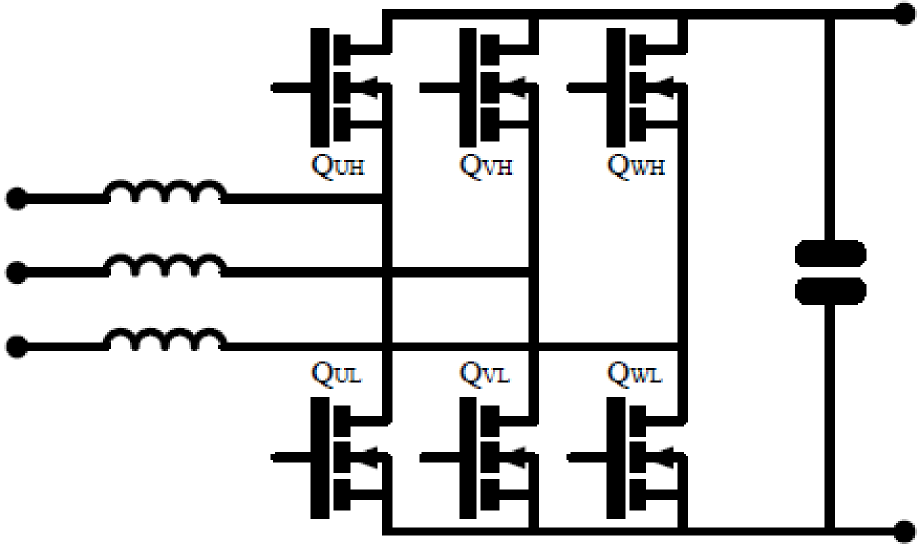
NPC boost PFC converter



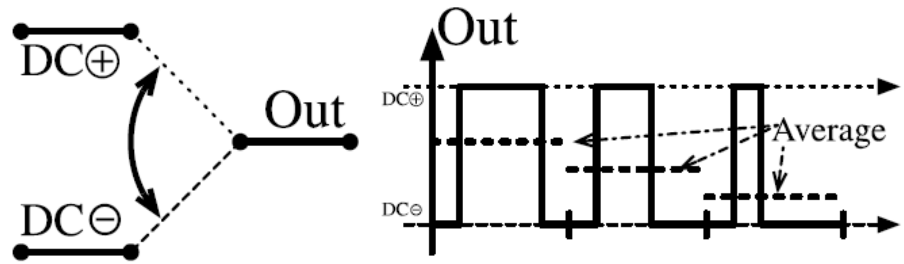
A-NPC boost PFC converter

- ❑ **Main Features are:**
- ✓ There are always two components (one diode and one switch) in series in the current path. **This NPC topology has higher conduction losses than the T-NPC.**
- ✓ Three switches are floating and need a floating gate drive. The three other switches are tied to ground.
- ✓ As there are no 1200-V diodes, this topology has a clear advantage in losses, with **fewer components compared to the original Vienna.**
- ✓ Replacing diodes with switches makes the topology bidirectional. This version is called A-NPC (for active-neutral point clamp).

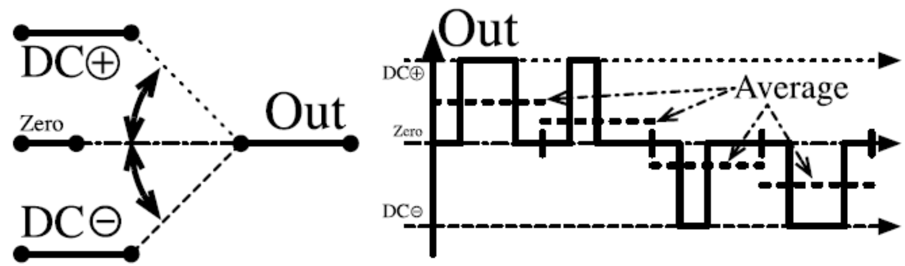
Fig. 19. Main introduced three-phase active rectifiers with PFC capability: NPC and A-NPC rectifier (Con.).



Six-switch PFC boost converter



Unipolar or two-level switching



Bipolar or three-level switching

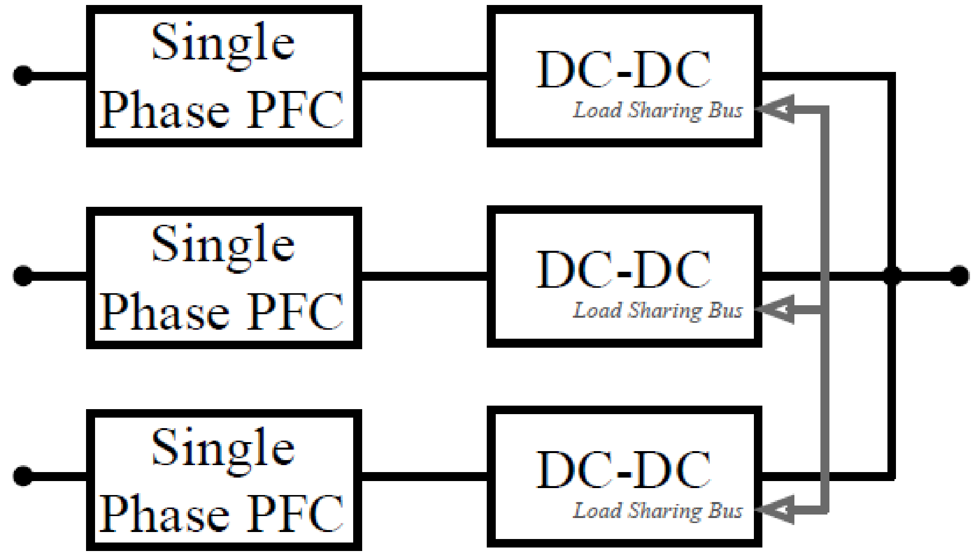
❑ **Main Features are:**

✓ As we have three half-bridges tied to ground, the drivers are much easier to build using half-bridge drivers and techniques like **bootstrapping** can be used to create a floating supply;

✓ This topology is **fully bidirectional by nature**;

✓ **The major disadvantages are linked to the fact it is a two-level topology.** This cause to **higher switching losses**, **higher current ripple in the inductors**, and **higher EMI** comparing to the three-level switching.

Fig. 19. Main introduced three-phase active rectifiers with PFC capability: six-switch rectifier (Con.).



Three Parallel Single-Phase With Neutral PFC converter

- **Main Features are:**
- ✓ In this configuration **the neutral is indispensable if the system is unbalanced,** even if the three single-phase PFC stages are tied to a load sharing control to split the power equally between the three phases.
- ✓ The advantage of this structure is that it is **much simpler** to design because single-phase PFC converters are well known and widely available.
- ✓ **The need for a neutral wire** makes the distribution network more expensive and not optimum.
- ✓ Also, **a single-phase PFC stage cannot handle power above several kilowatts.** Beyond that, paralleling is needed.

Fig. 19. Main introduced three-phase active rectifiers with PFC capability: Vienna rectifier.

Table 4. Comparison of the three-phase PFC topologies.

🟢: Very suitable/positive. 🟡: Average 🔴: Not suitable/negative.

	Vienna	*T-NPC*	*A-NPC*	*NPC*	*Six-switch*	*3x single-phase*
Switching levels	3	3	3	3	2	2
Reduced EMI	🔴/🟡	🟡	🟢	🟢	🔴	🟢/🟡
Efficiency	🔴	🟢/🟡	🟢	🟢/🟡	🟡	🟡
Power density	🟡	🟡	🟢	🟡	🟢/🟡	🔴
Overall BOM cost	🟢	🟡	🔴	🟡	🟢	🟡
Control complexity	🟢	🟢	🔴	🟡	🟢	🟢/🟡
Bidirectional	No	Can be	Yes	No (A-NPC)	Yes	No

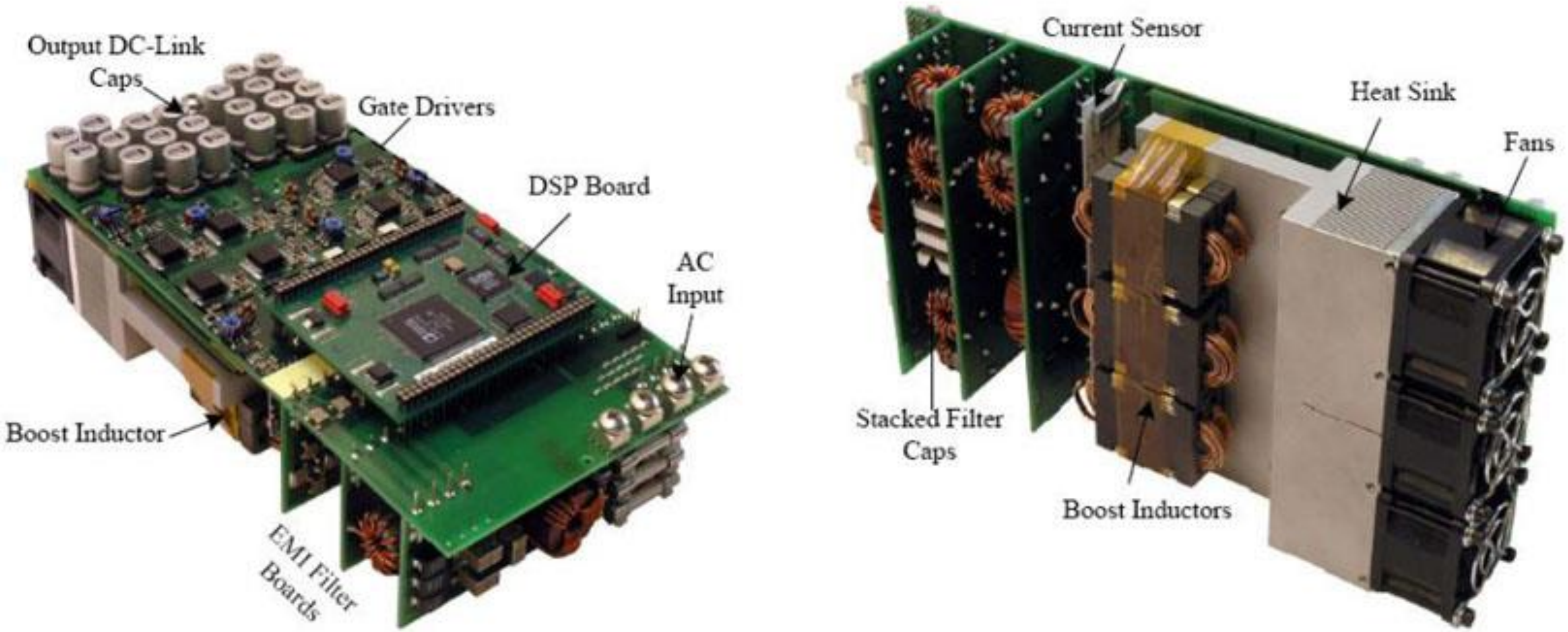


Fig. 20. Top and bottom views of an air-cooled 10kW-Vienna Rectifier (400kHz PWM).

3.2. DC/DC stage topologies

❑ The DC–DC stage requirements for battery chargers are:

1) Galvanic isolation (regulatory requirement);
2) Suitable for high power (>1 kW);
3) High efficiency (>95%);
4) Soft-switching (Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS));
5) Low EMI;
6) Low output voltage/current ripple (avoid battery heating);
7) Small size;
8) Cost effective;

basic phase-shifted full-bridge

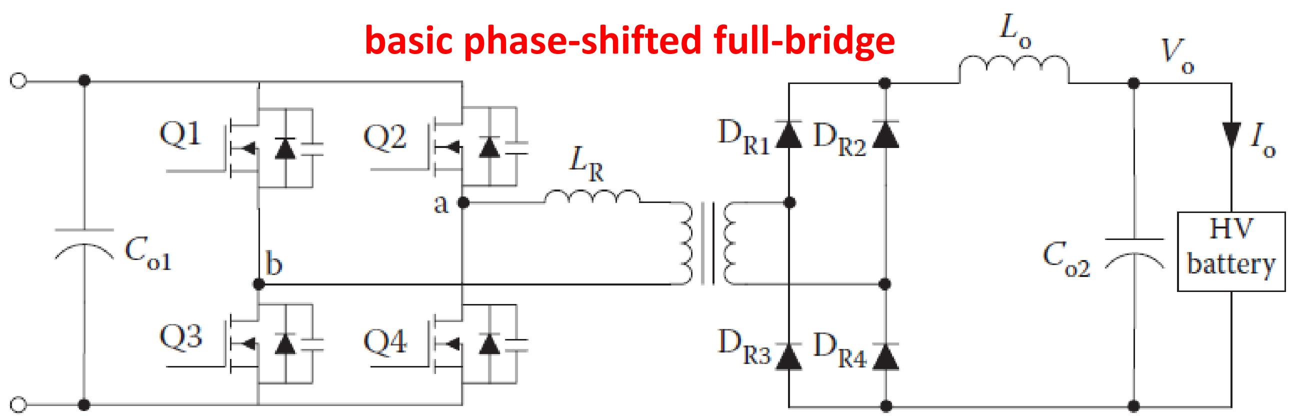


Fig. 21. Suitable introduced DC/DC stage topologies for a charger: basic phase-shifted full-bridge. (Con.)

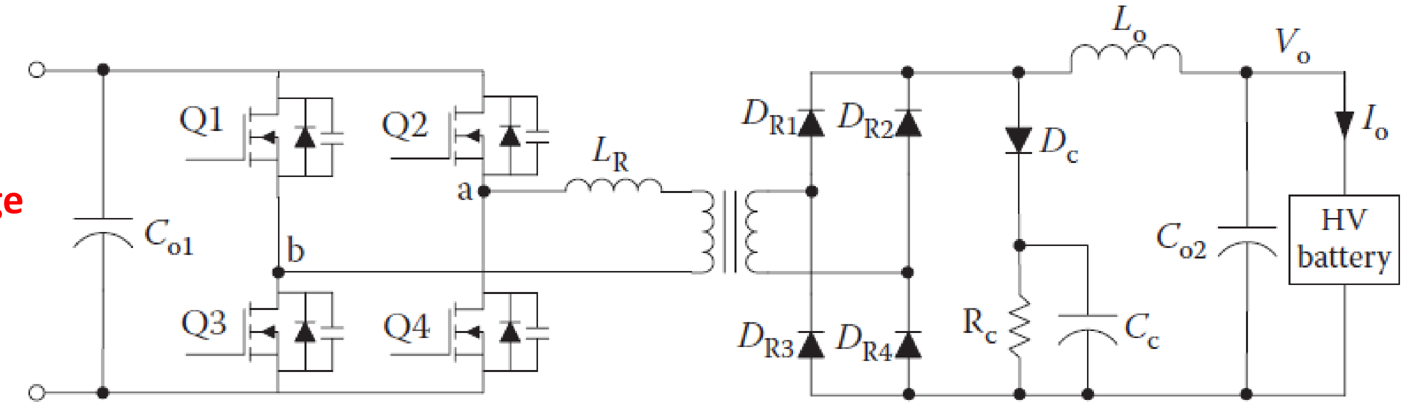
❑ **Main Features are:**

✓ **Suitable for low output voltage and high output current** (ringing in high voltage on the secondary-side rectifier diodes due to diode junction capacitance resonance with the leakage inductance of the transformer);

✓ **Duty cycle loss** (occurs for converters with inductive output filters when the output rectifiers commutate, enabling all of the diodes to conduct, which effectively shorts the secondary winding. This causes a decrease in the output voltage; thus, a higher transformer turn ratio is needed, which increases the primary peak current.);

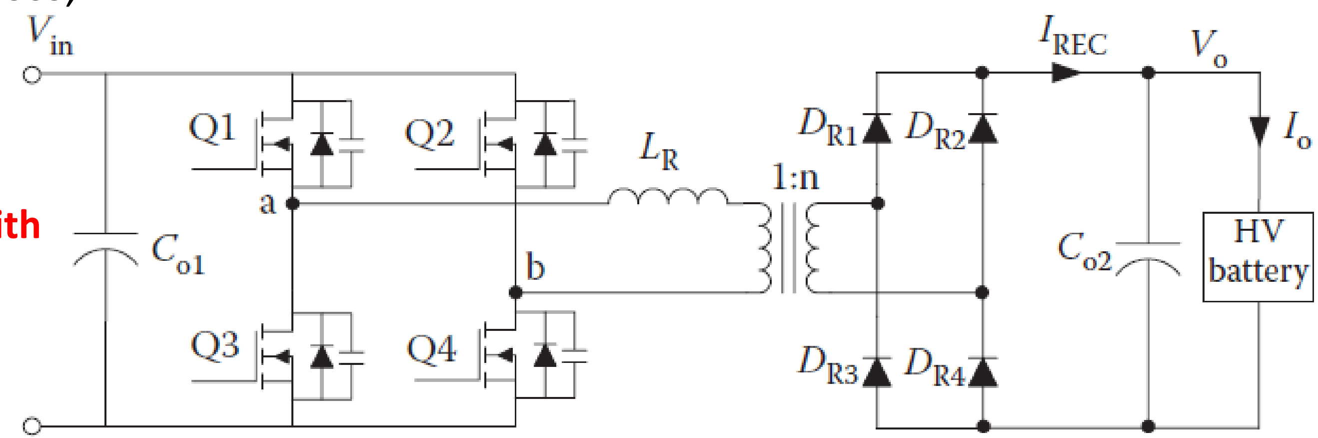
✓ **Limit range for ZVS** (requires an additional Zero Voltage Transition (ZVT) circuit to achieve ZVS for a wide variation in the load current);

Improved ZVS full-bridge trailing-edge



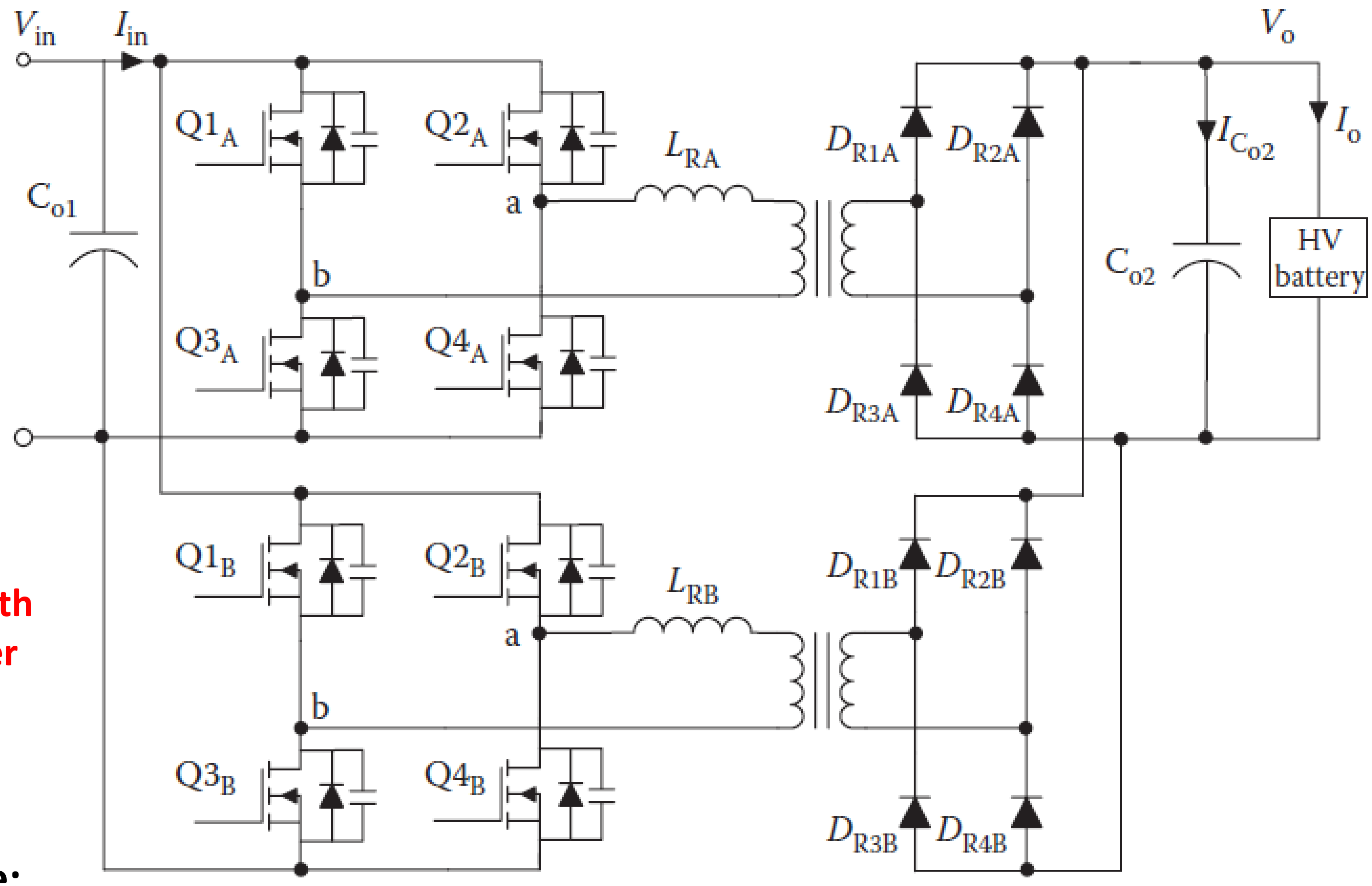
- **Main Features are:**
  - ✓ suitable for low output voltage and high output current applications;
  - ✓ A clamp network (D_C, R_C, and C_C) is across the output rectifier to clamp the voltage ringing;
  - ✓ suffers from duty cycle loss;

ZVS full-bridge trailing-edge with capacitive output filter



- **Main Features are:**
  - ✓ Inherently minimize diode rectifier ringing since the transformer leakage inductance is effectively placed in series with the supply-side inductor;
  - ✓ High efficiency can be achieved with ZVS;

Fig. 21. Suitable introduced DC/DC stage topologies for a charger: Improved ZVS full-bridge trailing-edge (upper), ZVS full-bridge trailing-edge with capacitive output filter (lower), (Con.)



Interleaved ZVS full-bridge trailing-edge with capacitive output filter

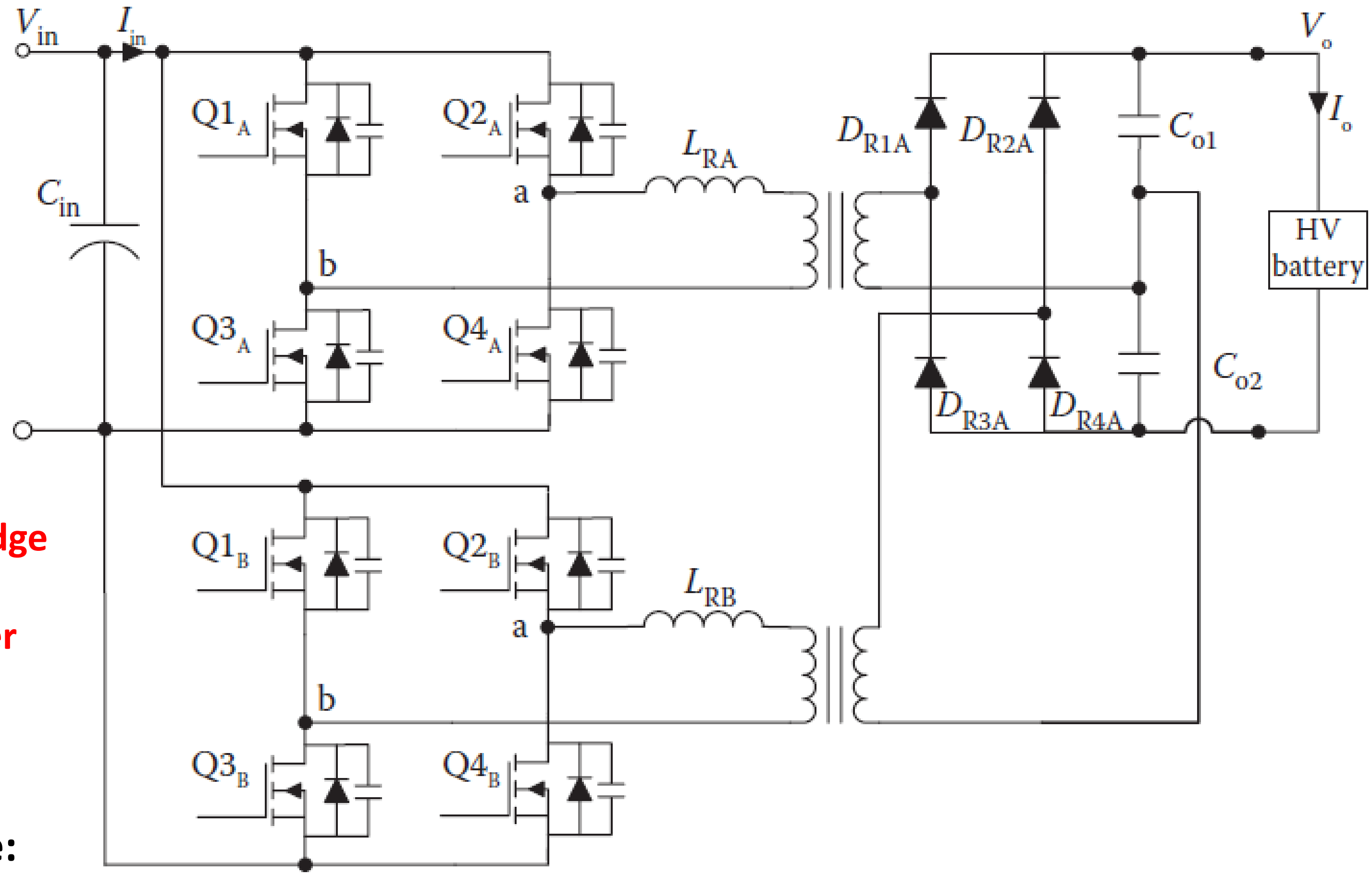
❑ **Main Features are:**

✓ The input and output filtering requirements and also the reverse recovery losses in the secondary rectifier diodes are reduced;

✓ Each cell shares equal power and the thermal losses are distributed uniformly among the cells;

✓ The input/output ripple is four times the switching frequency.

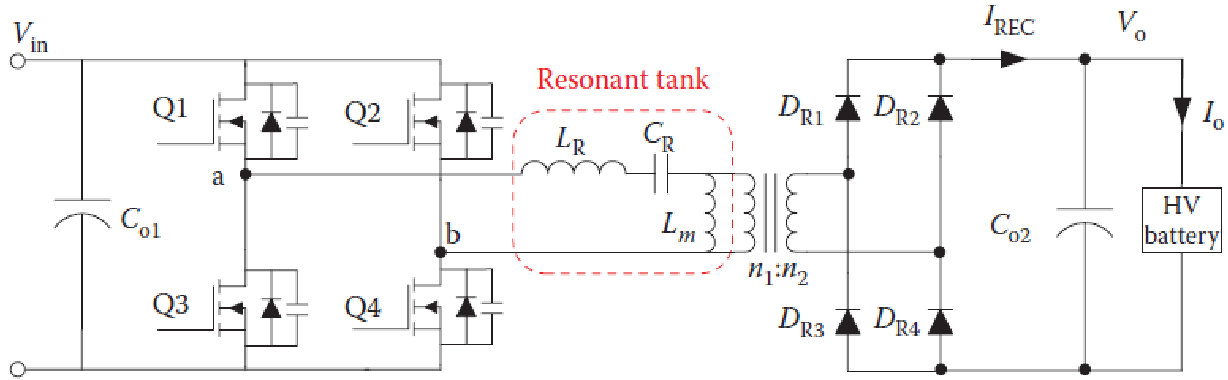
Fig. 21. Suitable introduced DC/DC stage topologies for charger: Interleaved ZVS full-bridge trailing-edge with capacitive output filter, (Con.)



Interleaved ZVS full-bridge trailing-edge with capacitive output filter and voltage doubler.

- ❑ **Main Features are:**
- ✓ The output voltage doubler rectifier significantly reduces the number of secondary diodes and the voltage rating of the diodes is equal to the maximum output voltage;
- ✓ Further reduce the ripple current and voltage stress on the output filter capacitors, as well as component cost reduction.
- ✓ Among operating modes, **DCM** (Discontinuous Conduction Mode) and **BCM** (Boundary Conduction Mode) are preferable.

Fig. 21. Suitable introduced DC/DC stage topologies for charger: Interleaved ZVS full-bridge trailing-edge DC/DC converter with capacitive output filter and voltage doubler, (Con.)



❑ Main Features are:

- ✓ High efficiency at the resonant frequency and its ability to regulate the output voltage during the holdup time, where the output voltage is constant and the input voltage might drop significantly.
- ✓ The wide output voltage range requirements for a battery charger are drastically different and challenging compared to telecom applications, which operate in a narrow output voltage range. unlike the telecom sector, EV applications require a wide operating range.

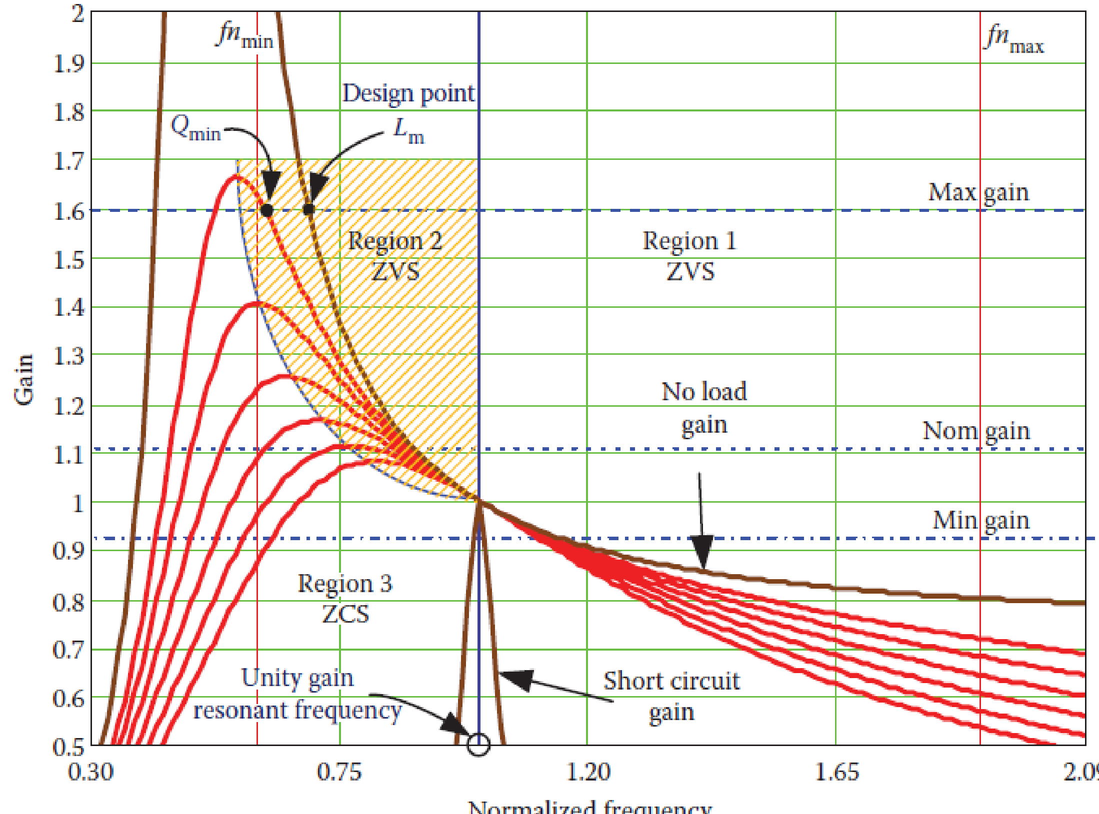


Fig. 21. Suitable introduced DC/DC stage topologies for charger: Full-bridge LLC resonant topology and its typical DC gain characteristics using Fundamental Harmonic Approximation (FHA).

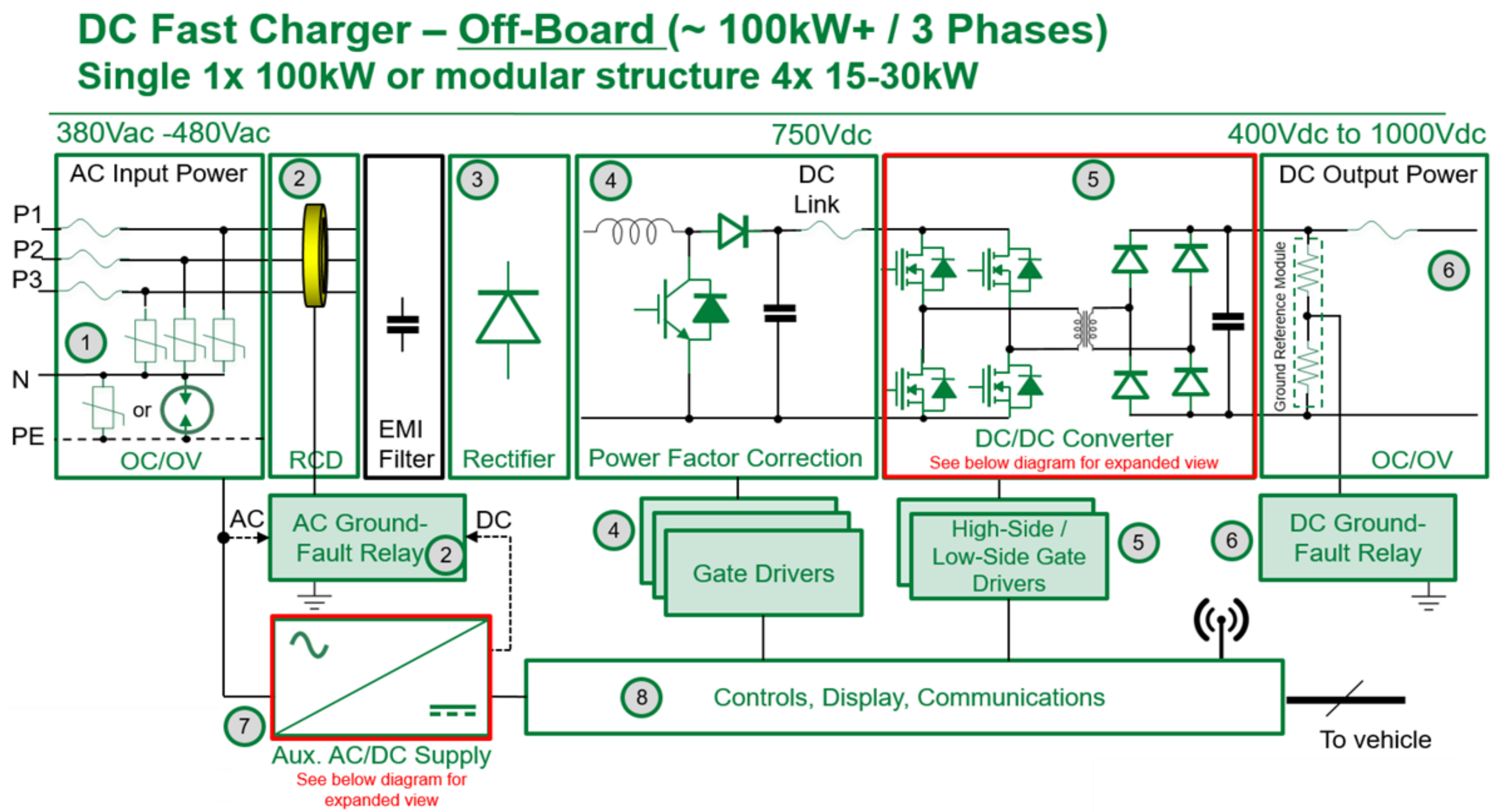


Fig. 22. Schematic diagram of power sector of a typical conductive battery charging system.

- A battery charger must be **efficient** and **reliable**, with **high power density**, **low cost**, and **low volume and weight**. Its operation depends on topology, components, control, and switching strategies. Charger control algorithms are implemented through analog controllers, microcontrollers, digital signal processors, and specific integrated circuits depending upon the rating, cost, and types of converters. **Low distortion** at **high power factor** to maximize the real power available from a utility outlet are also necessary. It can improve power quality of the power grid.

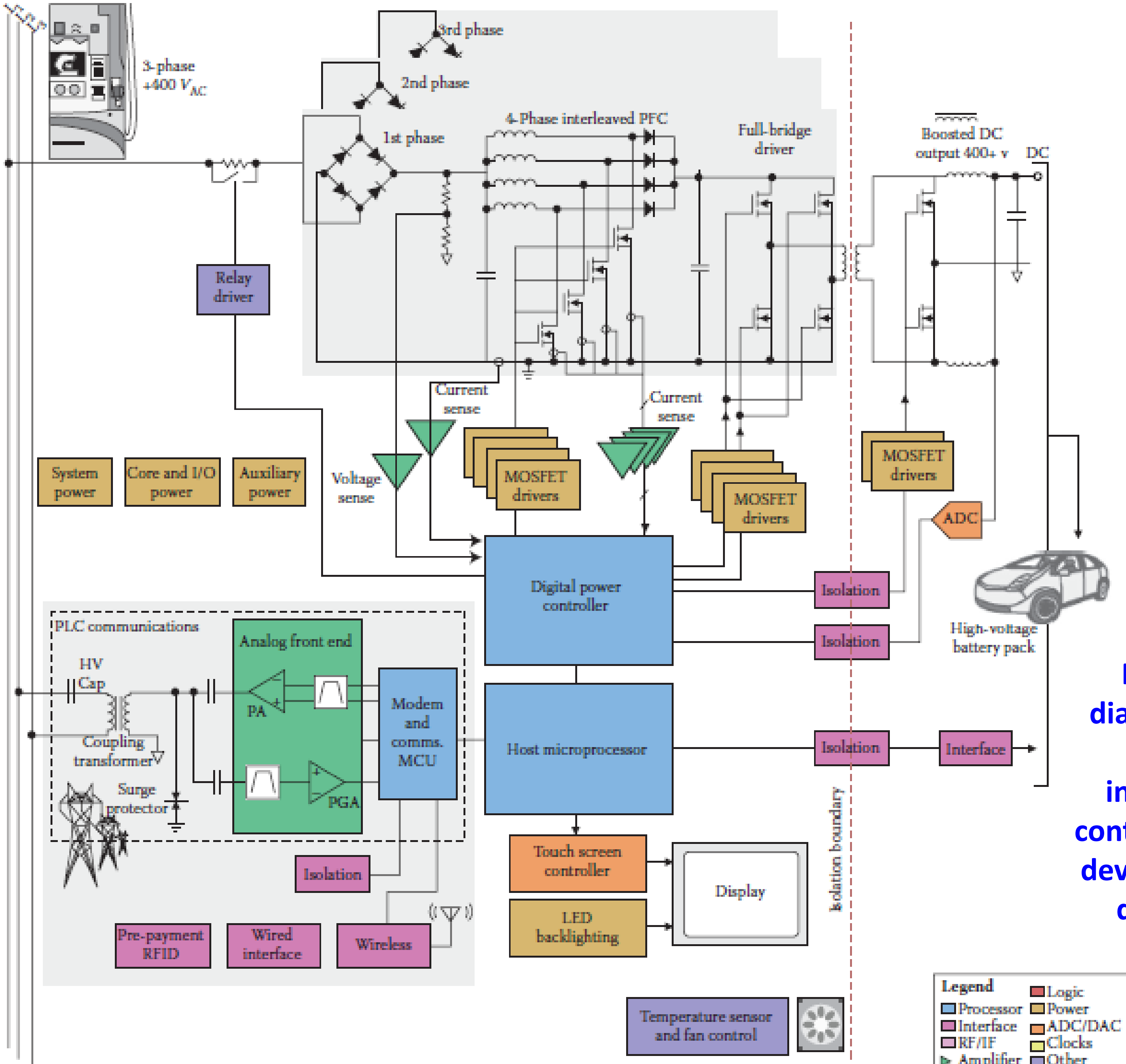


Fig. 23. Typical block diagram for a high power EV charger (level 3) including digital power controllers, communication devices, high-performance drivers, and interface devices.

5. Battery charging profiles

- Recently, various battery charging algorithms have been investigated to **extend the battery cycle life and reduce restrictions on battery use**. Most of these studies focused on developing charging algorithms and profiles **to reduce the battery charging time** by adopting a high C-rate current. They are as:

1) **Constant Current-Constant Voltage (CC-CV):** Batteries are charged with constant current until the maximum acceptable battery voltage is reached; after that, charging is continued with a fixed charging voltage, and charging is completed when the charging current reaches a preset small value.
2) **Multi-stage Constant Current (MCC):** that is another well-known fast charging method. Unlike the constant-current charging method, charging current is divided into several levels in the MCC method **to reduce the charging time and heat generated inside the battery during charging.** Generally, the charging current is controlled in a direction where the size of the charging current decreases as the charging time progresses.
3) **Constant Power (CP):** charging method maintains charging power during the charging operation. **High charging current is induced at the beginning of charging and it is gradually decreased as the battery voltage increases.**
4) **Boost charging method:** is also one of the basic fast charging methods based on the CC-CV charging profile. **It adopts a high current charging period at the beginning of the CC-CV charging profile to reduce the charging time.**

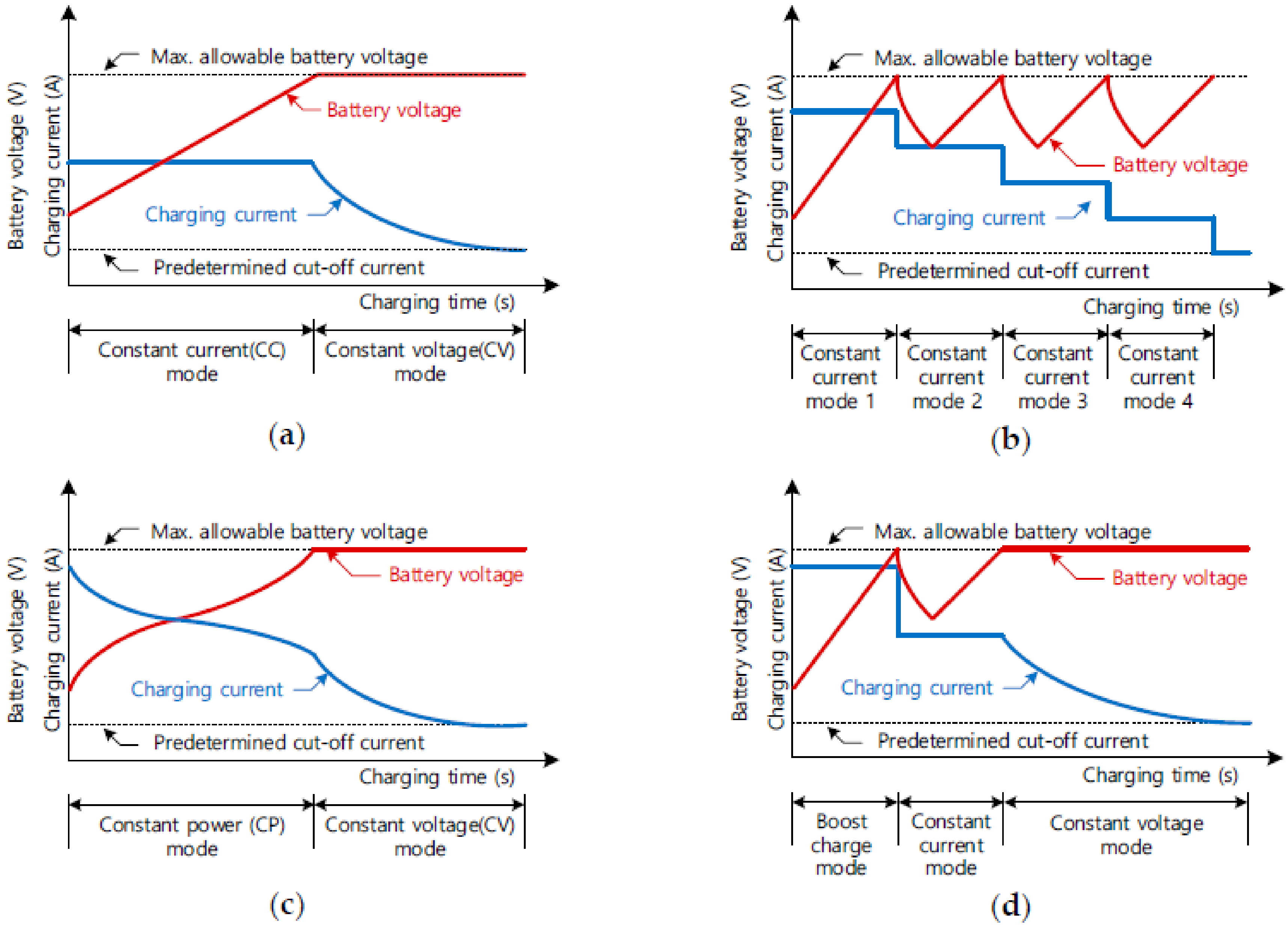


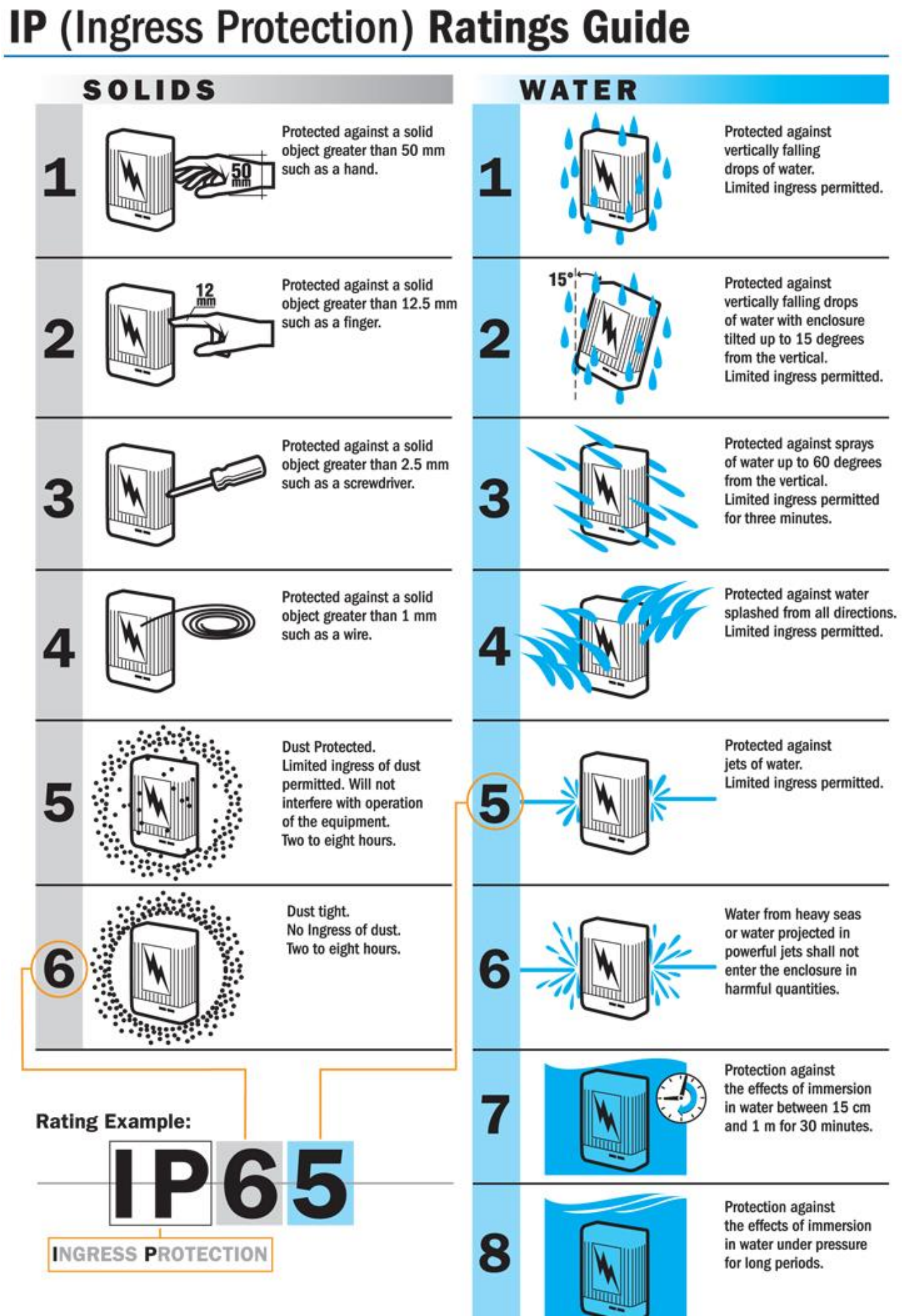
Fig. 24. Battery charging profiles: (a) Constant current-constant voltage (CC-CV) charging method; (b) Multi-stage Constant Current (MCC) charging method; (c) Constant power (CP) charging method; (d) Boost charging method.

6. EV charger design standards

- ❑ The safety standards that should be complied by the chargers are as:

- ✓ **Society of Automotive Engineers (SAE) J2929:** Electric and Hybrid Vehicle Propulsion Battery System Safety Standard;
- ✓ **ISO 26262:** Road Vehicles—Functional safety;
- ✓ **ISO 6469-3:** Electric Road Vehicles—Safety Specifications—Part 3: Protection of Persons Against Electric Hazards;
- ✓ **ECE R100:** Protection against Electric Shock;
- ✓ **IEC 61000:** Electromagnetic Compatibility (EMC);
- ✓ **IEC 61851-21:** Electric Vehicle Conductive Charging system—Part 21: Electric Vehicle Requirements for Conductive Connection to an AC/DC Supply;
- ✓ **IEC 60950:** Safety of Information Technology Equipment;
- ✓ **UL 2202:** Electric Vehicle (EV) Charging System Equipment;
- ✓ **FCC Part 15 Class B:** The Code of Federal Regulation (CFR) FCC Part 15 for EMC Emission Measurement Services for Information Technology Equipment;
- ✓ **IPxx/IKxx:** Ingress Protection/Impact Protection (**IP** is defined in **IEC 60529** which classifies and rates the degree of protection provided by mechanical casings and against dust and water. **IK Code** was originally defined in European Standard BS EN 50102. Following its adoption as an international standard in 2002, the European standard was renumbered **EN 62262**);
- ✓ −40°C to 105°C ambient air temperature/−40°C to 70°C liquid coolant temperature.

- ❑ There are different **current and voltage configurations** for charging, generally denoted as ‘**levels**’.



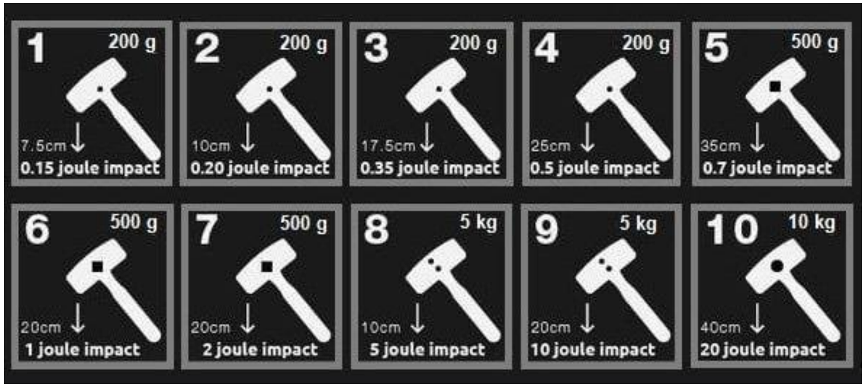


Fig. 25. IP and IK codes and classification for an instrument

Table 5. Operational standards for EV chargers.

Standard		Scope
IEC 61851: Conductive charging system	IEC 61851-1	Defines plugs and cables setup
	IEC 61851-23	Explains electrical safety, grid connection, harmonics, and communication architecture for DCFC station (DCFCS)
	IEC 61851-24	Describes digital communication for controlling DC charging
IEC 62196: Socket outlets, plugs, vehicle inlets and connectors	IEC 62196-1	Defines general requirements of EV connectors
	IEC 62196-2	Explains coupler classifications for different modes of charging
	IEC 62196-3	Describes inlets and connectors for DCFCS
IEC 60309: Socket outlets, plugs, and couplers	IEC 60309-1	Describes CS general requirements
	IEC 60309-2	Explains sockets and plugs sizes having different number of pins determined by current supply and number of phases, defines connector color codes according to voltage range and frequency.
IEC 60364		Explains electrical installations for buildings
SAE J1772: Conductive charging systems		Defines AC charging connectors and new Combo connector for DCFCS
SAE J2847: Communication	SAE J2847-1	Explains communication medium and criteria for connecting EV to utility for AC level 1&2 charging
	SAE J2847-2	Defines messages for DC charging
SAE J2293	SAE J2293-1	Explains total EV energy transfer system, defines requirements for EVSE for different system architectures
SAE J2344		Defines EV safety guidelines
SAE J2954: Inductive charging		Being developed

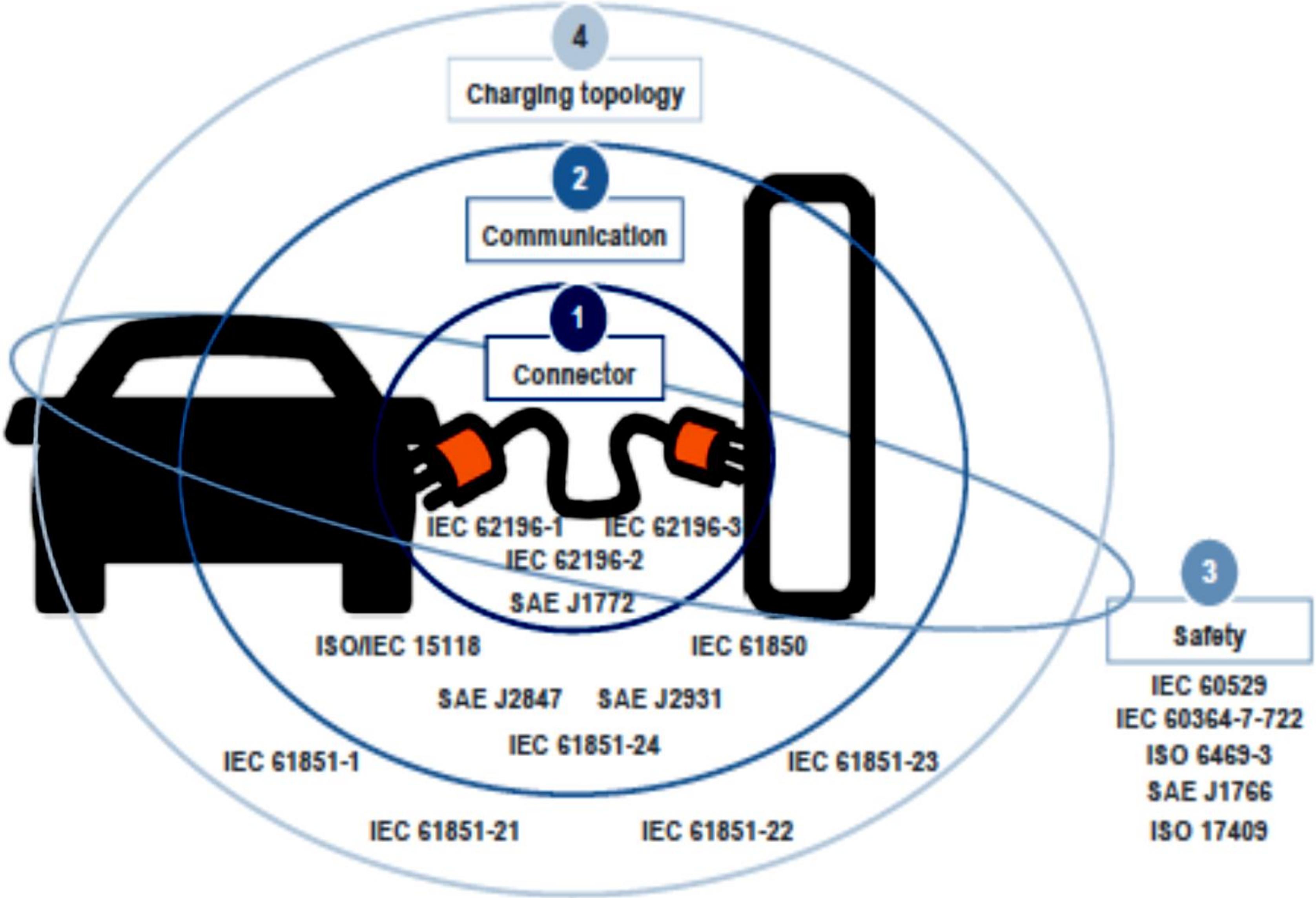


Fig. 26. Applied standards for EV charging design in various levels.

- **IEEE-1547**, **SAE-J2894**, **IEC1000-3-2**, and the U.S. **National Electric Code (NEC) 690** standards limit the **allowable harmonic** and **dc current injection** into the grid, and EV chargers are usually designed to comply.

Table 6. Detail list of international standards for wireless power transferring.

Organisation/Society	Relevant Standard/s	Standard Definition/Description	Year
Society for Automobile Engineers (SAE)	J2954 [55]	Wireless Power Transfer for Light-Duty Plug-In EVs and Alignment Methodology	2017
	J1772 [56]	EV/PHEV Conductive Charge Coupler (CCC)	2017
	J2847/6 [57]	Communication Between Wireless Charged Vehicles and Wireless EV Chargers	2015
	J1773 [3]	EV Inductively Coupled Charging	2014
	J2836/6 [58]	Use Cases for Wireless Charging Communication for PEV	2013
Institute of Electrical and Electronic Engineers (IEEE)	P2100.1 [59]	Wireless Power and Charging Systems	2017
	C95.1 [60,61]	Respect to Human Exposure to Radio Frequency (3 kHz – 300 GHz) Electromagnetic Fields	2006
Underwriters Laboratories Inc.(UL)	Subject 2750 [51]	Outline of Investigation, for WEVCS	2017
International Organization for Standardization (ISO)	19,363 [62]	Electrically Propelled Road Vehicles – Magnetic Field WPT – Safety and Interoperability Requirements	2017
International Electro-mechanical Commission (IEC)	61980-1 Cor.1 Ed.1.0 [3,51]	EV WPT Systems Part -1: General Requirements	2017
	62827-2 Ed.1.0 [3,51]	WPT-Management: Part 2: Multiple Device Control Management (MDCM)	2017
	63,028 Ed.1.0 [63]	WPT-Air Fuel Alliance Resonant Baseline System Specification (BSS)	2017
	15149-2 (ISO-IEC) [64]	Information Technology – Telecommunications and Information Exchange Between Systems – Magnetic Field Area Network (MFAN) – Part 2: In-band Control Protocol for WPT	2015
Japan Electric Vehicle Association (JEVS)	G106 [3]	Inductive Charging System for EVs-General Requirements	2000
	G107 [3]	Inductive Charging System for EVs-Manual Connection	2000
	G108 [3]	Inductive Charging System for EVs-Software Interface	2001
	G109 [3]	Inductive Charging System for EVs-General Requirements	2001

7. Connector types for EV chargers

- ❑ AC systems currently have three main types as:
- ✓ **Type 1:** Low power level for household sockets;
- ✓ **Type 2:** Most applicable;
- ✓ **Type 3:** is not applied yet;
- ❑ DC systems currently have three existing standards/protocol:
- ✓ **Combined Charging System (CCS):** applied for European EVs (Volkswagen, BMW, General Motors and Ford). It has to types as: **CCS1** and **CCS2**;
- ✓ **CHAdeMO:** applied for Japanese EVs (like Nissan, Toyota and Honda);
- ✓ **GB/T:** applied for Chinese EVs;
- ✓ **Supercharger:** only for Tesla EVs;

Current type	Region			
	Japan	America	Europe, rest of world	China
AC				
Plug name:	J1772 (or Type 1)	J1772 (or Type 1)	Mennekes (or Type 2)	GB/T
DC				
Plug name:	CHAdeMO	CCS1	CCS2	GB/T

Fig. 27. AC and DC plugs standard in Japan, America, Europe, and China.

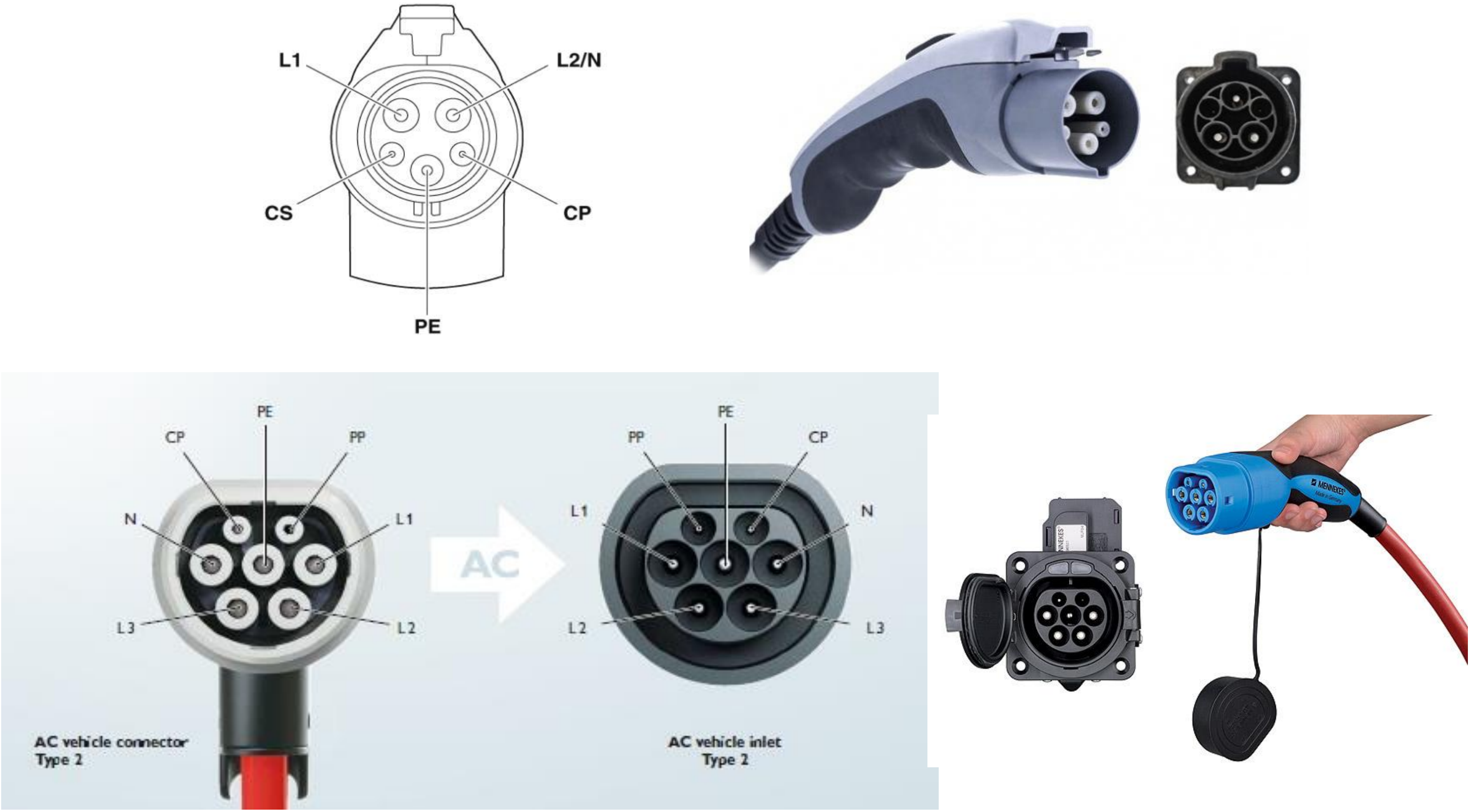


Fig. 28. Pin out of the AC Type 1 (high) and AC Type 2 (low) for both plug and socket.

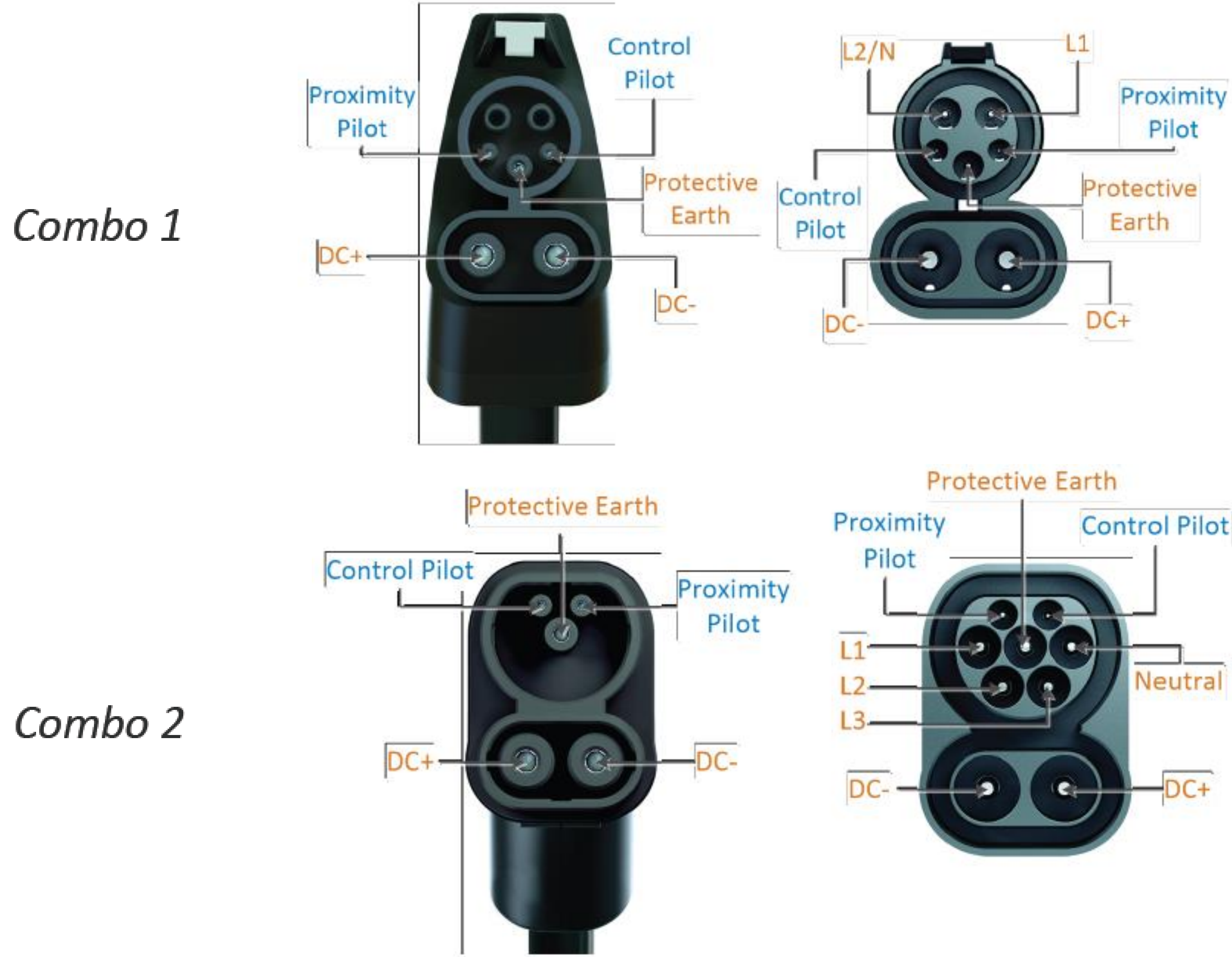


Fig. 29. Pin out of the CCS1 (high) and CCS2 (low) for both plug and socket.

- In general, CCS charger can deliver up to **350 Amps** at a voltage of between **200 to 1000V** giving a maximum power output of **350 kW.**

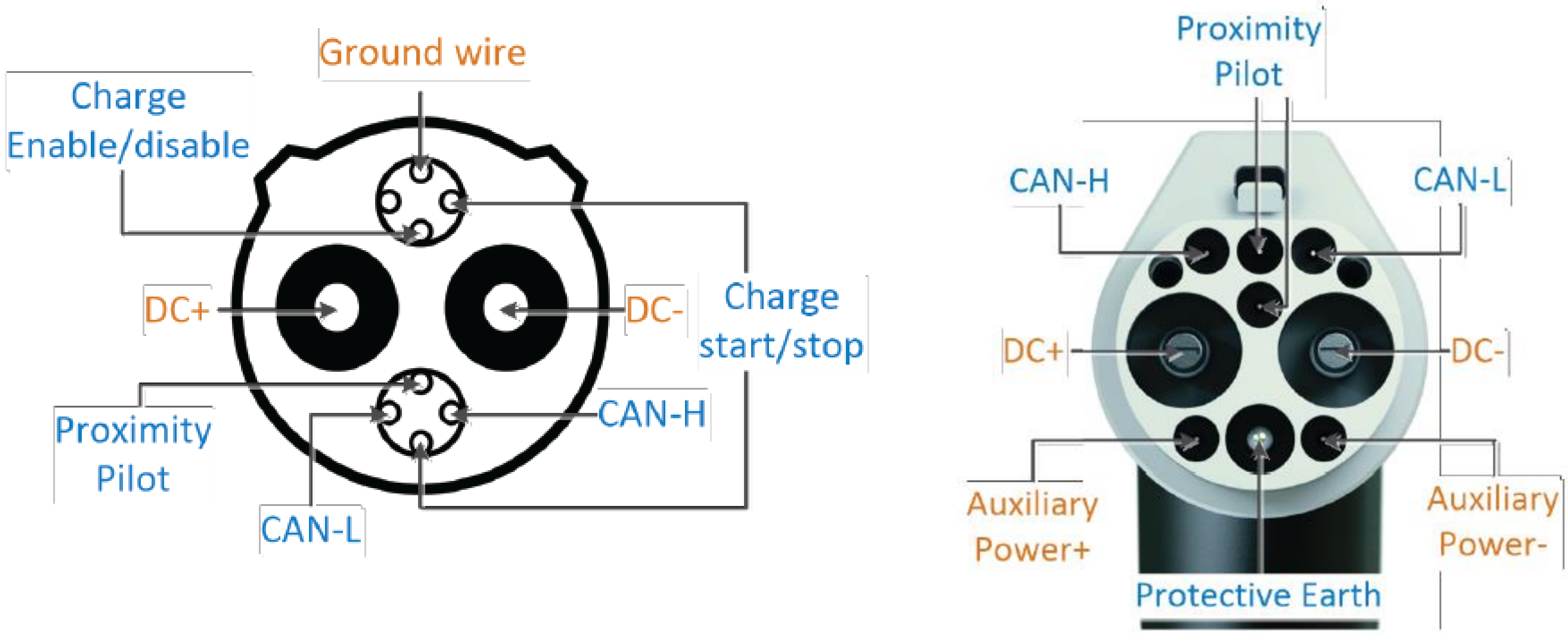


Fig. 30. Pin out of the CHAdeMO (left) and GB/T (right) for both plug and socket.

- For **CHAdeMO:** as of now, the voltage, current and power levels of CHAdeMO are **50-500V, up to 400A,** thus providing a peak power of **200kW.** In the future, it is expected that EV charging up to **1000V and 400kW** will be facilitated.

- For **GB/T:** as of now, the nominal voltages are **750V or 1000V,** and the current up to **250A** is supported by this charger.

AC Charging plugs

	USA - Japan	Europe	China
	Type 1  Tesla AC 	Type 2, Tesla AC  Type 3 	Based on Type 2 

DC charging plugs

	USA-Japan	Europe	USA-Japan-Europe	China
	Tesla DC 	Tesla DC 	Chademo 	GB/T 
	Combo 1: Combined AC & DC 	Combo 2: Combined AC & DC 		

Fig. 31. summary of commercial plugs and sockets for AC & DC chargers (Con.).

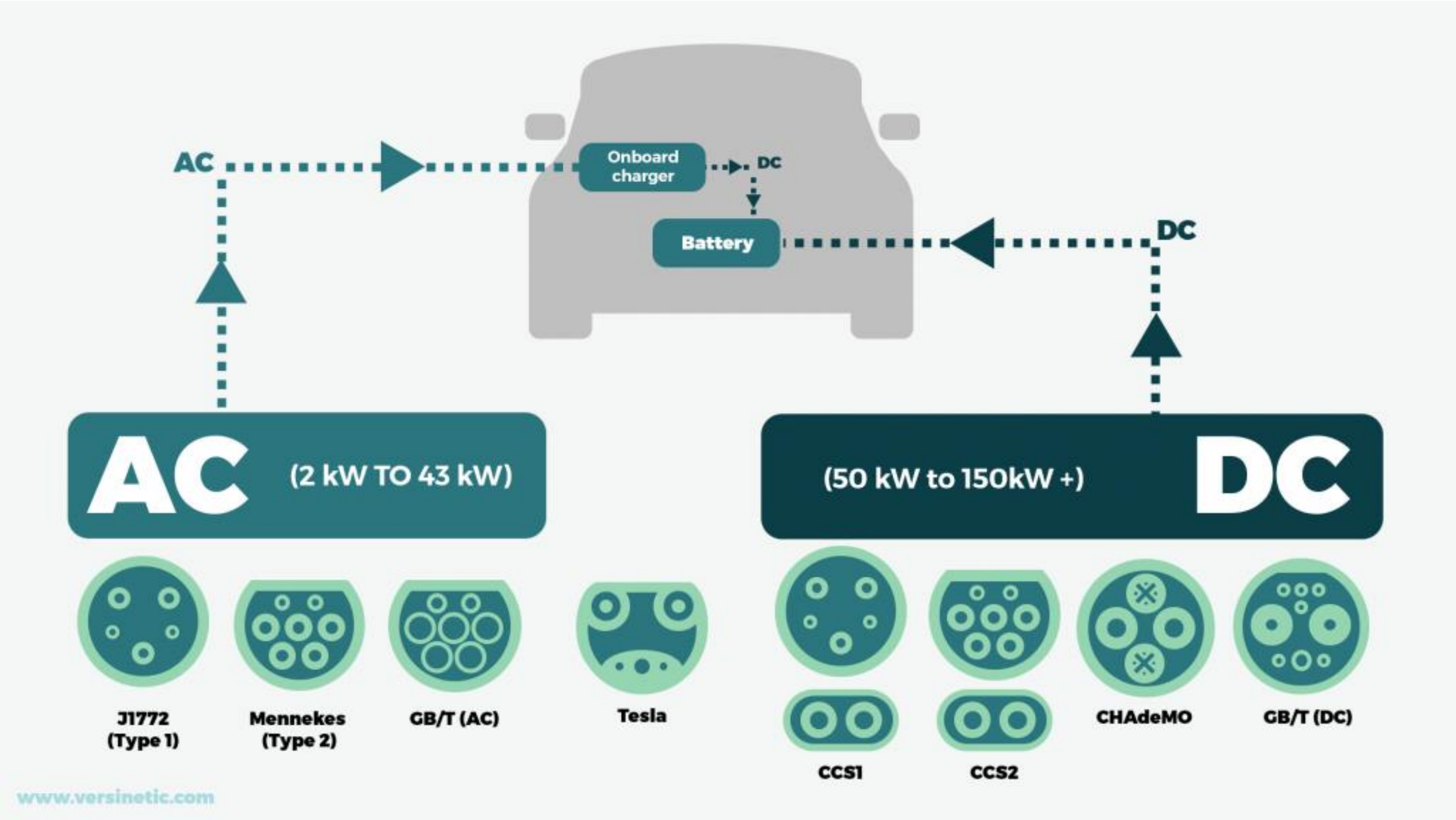


Fig. 32. summary of commercial plugs and sockets for AC & DC chargers.

Table 7. summary information of commercial plugs and sockets for AC & DC chargers: pin out & power rating.

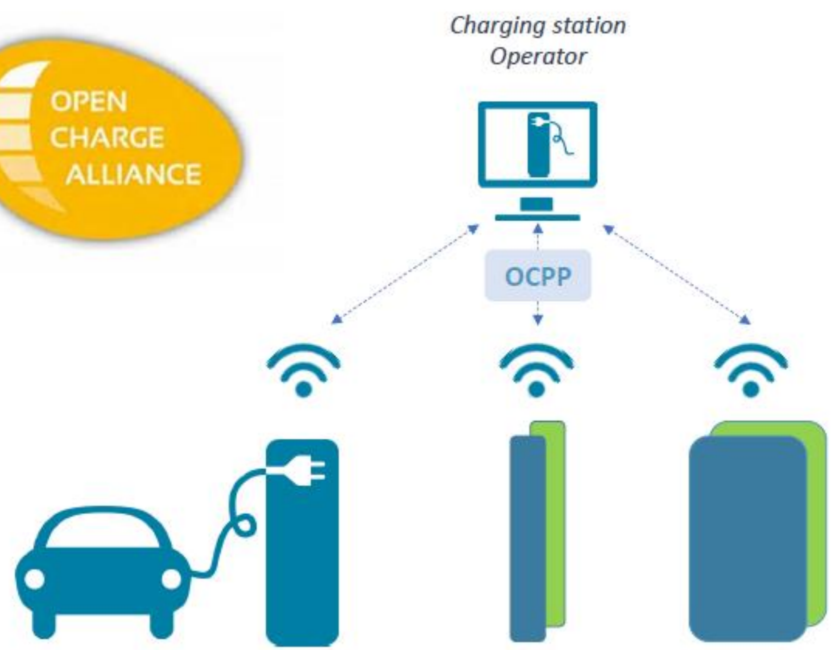
EV chargers: Power Levels

Plug	Pin configuration (Communication)	Voltage, Current, Power
Type 1 (SAE J1772)	3 power pins - L,N,E	1Φ 120V, ≤ 16A, 1.9 kW
		1Φ 240V, ≤ 80A, 19.2kW
Type 2	4 power pins – L1,L2,L3,N,E 2 control pins – CP, PP (PWM over CP)	1Φ 230V, ≤ 32A, 7.4kW
		3Φ 400V, 63A,43kW
Chademo	3 power – DC+,DC-,E 7 control pins (CAN communication)	200-500V, ≤ 400A, 200kW
CCS/ Combo	2 control pins – CP, PP (PLC over CP, PE)	200-1000V DC, ≤ 350A, 350kW
Tesla US	3 power pins – DC+,DC-,E (or) L1,N,E 2 control pins – CP, PP	Model S, 400V, ≤ 300A, 120kW

8. Chargers communication with power grid

There are various protocols for communication between Electric Vehicle Supply Equipment (EVSE) and higher systems for various types of support, power consumption monitoring, fault diagnosis, financial actions, reservation and etc. The main protocols are as:

1) Open Charge Point Protocol **(OCPP);**
2) Open Clearing House Protocol **(OCHP);**
3) Open Charge Point Interface **(OCPI);**
4) Open Inter-Charge Protocol **(OICP);**
5) Open Active Demand Response **(OADR);**
6) Open Smart Charging Protocol **(OSCP);**
7) Electro Mobility Interoperation Protocol **(EMIP);**



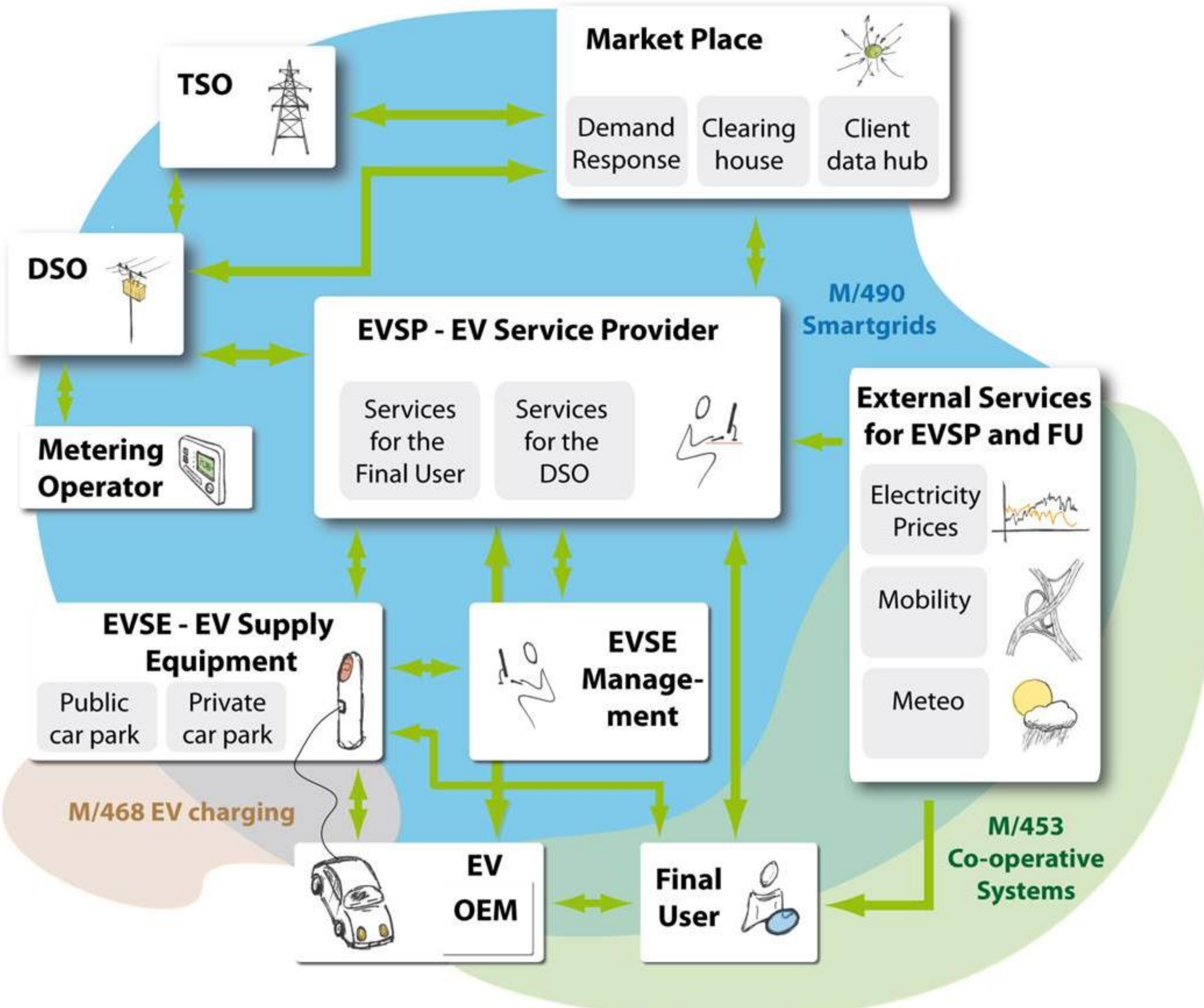


Fig. 33. conceptual presentation of various parts of a power management grid for EV power supplying and their interoperations.

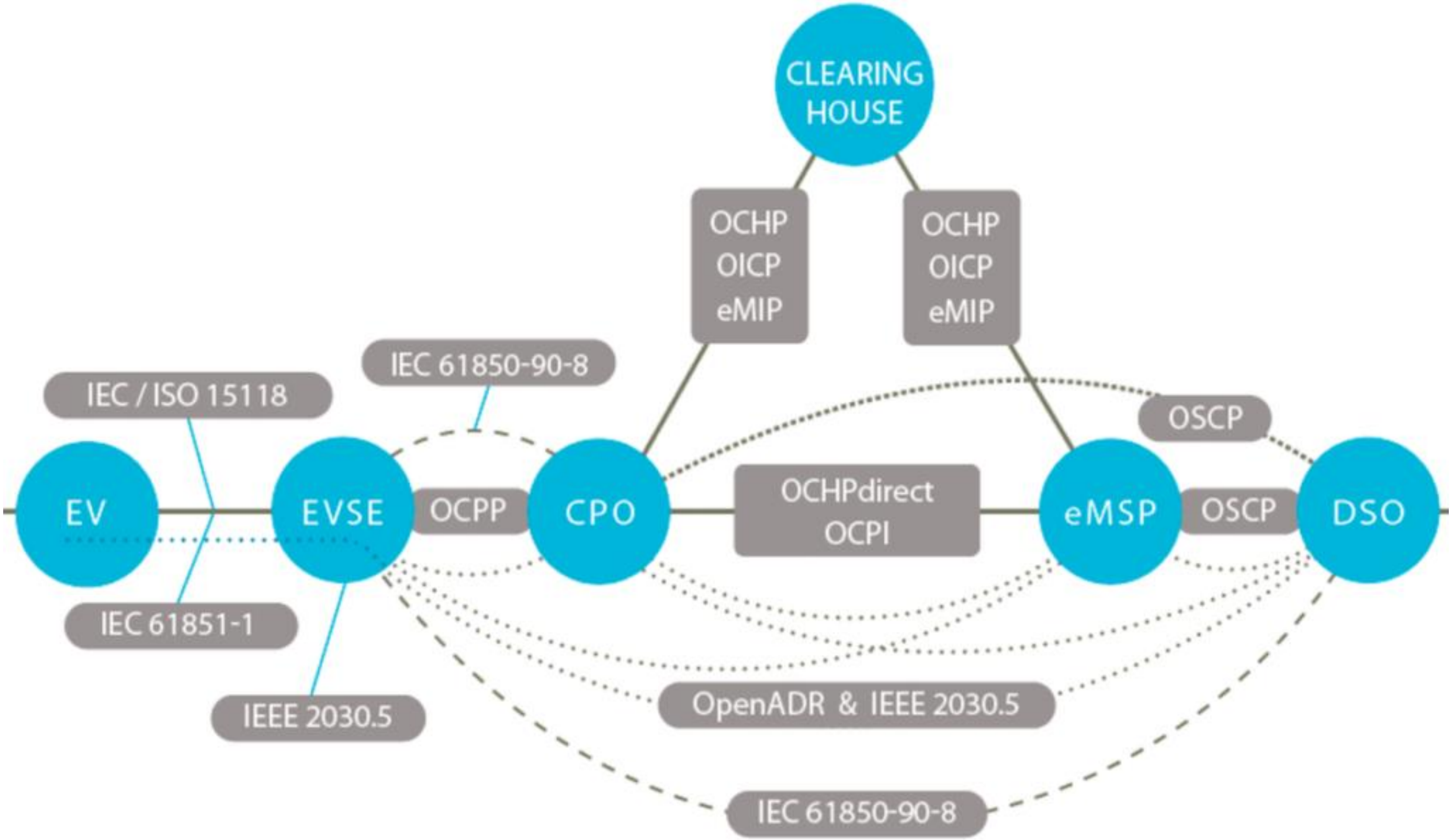


Fig. 34. Conceptual presentation of communication protocols among EVSE and power grid and upstream systems.

- ✓ **EVSE:** Electric Vehicle Supply Equipment;
- ✓ **CPO:** Charging Point Operator;
- ✓ **eMSP:** E-Mobilty Service Provider;
- ✓ **DSO:** Distribution system operators;

9. Electric bus chargers

- There are four main charging methods for E-buses charging as:

1) plug-based charging: for depot locations of E-buses, up to 350kW;
2) Flash charging: for bus stations in the various stations, lower that 100kW;
3) Opportunity charging based on pantograph: usually for first and final station in a line or in the depot locations, up to 600kW;
4) Trolley charging: using a continues power line in the rout;

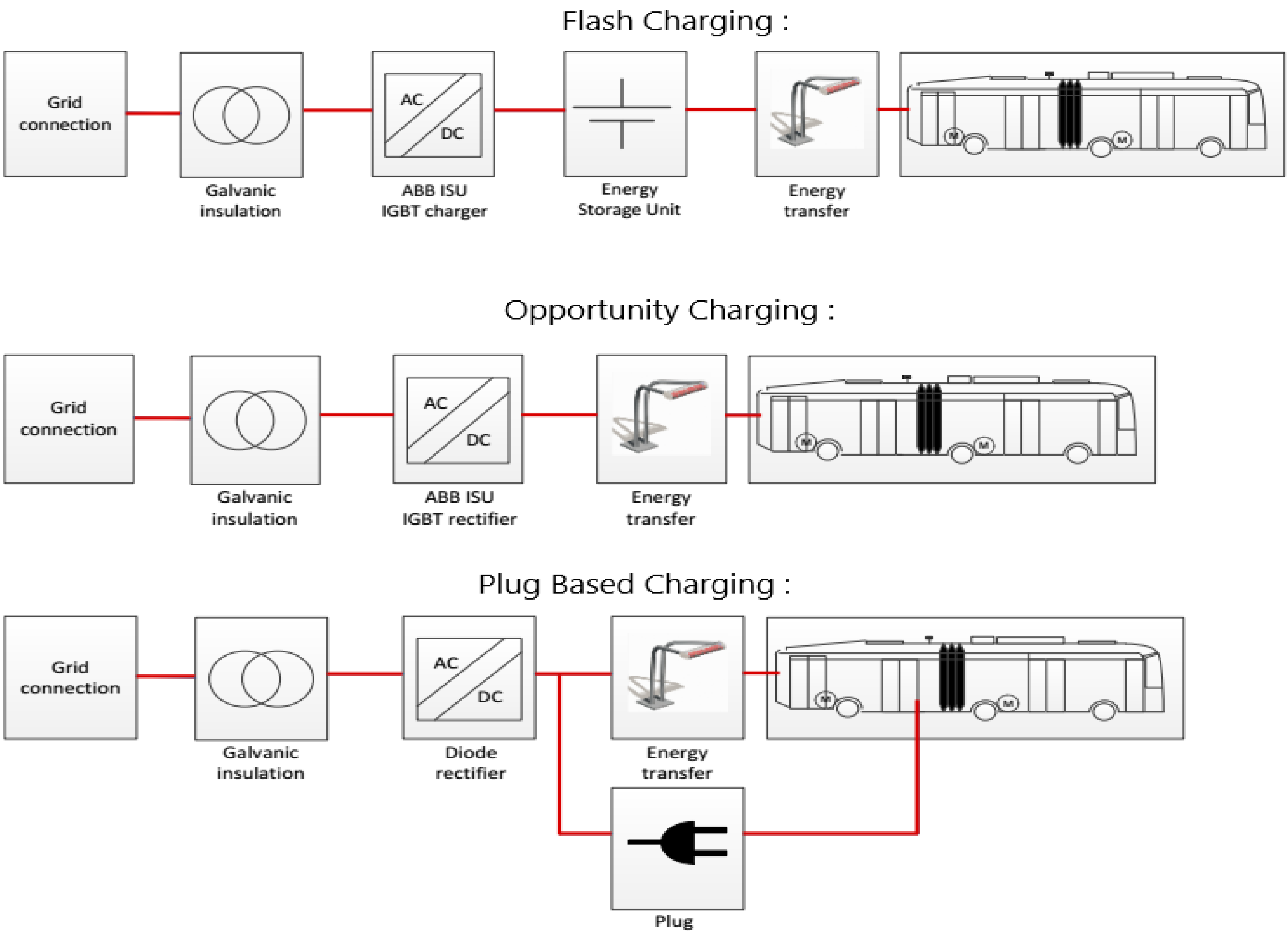


Fig. 35. Conceptual presentation for three main charging methods for E-buses.

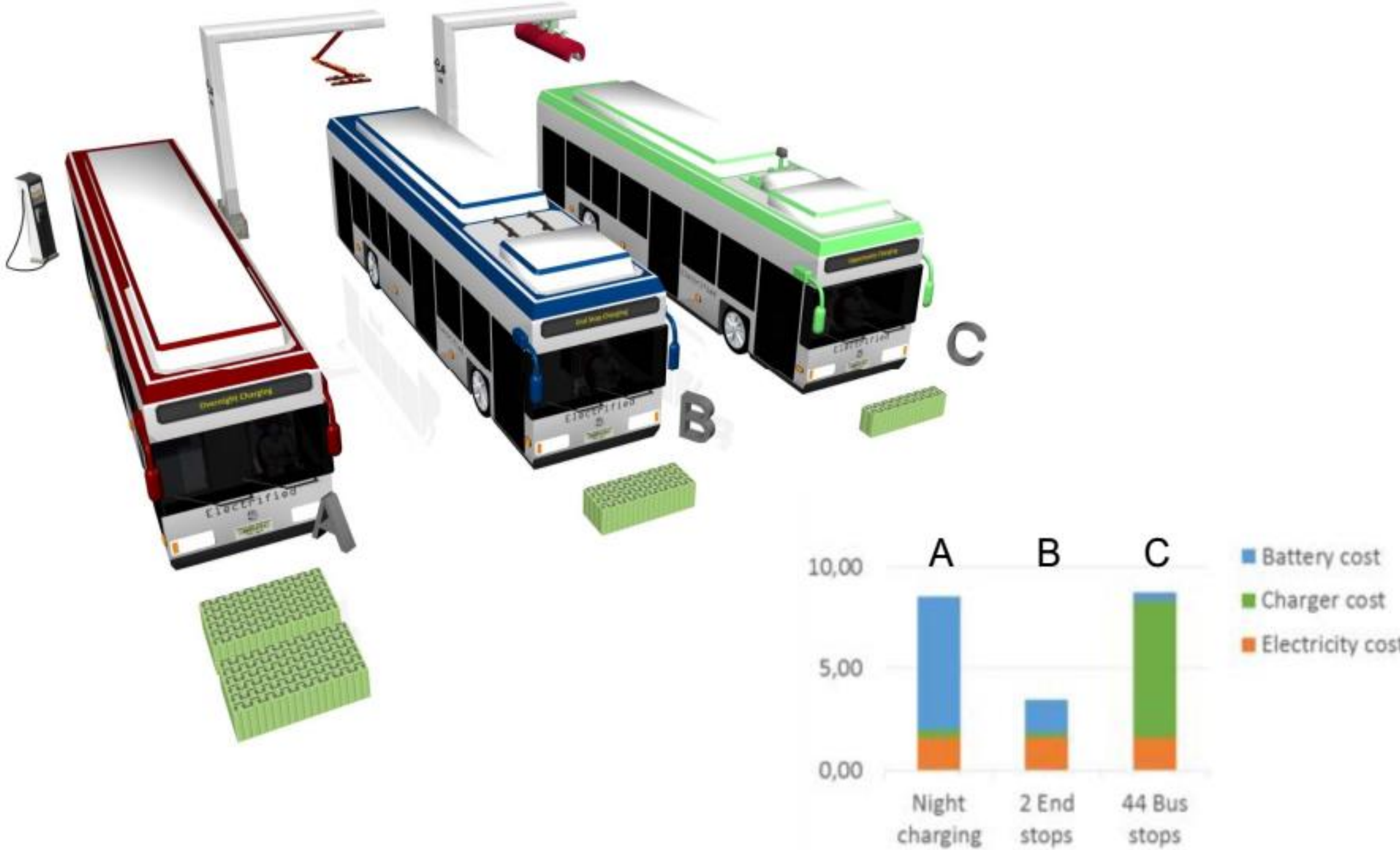


Fig. 36. Battery pack size and costs comparison among three main charging methods for an E-buse that wants to use one of three main charging systems.

Fig. 37. a plug-based charging station for E-bus (high) and a depot charging station for E-buses (low).

Fig. 38. A flash charging station (high) and an opportunity charging station based on inverted pantograph (low).

Fig. 39. Trolley bus charging method.

10. Chargers sample trend and market (ABB case study)

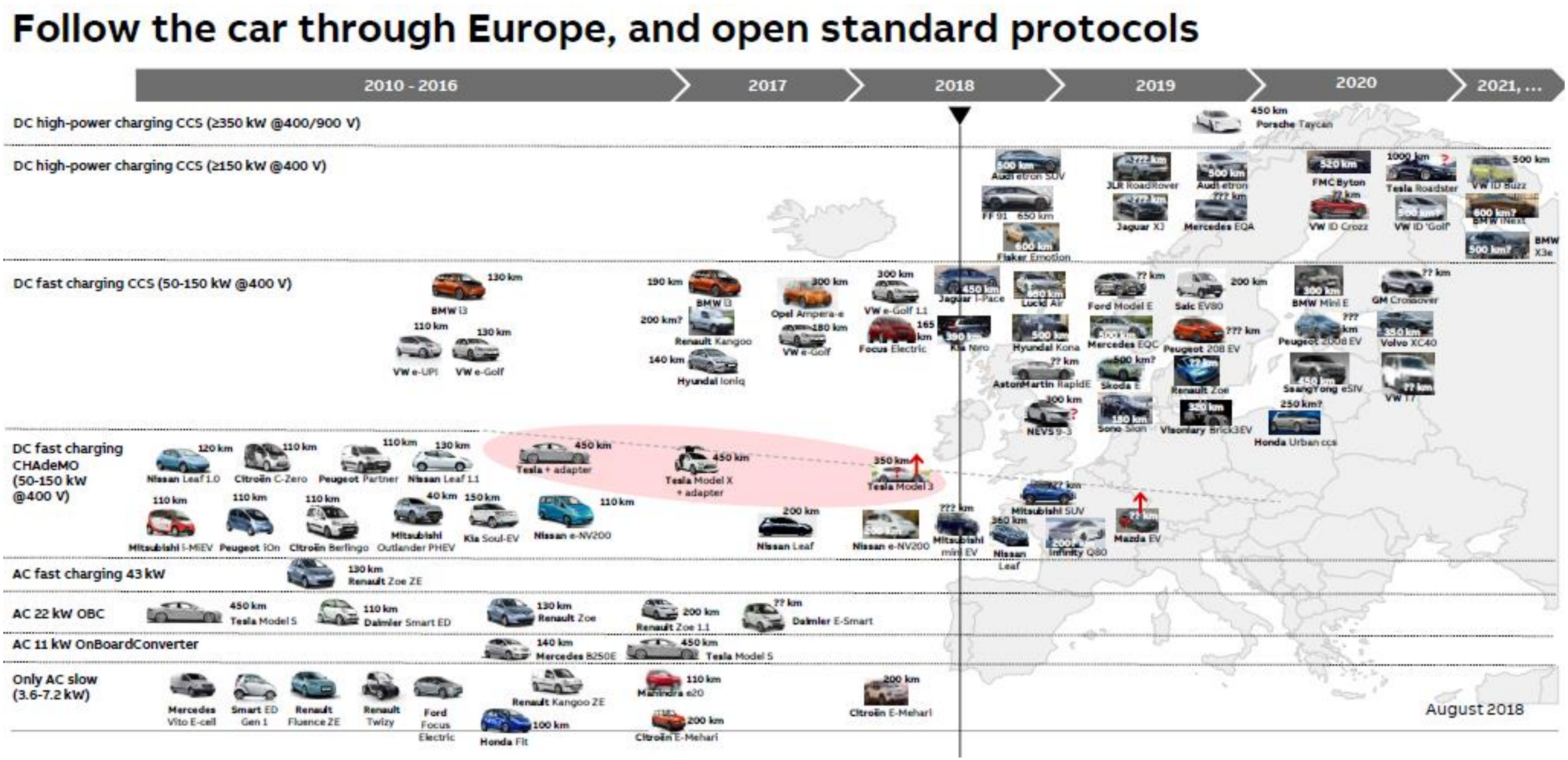


Fig. 40. Various charging scenarios and standards and EVs that use them.

Public and commercial EV Charging

AC destination	DC destination	DC Fast	DC High Power
3-22 kW	20-25 kW	50 kW	150 to 350 kW+
4-16 hours	1-3 hours	20-90 min	10-20 min
			
– Office, workplace – Multi family housing – Hotel and hospitality – Overnight fleet – Supplement at DC charging sites for PHEVs	– Office, workplace – Multi family housing – Hotel and hospitality – Parking structures – Dealerships – Urban fleets – Public or private campus – Sensitive grid applications	– Retail, grocery, mall, big box, restaurant – High turnover parking – Convenience fueling stations – Highway truck stops and travel plazas – OEM R&D	– Highway corridor travel – Metro 'charge and go' – Highway rest stops – Petrol station area's – City ring service stations – OEM R&D

Public and commercial EV Charging

AC destination	DC destination	DC Fast	DC High Power
3-22 kW	20-25 kW	50 kW	150 to 350 kW+
4-16 hours	1-3 hours	20-90 min	10-20 min

Fig. 41. Various charging scenarios from ABB group and their usage conditions.

EVLunic AC Wallbox

Portfolio details

Models

Fig. 42. AC Level 2 charger from ABB group.

EVLunic	**B**	– Entry level chargers with basic options
	B+	– Entry level chargers, with full power range available and with authentication options
EVLunic	**Pro S**	– Smart chargers with energy meter, connectivity, OCPP and load balancing through a smart master
	Pro M	– Smart chargers with energy meter, connectivity, OCPP and load balancing. Can serve as the central device for OCPP and load balancing for up to 15 Pro S devices

Global Outlook

BEV and numbers of AC level 2 chargers

- Morgan Stanley and Goldman Sachs expect 1 Bn BEV by 2050
- Estimated number of BEV by 2030 of approx. 100 - 150 Million
- Expected ratio: 1.6 level 2 AC Charger per car
- By 2030 the amount of installed AC Chargers will be between 160 Million and 280 Million

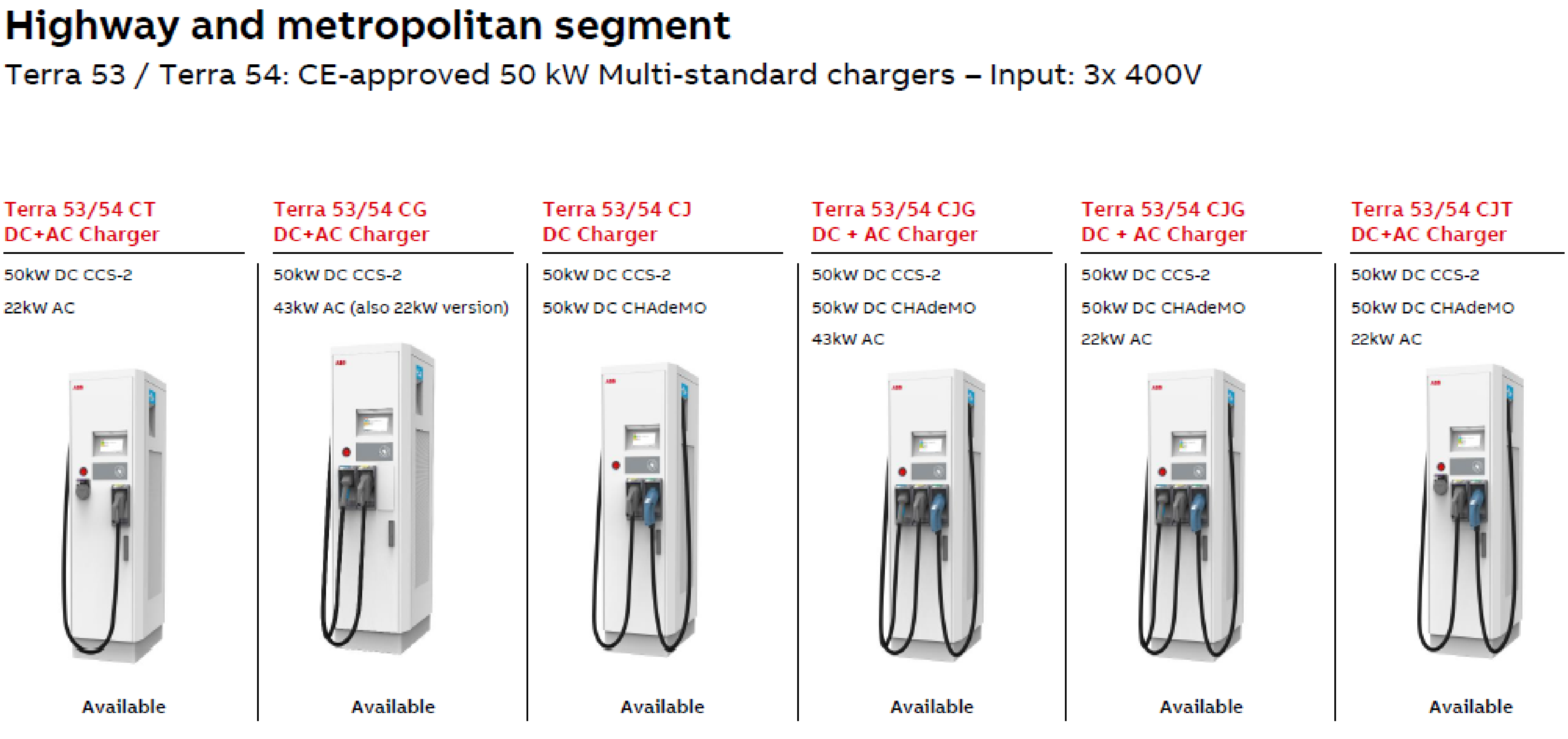


Fig. 43. DC fast chargers from ABB group.

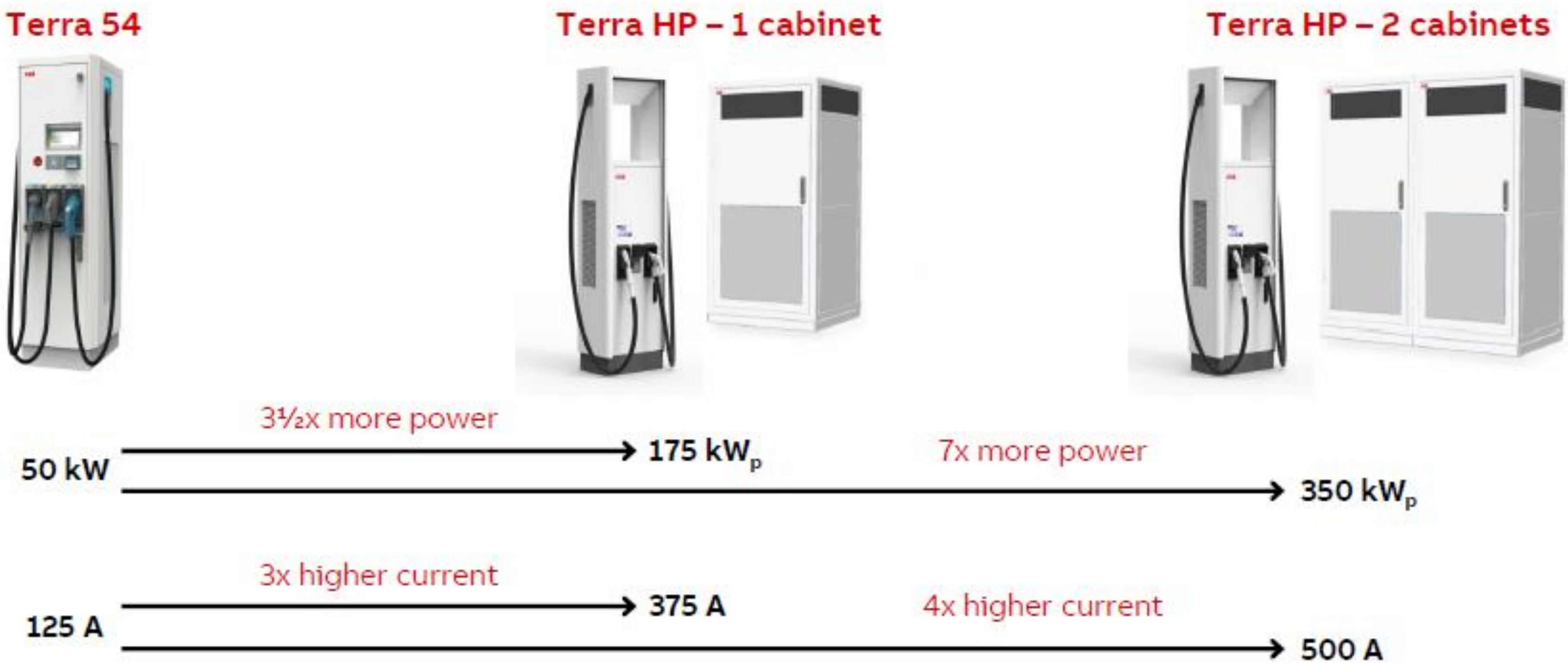


Fig. 44. DC High power chargers and DC fast chargers comparison.

Table 8. A charger main specifications.

Technical specifications	
Power	100 kW, 150 kW
Input AC connection	3P + PE
Rated input current & power (per 150 kW module)	100 kW: 3 x 170 A, 117 kVA 150 kW: 3 x 250 A, 173 kVA
Input voltage range	400 V AC +/-10% (50 Hz or 60 Hz)
Maximum output current (per 150 kW power cabinet)	100 kW: 166 A 150 kW: 200 A (limited by CCS cable)
Output voltage range	150- 850 V DC
DC connection standard	IEC 61851-23 / DIN 70121/ ISO 15118
Connection method between charger and bus	CCS 1 or CCS 2
Environment	Indoor / Outdoor
Operating temperature	Standard: -10 °C to +50 °C Optional: -35 °C to + 50 °C
Dimensions (W,D,H)	Power cabinet: 1170 x 770 x 2030 mm Depot charge box: 600 x 220 x 800 mm
Network connection	GSM / 3G modem 10/100 base-T Ethernet
Protection	Charge cabinet: IP54- IK10 Depot charge box: IP65- IK10
Sequential charging	Yes, up to 3 outlets per charger
Cable length between depot charge box and cabinet	Up to 150 m
Cable length between 2 depot charge boxes	Up to 30 m
Cable length connector	Standard: 3.5 m Optional: 7 m

MAPNA Group

Electric Vehicle Infrastructure and Development Center (EVIDC)

www.mapev.ir

Slow Portable Charger

Fast Wall-box Charger

Fast Charger Station

Slow Wall-box Charger

Slow Charger Station

Slow Street Charger

- Ethernet
- WIFI
- RFID Reader
- Multi Protocol
- OCPP 1.6
- LCD Display

Product highlight:

- Support Standards (Optional): CCS, CHAdeMO, GB and AC
- Nominal output power: 30 kW
- 94% efficiency
- Network connectivity (OCPP 1.6)
- Application and website
- Remote update
- Graphic visualization of charging progress
- RFID card and QR Code for user authentication

Output	Connectors (Optional)	CCS or CHAdeMO or GB or AC type 2.0
	Nominal power	30 kW
	Nominal Voltage	150-500 Vdc
	Max. current	60 A
Environmental	Operating Temperature	-25°C - 50°C
	Protection	IP55
	Application	Indoor / Outdoor