CAM CONSULTING

C-EVIL Chargers of Electric Vehicles in Learning

EGE UNIVERSITY

C-EVIL Chargers of Electric Vehicles in Learning

C-EVIL TRAINING MATERIAL

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PART A:

INTRODUCTION

1 HISTORY OF ELECTRIC VEHICLES

Before 1830s, transportation was only by steam-powered carriers. Michael Faraday discovered the laws of electromagnetic induction in 1831 and shortly after the DC motor is invented. These inventions enabled battery powered carriages. At the dawn of the development of electric vehicles (EVs), information about research and inventions spread much slower than today. Most of the inventors worked independently without knowing of each other's products and results. Also, research papers, patents and standards were less often submitted. As a result, we cannot say who developed the first electric vehicle; instead, we are going to explore the early developments of EVs.

1.1 The First Electric Vehicles

There are various inventors that took part in the long process of developing today's electric vehicles. One of the first was Ányos Jedlik, a Hungarian inventor who developed an electric motor and produced a model electric car in 1828. Robert Anderson, Scottish inventor, developed a crude electric carriage sometime between 1832 and 1839. In 1835, Dutch Professor Sibrandus Stratingh and his assistant Christopher Becker developed a small-scale electric car, powered by non-rechargeable battery cells [1].

Rechargeable batteries were not developed until 1859, when Gaston Planté, French physicist, invented the first lead–acid battery. Later in 1881, Camille Alphonse Faure improved the battery design and reached increased capacity. His work and developments led to the mass-production of lead-acid batteries [1]. One of the first human-carrying electric vehicles with integrated power source was tested in Paris, in April 1881. Gustave Trouvé, the inventor integrated a Siemens electric motor and a rechargeable battery into a tricycle, creating the Trouve Electric Tricycle as shown in Fig. 1.1 [2].

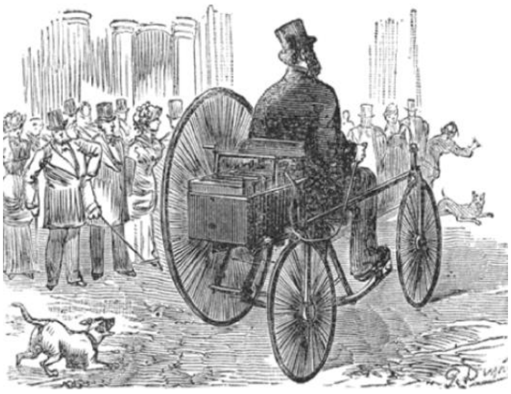

Fig. 1.1 Trouve Electric Tricycle [2]

In 1882, William E. Ayrton and John Perry of England also created a three-wheeled electric vehicle using a secondary battery. Its top speed was 9 mph (14.5 km/h), and it traveled a distance of 10 miles (16 km) to 25 miles (40 km). 2 years later, in 1884, the first mass-produced electric car was built by Thomas Parker, a British inventor [1].

1.2 The Golden Age of EVs

Steam, gasoline and electric powered cars were seen together on roads in 1880s. Gasoline cars were very uncomfortable, because they were unstable and could stop from time to time on road and had to operate manually by hand as shown in Fig. 1.2. Moreover they were noisy, had vibration and bad smell. Steam powered cars were also noise and had vibration. Additionally, their start-up times were very long, up to 30 minutes in cold weather. On the other hand, the electric cars were more comfortable; there was no vibration, noise or odor. They didn't have gearshift and operated without need for manual starting.

Fig. 1.2 [3]

While steam-powered cars had advantages for long driving distances, the electric cars were popular as city cars in relatively short distances. Around the late 1800s and early 1900s (the Golden age of electric cars), EV manufacturing was already a relatively robust and successful industry. In 1899, there were 12 EV manufacturers in the United States, and due to the short range, they were mostly producing cars for city use and for taxi companies. In 1900, 4200 automobiles sold in USA; 40% steam powered, 38% electric powered and 22% gasoline powered [4]. In this period, EVs were considered clean, quiet and efficient compared to other solutions.

One of the biggest obstacles for EVs was the lack of practical and rechargeable battery solutions. Even though Thomas Edison managed to develop the nickel-iron battery and provide over 100 miles range, this technology was not perfect. Its weight, sensitivity for damages and high cost did not let the nickel-iron batteries revolutionize the EV industry.

In the early 1900s, the gasoline cars began to gain popularity in the market. The electric starter motor (cranking system) was invented in 1911 that were greatly increased the comfort of gasoline cars. Additionally, exhaust systems, which significantly reduce the car noise, and coil spring suspension, which reduces vibration, were developed. These three technologies have had major impact on the comfort of gasoline cars, and thus customer preferences have shifted to gasoline cars. Fast filling the gas tank, long driving range and low cost were the biggest advantages of gasoline cars. Henry Ford's Model T played a role in ending the Golden age of electric cars by providing the customers what they needed: a reliable, easy-to-use, and affordable car. Also, the developing road network and the discovery of cheap Texas crude oil contributed to the decline of electric vehicles. By 1935, most of the EVs disappeared from the streets.

Later, during World War II due to oil shortage and in the 70's due to the oil and energy crises, interest in EVs appeared again. Still, batteries did only allowed a limited number of applications with a low capacity.

1.3 Today's Electric Cars

Long years passed without significant market interest in EVs. The development towards marketable EVs restarted due to environmental considerations. The most important technological enabler that contributed to today's EV development was the invention of lithium-ion battery in the 1980s, commercialized by Sony in 1991. The most important unit of the lithium-ion battery, the cobalt-oxide cathode was invented by John Goodenough and his team at Oxford University. After, this technology made possible the development of consumer electronics and EVs with longer range. In 2019, Goodenough and two other researchers received the Nobel Prize for helping to develop and improve lithium-ion batteries [5].

Thanks to the lithium-ion technology, the development of EVs received a tailwind. Some milestones of EV technology are listed below [5]:

- 1881: Trouve Electric Tricycle
- 1959: Henney Kilowatt, top speed 60 mph, range 60 miles. 47 sold.
- 1996: General Motors EV1, available only for lease (battery: 16.5 kWh, range: 89 km)
- 1997: Toyota Prius is released which is the first mass-produced hybrid electric car (HEV).
- 2006: Tesla Roadster is introduced. It is the first passenger car in serial production. It costs $80.000. (battery: 53 kWh, range: 320 km)
- 2009: Mitsubishi i-MiEV (battery: 16 kWh, range: 100-160 km)
- 2010: The first Plug-In Hybrid Car, Chevrolet Volt was introduced.
- 2010: Nissan Leaf (battery: 24 kWh, range: 117-175 km)
- 2012: Tesla Model S released, from $50,000 (battery: 75-100 kWh, range: 401-647 km)

- 2016: Tesla Model 3: the world's best-selling electric car in history, with more than 500,000 units delivered as of 2020, from $35,000 unit price. (battery: 50-75 kWh, range: 350-518 km)

Despite Tesla's dominance in EV technology and marketing, there is a growing competition on the EV market. For example, Rivian, Nikola Motors or Lucid Motors in the USA and Nio, WM Motor or Xiaopeng Motors in China are mass producing EVs. The traditional automotive players are also in the competition (e.g. Nissan, Kia, VW, PSA Group, etc.)

There are different setups of EVs running on solely electric motors or when the electric motor works as an extension of the Internal Combustion Engine (ICE). A hybrid electric vehicle (HEV) derives part of its power from a conventional ICE and part from an electric motor and battery, while all of its energy is generated by burning gasoline or diesel. A HEV's battery is usually recharged by regenerative braking technologies and it results in better average litres/km. Some of the models are charging the battery directly by the ICE.

PHEVs are generally designed with a relatively small battery that is covering daily commuting of owners (approximately 50km), while for longer trips the ICE comes in. This setup is favourable for many customers as it provides as low emission solution for cities and it still has the comfort of filling tanks traditionally. PHEVs are the link between EVs and ICE cars. Today, there are BEVs with ranges from 200 km up to 800 km.

PHEVs are expected to phase out by the time EVs with longer ranges become affordable for the people. Additionally, more and more countries are placing bans on the production of ICES from the years of 2035 or 2045, which will mean the end of PHEV production as well.

A battery electric car (BEV) gets driving power from the electric motor(s), while the energy is from a battery, being recharged from the electricity grid. BEVs use regenerative braking to increase efficiency as well. In everyday language, the phrase electric car is meant for battery electric cars.

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1.4 The Present and Future of EVs

The significance of the EV market can be explained by the sales number of today and of the close future. Let's take a look at BloombergNEF's Electric Vehicle Outlook 2020 forecasts:

EV sales:

There were 450,000 passenger EVs sold in 2015, while in 2019, the number was 2.1 million. In 2020 this number is continuing to rise rapidly, while batteries are getting cheaper, thanks to R+D activities and the energy density of batteries is increasing. In the meantime, the charging network is growing to accommodate the increased demand of EVs. By 2030, 26 million and by 2040, 54 million EVs are predicted to be sold.

EV share of new car sales:

The share of sales of EVs is still small, approximately 2% in 2020. However, it is rising fast and by 2040 more than half of the passenger vehicles sold will be electric. It is important to mention, that in developed countries the ratio will be significantly higher compared to emerging markets, which reduce average market penetration significantly. By 2030, BloombergNEF predicts that 28% of the new cars sold will be EV. By 2040, this number increases to 58%.

Size of the global EV fleet: EVs will become a common sight in the following years. Most of them will be BEV, but PHEV will also play a role in the next 10 years. Then, as mentioned before, low prices and the regulatory environment will be favourable for pure BEVs. In 2020, 8.5 million EVs are on the road, which number is expected to increase to 116 million by 2030.

Global vehicle fleet: Despite the rapid development of EV related technologies, the improved charging network or the environmental advantages, in 2030, there will be 1.4 billion passenger vehicles on the road from which EVs account for only 8%. As the ICE fleet is getting older, by 2040 31% of passenger cars are expected to be the EVs.

1.5 Automotive Industry in Transition

The following years are bringing an important change in the automotive and energy industry. A global energy transition towards a more sustainable system based on decentralized, renewable energy generation and technologies that make it happen, such as batteries and smart grid solutions. There are 3 main factors that are driving the transition of the automotive industry; technological development of batteries, policymaking, and change in customer needs. These three main factors explained in detail in following.

1.5.1 Technological development of batteries

Battery prices are decreasing, while the technology is maturing, and the power and capacity of batteries are increasing. The price of the most widely adopted Li-ion batteries is around 156 USD/kWh today. According to BloomberNEF, reaching 94 USD/kWh price by 2024 and 62 USD/kWh by 2030 is possible as shown in Fig. 1.3(a). The demand to batteries is expected to increase exponentially in the next ten years as shown in Fig. 1.3(b) [6].

1.5.2 Policymaking

Accelerating the rate of EV adoption is clearly an objective of many countries to mitigate negative effects of the use of fossil fuels for passenger vehicles and transportation. Policymakers are introducing higher and higher standards towards vehicles concerning emissions, while more and more companies are aiming to become carbon-free and to contribute to sustainable development goals. As a result, low-carbon transport solutions are taking over the market.

In October 2019, 35 cities pledged to transform "a major area" of their city center emissions-free by the year of 2030. The C40 Fossil-Fuel Free Streets Declaration was signed by 17 European cities incl. Barcelona, Berlin, Amsterdam, Manchester, Copenhagen, Madrid and Warsaw. Some examples:

Oslo	Fossil-free city centre by 2024. All city fossil-free by 2030.
Paris	Diesels banned by 2024 and petrol cars banned by 2030
Rome	Emissions-free transportation only in the city center by 2030
London	Central London to be a zero emission zone by 2025
Brussels	Diesels banned by 2030 and petrol (incl. LPG) cars banned by 2035

Additionally, several European countries pledged to phase out the sale of new ICE vehicles soon. After the date, only emission-free vehicles can be sold new; 2025: Norway; 2030: Denmark, Iceland, Ireland, the Netherlands; 2032: Scotland ; 2035: United Kingdom; 2040: France, Spain

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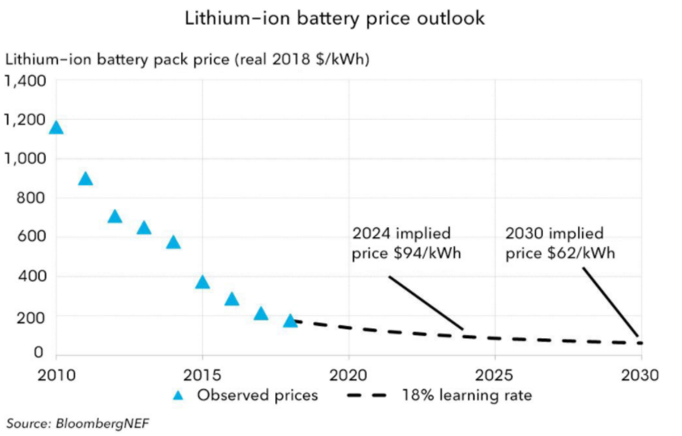
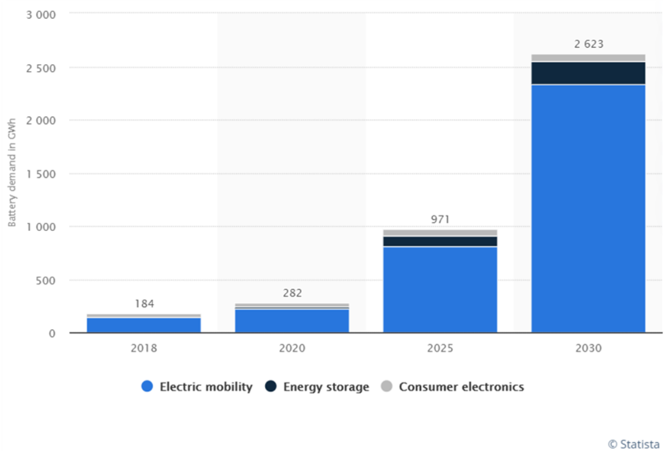


(a) [BloombergNEF]



(b) [6]

Fig. 1.3

1.5.3 Change in customer needs

Urbanization requires cleaner technologies in cities, with zero local emission. Also, consumer preferences in cities are in change and car-ownership started decreasing. The way customer's access, purchase, and use cars and other ways of transport are changing thanks to increasing connectivity and the use of e-commerce. New technologies, IoT, and the use of internet have a great impact on mobility. It is clear, that the future is less product and more service [7].

1.6 Business Opportunities of the Sector for Professionals

The number of EVs and charging stations is growing hand in hand. To develop, produce and maintain EVs and the charging infrastructure, a great number of professionals are needed. Engineers, technicians, electricians, and different specialists are and will be demanded by the industry. It can be stated, that the EV industry is promising in terms of career.

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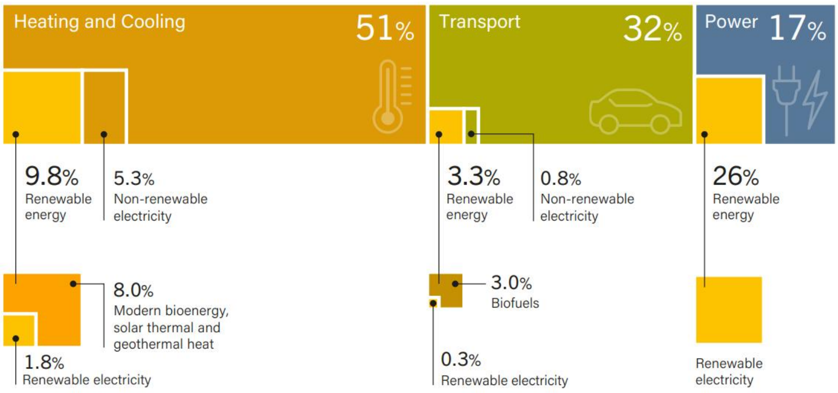
2 ENVIRONMENTAL EFFECTS OF ELECTRIC VEHICLES

Today environmental concerns are high since global warming and environmental pollution seriously threat the human life on earth. The average temperature of Earth surface steadily increasing after industrial revolution at 1900s. Scientific investigations revealed that the global warming is caused by greenhouse gases, i.e., CO_2, methane etc. Their concentration in the atmosphere is increased by human activities. The main contribution to greenhouse gas emission is coming from combustion of fossil fuels. Therefore, it is obligatory to stop the usage of fossil fuels as soon as possible.

The fossil fuels are not used in cars only. The majority of them are used in industry. In order to reduce harmful emissions, all of them should be replaced with renewable sources. According to the REN21, Renewables 2019 Global Status Report, the 32% of World energy consumption is used by transport sector as shown in Fig. 2.1. But only 3.3% of that is supplied by renewable sources, e.g. wind, solar, biofuel etc. It is very small percent. The ultimate goal is to make it 100% renewable.



Source: REN21, Renewables 2019 Global Status Report
Fig. 2.1

To reach the 2030 emission targets of European Union, a considerably higher ratio of EV is needed on the roads. Driven by customer needs and policy making, the car industry is trying to find solutions to meet the targets and to reduce emissions.

We all know that EVs have zero local emission while running. This statement is true for greenhouse gas (GHG), NOx and particle emissions. However, still there are emissions, when we are charging the batteries and when producing the batteries and even the car.

There have been extensive researches to answer the question: if EVs are more beneficial for the environment then traditional Internal Combustion Vehicles (ICVs) or not. Several researchers used Life Cycle Analysis to find out the answer, more specifically Well-to-Wheel analysis (WTW).

2.1 Greenhouse Gas Emissions

The Well to Wheel analysis is analysing all the CO_2 emissions that happen from the production of parts (i.e., mainly batteries), transport and fuel/electricity consumption of car while on the road. Also, it is important to mention that recycling or treatment of used batteries at the end of their life is a significant event that has to be considered when evaluating environmental friendliness of EVs.

Vrije Universiteit Brussel and the Transport & Environment NGO did a WTW analysis for a diesel-powered car and an EV [1]. The calculations considered 200,000 km distance and calculated to have the battery of the EV replaced once in this time period. After calculating the CO_2 emissions of producing diesel and electricity, the chassis of the cars, the engines, the battery and the electronics, the results showed that EVs emit less than half of the CO_2 as diesel ICVs. Researchers used the CO_2 emissions data of the EU energy mix. In case of EVs, 15% of the CO_2 emissions were from the production and recycling of batteries, while the electricity used for driving was the major source of CO_2. Considering the increasing ratio of renewable energy in electricity production, the CO_2 emission of EVs is only getting lower in the following years.

Certainly, CO_2 emission is not the only harmful environmental effect of EVs (neither of ICVs). Therefore, it is misleading to consider only CO_2 emissions when analysing environmental friendliness.

2.2 Effect of the Production of Lithium-ion Batteries

Manufacturing Li-ion batteries need several raw materials, like lithium, copper, nickel and cobalt. Lots of different chemicals and water is used for mining, cleaning or recycling these materials that lead to water and soil pollution.

The main source of cobalt for Li-ion batteries, both for EVs and for consumer electronics is the Democratic Republic of the Congo. 70% of the World's cobalt is mined here of which 30% is connect to informal (illegal) miners and child labour. Electronics giants have taken steps in order to improve cobalt purchasing from reliable sources [2].

In case of Lithium, Brazil, Chile, Bolivia, Argentina and China have the biggest resources. By 2030, less than 1% of the known lithium reserves will be mined. Thanks to the diversity and size of reserve, lithium for battery production can be considered stable in the future.

The recycling of Li-ion batteries is not solved as of today. Reusing and recycling is a growing market, as there are regulations coming to force in the future to make EV producers to increase recycling rate. Unfortunately, these processes are costly today compared to mining in third countries. According to Li-Cycle, a Canadian battery recycling enterprise, by 2030 there will be 11 million tons of used Lithium-based batteries accumulated on planet Earth [3].

There is intensive research in reusing second-hand batteries after the end of their lifetime. Reusing in electricity storage is one of the potential applications. Such opportunities are expected to reduce the lifetime environmental impact of battery production.

2.3 Zero Local Emission

Today, the biggest benefit of EVs is that they have zero local air pollution (CO_2, NO_x or particles). EVs improve air quality of big towns and cities as the pollution happens outside of the cities in power plants or in the factories. Clean air contributes to a favourable environment for pedestrians and cyclists as well.

Besides air pollution, EVs reduce noise pollution as well. Especially in low-speed zones in cities, EVs create a calmer environment for the ears.

Even though the production of batteries and the use of EVs have harmful effects on environment, it is considerably lower than traditional ICVs. Technological developments of batteries, increasing renewable penetration in electricity production are all working in favour of EVs. In the long run, pros outweigh the cons and EVs are contributing to a cleaner and more sustainable future [4].

2.4 Electricity Consumption

According to the International Energy Agency, by 2030 EVs (including two/three-wheelers like e-bikes) will consume between 550 – 1000 TWh. In Europe, EVs will count for more than 4% of total electricity consumption. As shown on the Fig. 2.2 [5], EVs are predicted to avoid between 2.5-4.2 million barrels of oil products per year by 2030. Due to the dominance of private charging, most of the consumption will happen at home. To unleash the full climate change mitigation potential of EVs, reducing CO_2 emissions of power generation is crucial.

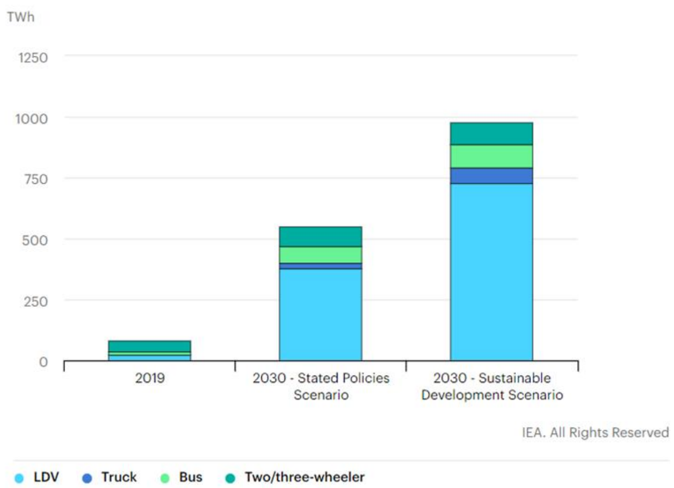


Fig. 2.2: Electricity demand from the electric vehicle fleet by mode, 2019 and 2030 [5]

2.5 The Future of Electricity Grid Infrastructure

As the electric consumption increase by EVs and other consumers, the conventional electricity generation and distribution network cannot meet the requirement. As we learned above, the electricity should be generated from renewable sources in order to reduce emissions. However, renewable sources cannot generate continuous power; most of them are intermittent energy source. Thus, electricity grid network must have energy storage devices and also smart management systems. This system is called as "Smart grid" which is illustrated in Fig. 2.3 [6]. The EVs are the important part of smart grid systems, some studies claim to use the EV batteries bi-directionally to support the grid. Smart grid is not realized yet, but there are many academic researches on it. In the future, electricity grid will be transformed into the smart grid, and all the energy will be supplied by renewable sources. For that time, EVs will be all green and no greenhouse footprint.

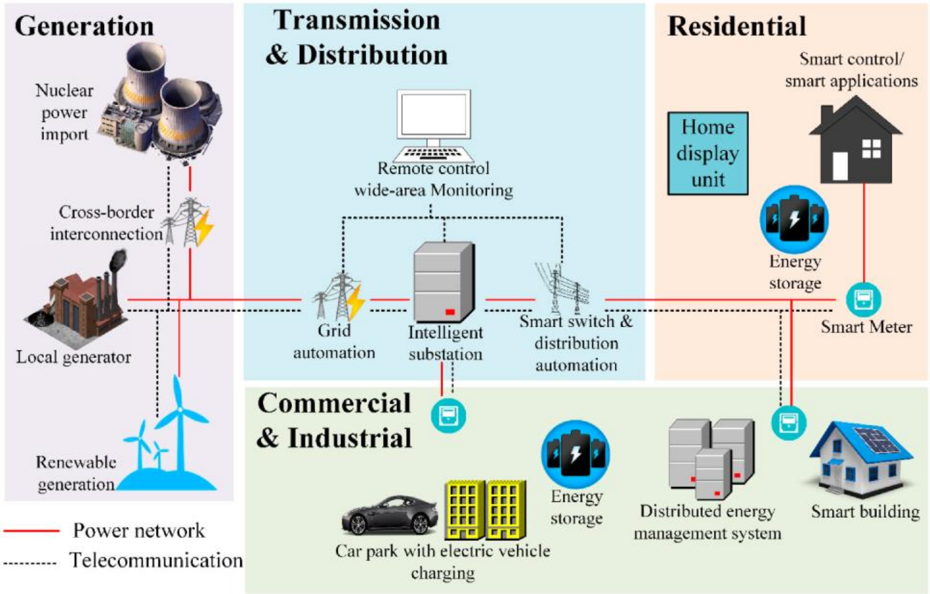

Generation
Nuclear power import
Cross-border interconnection
Local generator
Renewable generation
Transmission & Distribution
Remote control wide-area Monitoring
Grid automation
Intelligent substation
Smart switch & distribution automation
Residential
Smart control/ smart applications
Home display unit
Energy storage
Smart Meter
Commercial & Industrial
Energy storage
Distributed energy management system
Smart building
Car park with electric vehicle charging
Power network
Telecommunication

Fig. 2.3 [6]

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3 EV TECHNOLOGY OVERVIEW

Throughout the evolution of the EVs, mainly three types of EV have been emerged today as shown in Fig. 3.1; Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV) and Battery Electric Vehicle (BEV). Details about the EV car technologies will be introduced in this chapter.

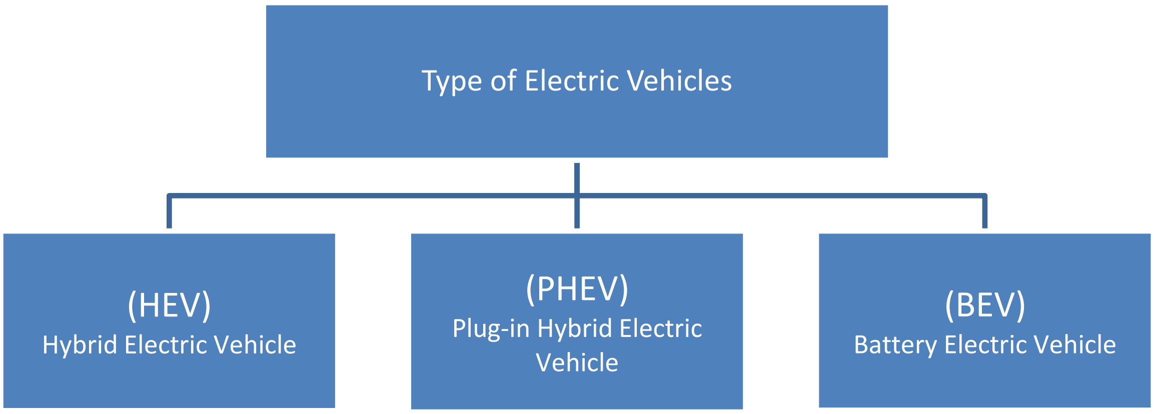


Fig. 3.1

3.1 Hybrid Electric Vehicle (HEV)

Hybrid electric vehicles (HEVs) are powered by an internal combustion engine (ICE) in combination with one or more electric motors that use energy stored in batteries. Hybrid electric vehicles are not plugged in to charge the battery. Instead, the battery is charged internally by the gasoline engine. The battery can also be charged from braking system that is called "regenerative breaking" where the electric motor operates as a generator to convert car's kinetic energy into electric. But regenerative energy can only increase energy efficiency of the car; it is not a main energy source.

There are two power train sources in hybrid cars: ICE and electric motor. In hybrid cars, the battery has a function to support dynamic component of load power as illustrated in Fig. 3.2. Therefore, the ICE supplies nearly constant power, and then it can operate more fuel efficiently. The HEV is driven by only electric motor during start-up and at low speed where ICE operates inefficiently. This operation provides fuel economy since fuel consumption of ICE is high for those conditions. The battery capacity is kept low for standard HEV, so it can have about 2-3 km range before gasoline engine turns on. When the speed reaches a certain level the ICE is activated and ICE powers the car and also charges the battery. If extra power or torque is needed during acceleration, ICE and electric motor can both be operated simultaneously in parallel by an internal computer to boost the performance.

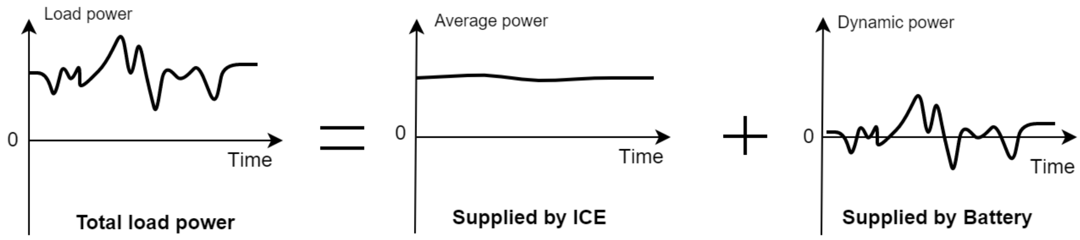
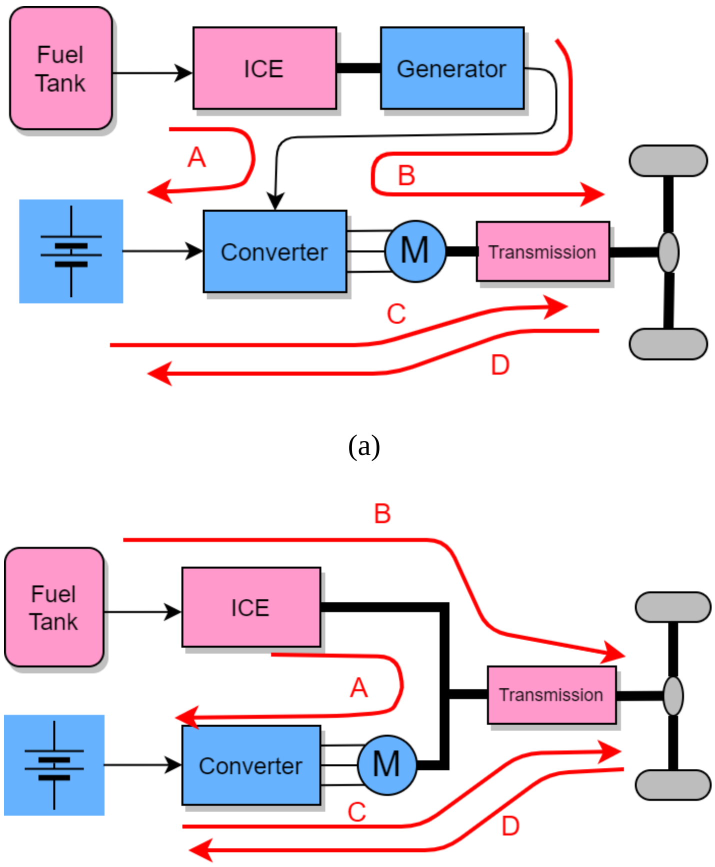


Fig. 3.2

According to their combining method, two types of hybrid cars are commonly used: series hybrid and parallel hybrid cars [1].

In series hybrid cars, two power trains are coupled electrically as shown in Fig. 3.3(a). The ICE is connected to a generator and provides all the power required by the car. The electric motor is the only traction motor and gets power from the generator and also from battery as depicted by paths B and C in Fig. 3.3(a). Battery is mainly charged by the generator as shown in path A in the same figure. On the other hand, the energy created by regenerative breaking can also be accumulated in the battery as indicated by path D. The advantages of series hybrid are that there is no mechanical connection of ICE to the wheels, and therefore, it can be operated at high speed and most efficient operating point continuously. The efficiency is increased and emission is reduced. On the other hand, the wheels are driven by electric motors which do not need gear system which significantly reduce the cost. Furthermore, two motors, one for each wheel, may be used so that mechanical differential component can be removed. Control is easy. However, the mechanical power created by ICE from fuel is converted twice to reach the wheels; first is mechanical to electrical, second electrical to mechanical, which reduces the conversion efficiency. Series hybrid car also needs an extra generator which increase the cost.

In parallel hybrid cars, the two power trains are coupled mechanically as shown in Fig. 3.3(b) where the traction power is mainly supplied by the ICE engine as highlighted by path B. The electric motors only support small fraction of total load or only dynamic parts through path C in the figure. For this reason both electric motor and battery size are small with respect to the series hybrid. The battery can be charged by the ICE motor through path A where the electric motor is operated as generator. Main advantages of parallel hybrid car are no energy loss for extra mechanic/electric conversion and no need to extra electric generator. However, the ICE cannot operate at constant speed at high efficiency operating point and they are complex and difficult to control [1]. There is also series-parallel hybrid method where both mechanical and electrical couplings are existed together.



(a)

(b)

Fig. 3.3

3.2 Plug-in Hybrid Electric Vehicle (PHEV)

Plug-in Hybrid Electric Vehicles (PHEV) is a transition model between full gasoline car and full electric cars. It solves the range anxiety problem of the full electric cars since it has a gas tank. PHEVs operation modes are very similar to HEV, but there is no path to charge the battery from ICE. The battery can only be charged by plugging into the utility grid. Therefore, PHEV should have an on-board charger as shown in Fig. 3.4

The battery capacity is considerably higher than conventional HEV since the manufacturers want to cut down the carbon emission of PHEV by powering it from battery as much as possible in daily usage. For this reason, a PHEV can go to 10-60 km with only battery power without ICE support. This range may vary with car models of different companies. If daily range is around 10-60 km for a PHEV, it may provide emission less operation and also can save fuel. However, the more daily range removes the advantages coming from the battery power.

Since the PHEVs use the energy inside the battery as much as possible, the number of full charging/discharging cycle for PHEV battery will be considerably higher than HEV. Therefore, the battery lifetime should be expected short for a PHEV compared to conventional HEV, due to the number of charge/discharge cycles for every battery is limited. As a conclusion, the large battery capacity increases the car cost significantly for PHEV. Additionally, the operational cost will also be high since the battery may be replaced a few times during car lifetime. Therefore, the PHEV is the most expensive EVs today. But it should be remembered that for short distance driving PHEV uses only electric power and therefore, is a green technology, no fossil fuels are used. However, in long distance drive, it will not be green. The ultimate goal is to stop fossil fuel usage. Therefore, the full electric car models are only candidate for green sticker.

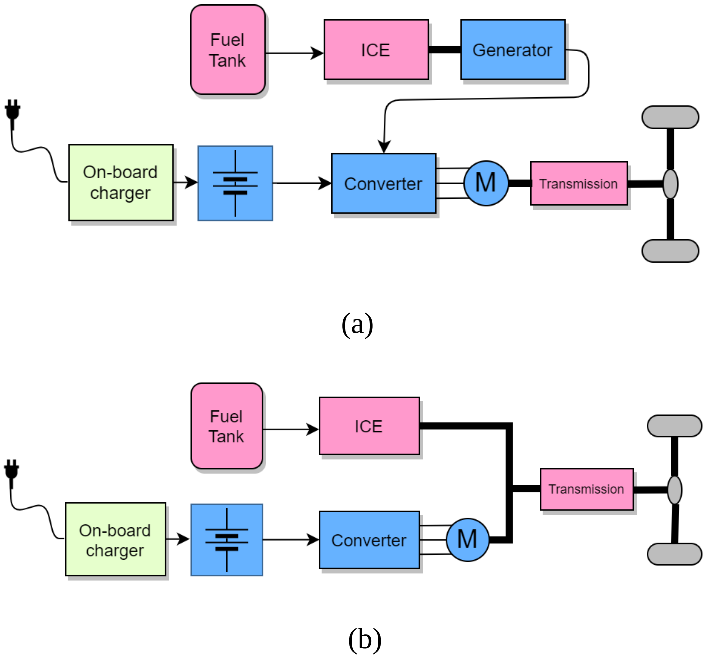


Fig. 3.4 PHEV structured a) series b) parallel

3.3 Battery Electric Vehicle (BEV)

Battery electric vehicles (BEVs), mostly called electric vehicles (EVs), are full-electric vehicles with rechargeable batteries. It stores all energy required for travel in the high-capacity on-board rechargeable battery pack. It doesn't have any conventional fossil fuel engines, and in turn, any harmful emission like as conventional gasoline cars. Therefore, it becomes completely green vehicle if battery energy is supplied by the renewable sources.

As shown in Fig. 3.5, on board battery pack supplies energy not only to electric motors, but to all onboard electronics through suitable power converters and control circuits, such as air condition (AC), radio, headlights, interior and exterior lights, power windows, power steering, windshield wipers etc. Therefore, EVs have the largest battery capacity among electric vehicles. Accordingly, it will need a lot of energy to fully charge. All EVs have on-board charger but its capacity cannot be large enough to quickly charge the battery due to size and weight restrictions of the vehicle. Thus, the full charge time of EV battery using on-board charger can be very long, up to 8 or 10 hours. This is very inconvenient while driving long distances. However, a PHEV does not need to be fast charged, because they have gasoline option for

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long distance drive. Therefore, EVs require fast charging stations where the charging time is less than 30 min. This significantly improves the comfort but fast charging is heavily depends on the battery technology, and requires powerful utility grid infrastructures as will be discussed later.

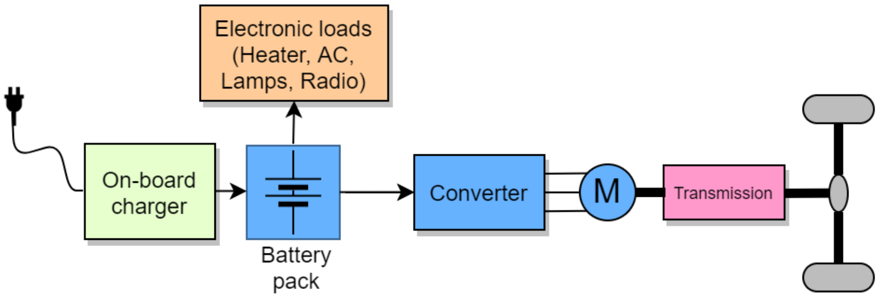

Fig. 3.5

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[1] M. Ehsani, Y. Gao ve A. Emadi, Modern Electric, Hybrid Electric and Fuel Cell Vehicles Fundamentals, Theory and Design, CRC Press, Taylor&Francis, 2010.

4 BATTERY TECHNOLOGIES FOR EV

The energy can be stored in many different forms, but the following three methods are more related for vehicles.

- *Biological storage*: The heat can be produced by burning the organic materials. Most known example for biological storage is fossil fuels that have been stored underground for millions of years, e.g., oil, coal, natural gas etc. But they have greenhouse gas emissions when burned. On the other hand, although biomass is burned as a fossil fuel, it is a renewable energy since it has no carbon footprint.
- *Chemical storage*: Energy can be stored in the bonds formed by chemical compounds and recovered through exothermic reactions (Reactions, that release heat, are called exothermic) The best-known chemical storage materials are hydrogen and ammonia. The hydrogen can be used to store and release electric energy using fuel cells. Today, there are vehicles, busses, even submarines powered by fuel cell. But the size and cost restrictions are the main barriers for hydrogen fuel cell storage today. Fuel cell technology has been undergoing extensive research; it could be source of energy for mobile devices and vehicles in near future.
- *Electro-chemical storage*: They are based on redox reaction where the electrons transferred between anode and the cathode electrodes according to the charge or discharge state. There are two type of electrochemical batteries: primary and secondary. Primary types, for example alkaline batteries, are not rechargeable. The secondary batteries can be charged and discharged many times. Most known secondary batteries are lead-acid, Ni-MH, Ni-Cd and Li-Ion batteries.

The nominal specific energy of some energy sources is given in Table 4.1 [1]. It is clear that, the hydrogen has the biggest specific energy value of 33 kWh/kg. The fossil fuels follow it. Unfortunately, the specific energy of batteries is very low as compared to others. This is why the electric vehicles have relatively shortest driving range. It can be seen in Fig. 4.1, where the average efficiency of conventional gasoline car is taken as 20% and the efficiency of EV as 90%. For this condition, to produce same shaft energy as gasoline car, the lithium polymer battery should be approximately 6 times bigger in size and 13 times heavier. However, battery electric

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vehicles use the energy very efficiently then ICE motors, therefore, do not need excessive specific energy like as conventional fossil cars.

Table 4.1 Nominal energy density of sources [3]

Energy Source	Nominal Specific Energy (Wh/kg)
Gasoline	12500
Natural gas	9350
Methanol	6050
Hydrogen	33000
Coal (bituminous)	8200
Lead-acid battery	35
Lithium-polymer battery	200
Flywheel (carbon fiber)	200

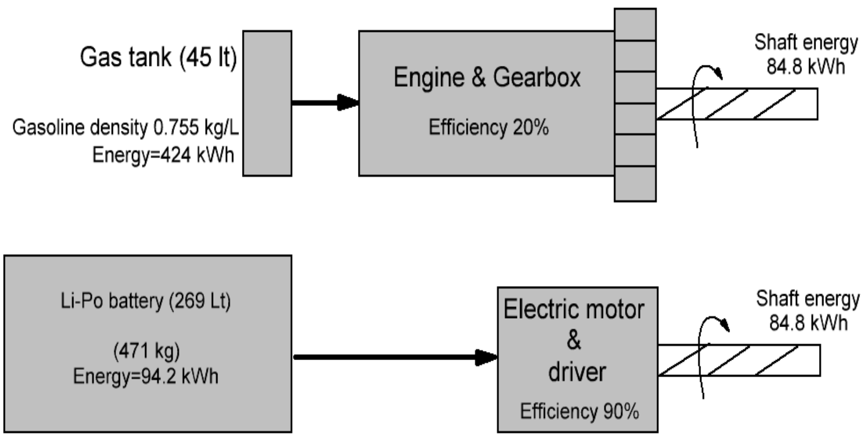

Fig. 4.1

The first battery invented by Alessandro Volta in 1799 is a non-rechargeable battery. Gaston Plante developed the first rechargeable lead-acid cell in 1859. Many types of rechargeable battery technologies have been developed as shown in Table 4.2. The most-popular ones for today are,

- Lead-acid (Pb-acid) batteries
- Nickel based batteries: Nickel-cadmium (NiCd) and Nickel-metal-hydride (NiMH)
- Lithium-based batteries: Lithium-ion (Li-ion) and Lithium-polymer (Li-po)

The lead-acid battery is mature technology for over a century, and still widely used in industrial applications such as forklifts, golf carts and uninterruptible power supply etc. It is inexpensive, safe, reliable, and has high-power capability. Unfortunately, its specific energy[1] is very low as

[1] Specific energy (Wh/kg) is a property of batteries that describes the energy density per weight.

seen in Table 4.2, therefore, it is not suitable for use in electric vehicles. Cycle life[2] is also lowest one among the battery types. Ni-Cd batteries, invented by Waldemar Jungner in 1899, have superior low temperature performance compared to lead-acid batteries. The biggest drawbacks of Ni-Cd batteries are the memory effect (voltage suppression issue that occurred in aging batteries) and including toxic materials. The Ni-Mh batteries solve some problems of Ni-Cd batteries, and are more suitable for EV applications; however, it suffers from low energy efficiency. Metal-air batteries (i.e., aluminum-air and zinc-air) are primary battery with high specific energy. Despite non-rechargeable property of primary batteries, the metal-air batteries can be mechanically rechargeable by replacing the discharged metal electrode (i.e., aluminum or zinc electrodes) rapidly. The discharged electrodes can be recharged again in the recycling facility. However, their energy efficiency and cycle life are low. Sodium based batteries need high temperatures (~300°C) to operate and suffer from high cost. Among them, the lithium-based batteries have high specific energy (~350 Wh/kg), high conversion efficiency (~95%) and high cycle life (>1000). The Li-ion based batteries are the smallest and lighter one among the batteries as shown in Fig. 4.2 [2], and therefore, more suitable battery type for EV cars today.

Table 4.2 Properties of Battery Technologies [3]

Battery Type	Specific Energy (Wh/kg)	Specific Power (W/kg)	Energy Efficiency %	Cycle Life	Estimated Cost US$/kWh
Lead-acid	35-50	150-400	80	500-1000	100-150
Nickel-cadmium	30-50	100-150	75	1000-2000	200-350
Nickel-metal-hydride	60-80	200-300	70	1000-2000	200-350
Aluminum-air	200-300	100	<50	-	-
Zinc-air	100-220	30-80	60	500	90-120
Sodium-sulfur	150-240	230	85	1000	200-350
Sodium-nickel-chloride	90-120	130-160	80	1000	250-350
Lithium-polymer	150-200	350	-	1000	150
Lithium-ion	80-130	200-300	>95	1000	200

[2] Cycle life is the number of charge/discharge cycle during battery lifetime.

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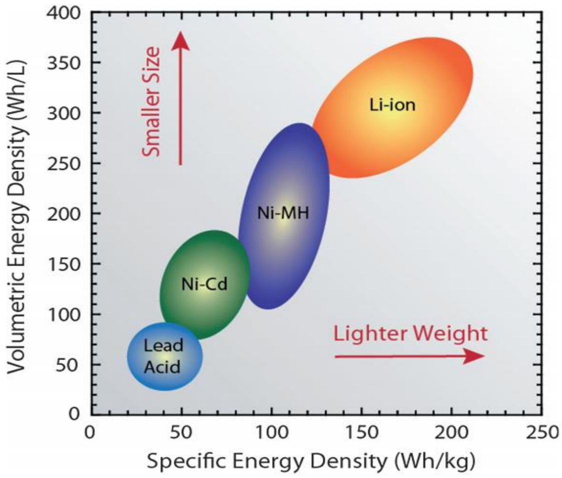

Fig. 4.2 [2]

The cycle life of a storage technology is the number of charge/discharge cycle throughout its effective lifetime. The cycle life vs. efficiency characteristics of some storage technologies are shown in Fig. 4.3 [3], where the super capacitor and flywheel seems as good candidate regarding high cycle life and efficiency. The flywheels consist of very high-speed shaft inside, therefore, gyroscopic forces restrict the vehicle maneuverability. Moreover, it needs a special vacuum container for proper operation, and can be very dangerous if flywheel is damaged by accident when the stored energy is released in very short of time. The super capacitors are very expensive and also its energy density is very low. Consequently, in case of EVs, there is no perfect choice for a battery technology, but Li-ion technology is a good candidate for today. The most important factors are specific energy, specific power, safety, life span, cost and performance.

Advantages of Li-ion technology:

- High specific energy (Wh/kg)
- Long cycle life
- High efficiency

Disadvantages of Li-ion technology:

- High cost to produce
- Complex safety and monitoring system are needed

For some specific applications, more than one storage method can be used together, such as Li-ion battery with a super capacitor etc. But in future, new battery technologies may emerge that have better properties than existing technologies.

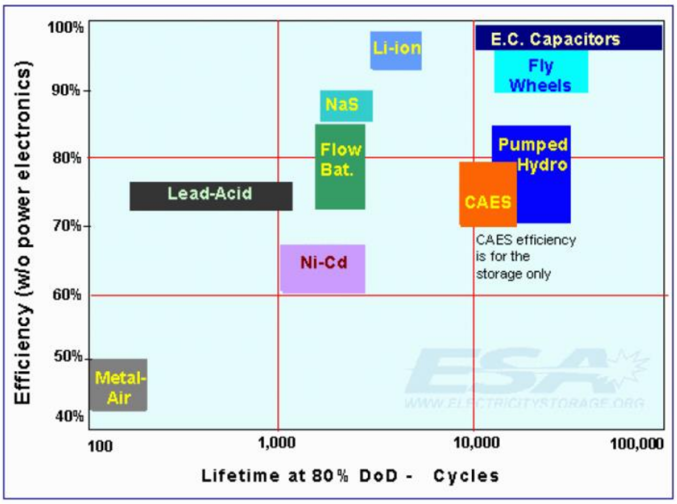

Fig. 4.3 [3]

There are different cell chemistries that are used to design Li-ion batteries. Usually, carbon acts (e.g. graphite) or lithium titanate ($Li_4Ti_5O_{12}$) are used as the negative electrode with new Li metal and Li(Si) alloys. The electrolyte is usually made of a mixture of Lithium salts and an organic solvent. There is always a separating membrane that prevents short circuit inside the battery but lets lithium ions pass between electrodes. When the battery is discharging, electrons are travelling from the negative electrode to the positive electrode. In the meantime, positive Lithium ions are travelling from the negative electrode to the positive electrode. This is shown on the Fig. 4.4 [4]. When the battery is charging (storing energy) this process is reversed.

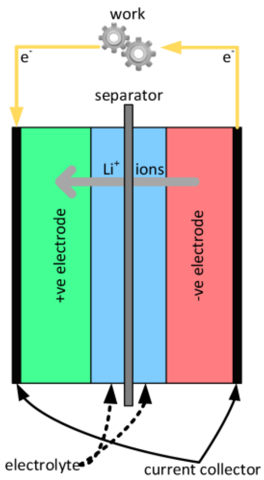

Fig. 4.4 [3]

Currently 4 types of lithium-based battery are popular for transport applications [5], which are;

- $LiFePO_4$ (LFP);
- $Li_4Ti_5O_{12}$ (LTO);
- $LiNiMnCoO_2$ (NMC);
- $LiNiCoAlO_2$ (NCA).

Energy density for all types is high that is very important parameter for vehicle applications. However, among them, LTO has the lowest energy density. LFP and NMC have nearly same energy density values. The highest energy density value belongs to NCA as shown in Table 4.3.

Table 4.3: Energy densities for lithium battery types [4]

Cell type	Energy density per weight [Wh/kg]	Energy density per volume [Wh/lt]
LTO	90	200
LFP	130	247
NMC	150	300
NCA	240	670

All electrochemical processes affected by temperature and require specific temperature range for efficiently operation during charge and discharge process. Especially the operation of battery at low temperatures leads to capacity loss as shown in Fig. 4.5. The internal cell resistance of battery increases at low temperatures which causes capacity loss even at allowed temperature range by manufacturer. The capacity reduction causes over-sizing of battery in order to keep reasonable driving range for an EV. Therefore, the temperature has significant impact on performance, lifetime and safety of Lithium batteries. The desired temperature range of Lithium batteries for rated power is between 15°C to 35°C [6]. Lower temperature values reduce the charging current rate of Lithium-ion battery significantly as seen in Table 4.4. This property is very important for fast charging of EV batteries, that means during winter season the fast-charging performance will not be good, and charging time will be longest. Similar situation may also happen when battery pack is too warm, then charging current need to be reduced to prevent battery overheating and thermal runaway. Therefore, battery thermal management can be useful for cold temperatures to keep the EV car performance at optimum level. To compensate the temperature variation, it is possible to use passive or active thermal conditioning systems with the battery packs. These systems can be based on air or liquid based heating or cooling functions.

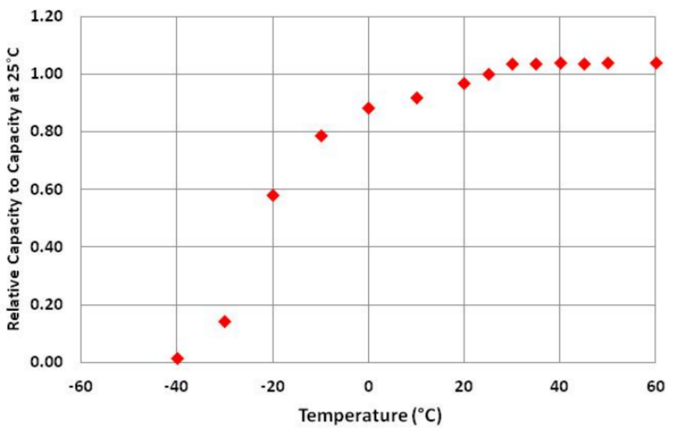

Fig. 4.5 Relative capacity vs. Temperature for LiFePO4 [6]

Table 4.4 Charge rate by temperature for ALM12V7 [10]

Temperature [°C]	Charge rate
-20	0.2C (0.9A)
-10	0.5C (2.3A)
0	1C (4.6A)
10	2C (9.2A)
20	4C (10A max. recommended limit)

4.1 Lifecycle of a Battery

Lifecycle is the number of charge/discharge cycle of a battery until its effective capacity drops to 80% of its original value. However, it depends on many parameters, such as charging and discharging rates, depth of discharge (DoD) level and temperature etc. It can be seen from Table 4.5 that LTO battery has excellent cycle number. If a LTO battery full charged and discharged once every day, it can service 15000 days, i.e., 15000/365=41 years. Under same condition, LFP can survive 10 years, NMC 8 years and NCA 1.38 years. At first glance, it might seem that the NCA's lifespan is very short and not suitable for EVs. But the depth of discharge (DoD) affects the total number of charge cycles that a battery can accommodate over its life span. DoD is used to show a battery’s state, similarly to SOC. When DoD increases, SOC decreases. DoD is often indicated in Ah or % (for example 0 Ah is full, 100Ah is empty, or 0% is full and 100% is empty). The DoD level is very important parameter for determining the cycle life as seen in Table 4.6. If battery capacity doubled (that corresponds to DoD level becomes 50%), the battery cycle life will be fold more than twice. However, it should be remembered that doubling the battery capacity, doubles the size, weight and cost too. Therefore, an optimum design capacity should be find according to the design specifications of EVs and application area.

Table 4.5 Life cycle for lithium batteries [4]

Cell type	Life cycle for 100% DoD
LTO	15000
LFP	3600
NMC	3000
NCA	500

Table 4.6 Cycle life vs. depth of discharge for LiFePo4 [10]

Depth of Discharge (DoD)	Cycle life for capacity ≥80% of nominal
80%	2500 cycle
70%	3000 cycle
50%	5000 cycle

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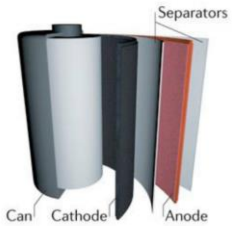
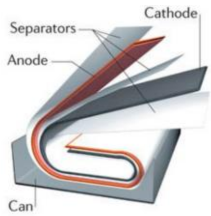
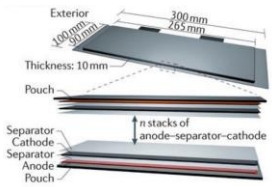
4.2 Battery Cell and Battery Pack

Li-ion cells are designed in various ways. The main designs are cylindrical, prismatic or pouch as shown in Table 4.7. The design of a battery highly depends on the customer application and, of course, on the price of production. The arrangement of electrodes, mechanical durability, heat management, energy density and specific energy are different of each design.

Table 4.7: Cell types of Li-Ion battery [4]

	Cylindrical	Prismatic	Pouch
Diagram			
Electrode arrangement	Wound	Wound	Stacked
Mechanical strength	++	+	–
Heat management	–	+	+
Specific energy	+	+	++
Energy density	+	++	+

The prismatic cells are more compact and space savings. For this reason, it is mostly preferred in cell phones or tablets or other lightweight devices. However, it is expensive to manufacture, thermal management is less effective and there are limited number of standardized sizes. On the other hand, the cylindrical cells are cost effective due to easy production, and very safe. The space between cylindrical cells is suitable to install thermal regulation solutions. It is generally used in portable devices like laptops. Large cylindrical cell sizes of 18650 and 26650 are popular for electric vehicles as shown in Fig. 4.6. However, prismatic cells can also be used for EV applications.

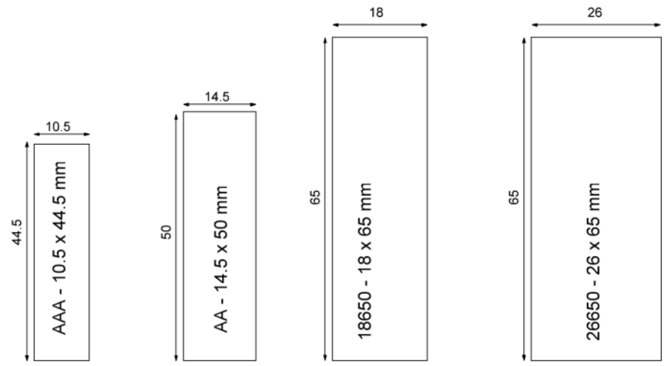


Fig. 4.6: Standard cylindrical battery cell sizes

Single 18650 Lithium-ion battery cell has approximately 3.7V terminal voltage and 3.2 Ah capacity. These ratings are not enough to supply the electric circuits of EV. Then, voltage and capacity must be increased to a suitable level. For this purpose, battery cells are connected in series in order to increase terminal voltage. Serially connected cells can be combines in parallel in order to increase the Ah capacity. Series and parallel connection of the cells constitute a battery module as shown Fig. 4.7. The Tesla Model S EV battery pack consists of 7104 individual 18650 Lithium-ion cells to achieve 350V battery pack voltage and 84 kWh capacity. The battery pack comprised of 16 battery module each has 444 cells stacked in a 6 series and 74 parallel (6s74p) configurations as shown in Fig. 4.8 (a). The stacking arrangement for battery module is shown in Fig. 4.8 (b) where the red cells indicate +ve side up. This battery module has 6*3.7V=22.2V terminal voltage and 74*3.2Ah=236.8 Ah (Ampere-hour) capacity. The energy inside a battery module is 22.2V*236.8Ah=5.25 kWh.

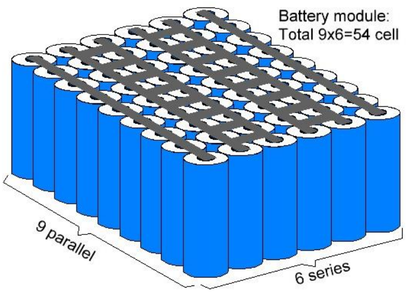
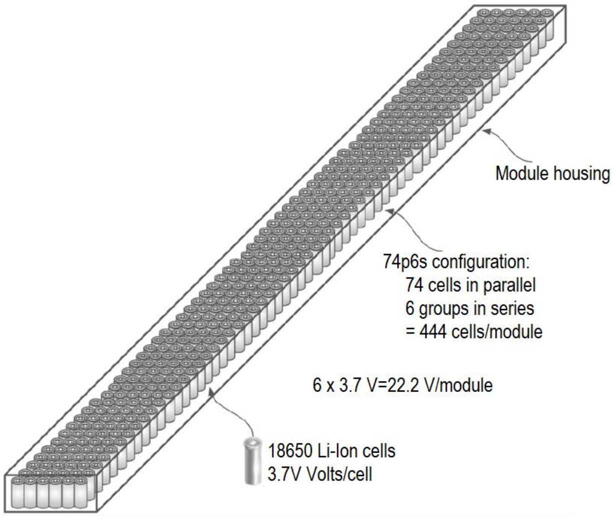
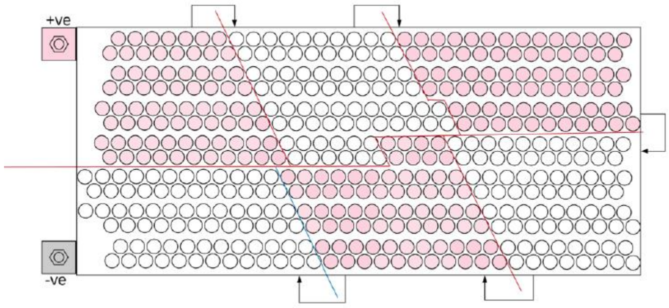


Fig. 4.7 15s13p battery module



(a)



(b)

Fig. 4.8 Tesla model S single battery module [11]

16 battery modules are combined together by connecting all of them in series and the Tesla model S battery pack is obtained as shown in Fig. 4.9. So, the pack voltage reaches to 16*22.2V=355.2V and total energy will be 16*5.25 kWh=84 kWh.

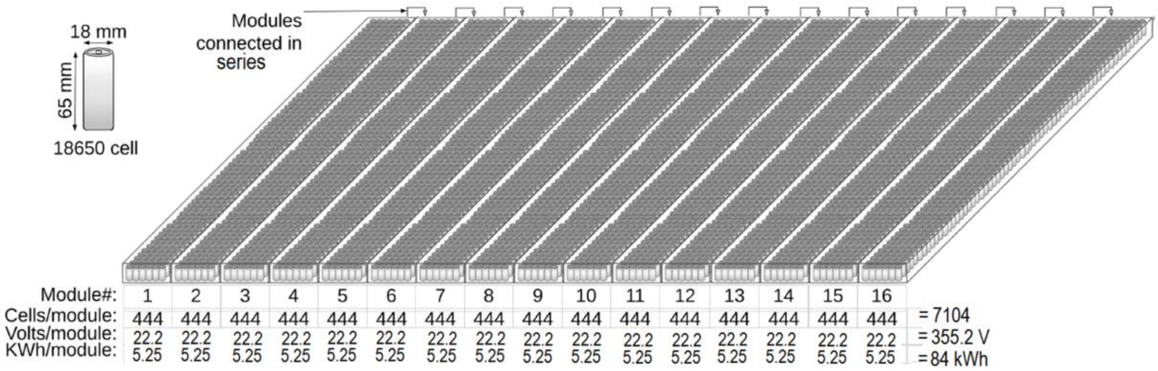


Fig. 4.9 Tesla Model S battery pack schematic [11]

4.3 Battery Management System

It is seen from Tesla battery pack that more than seven thousands of Li-ion cells should operate collectively. Even two cells fabricated on the same production line may have differences. Moreover, the temperature variations inside the pack -even the cabling resistance variation- may create significant differences in the operating point of cells. As a result, one or more cells in the package are always poorly charged. This effect builds up over time and finally the entire battery pack may become useless much before than its expected lifetime.

In order to increase lifespan and safety of Li-ion batteries, Battery Management Systems (BMS) are developed to monitor and control the battery state. Charging, discharging, cell equalization can be regulated; temperature can be monitored by such a system. In case of EVs, battery data is logged and transmitted to the Supervisory Control Module (SCM) to improve the performance of the battery and to optimize the operation of the cars.

The following aspects are optimized by BMS in EVs:

- Protects from electrical fires or shock
- Provides optimal operational environment of the battery to enhance battery life and efficiency: temperature (approx. 30-40 Celsius), SOC, depth of discharge (DOD), power, cell balancing.
- Predicts battery state to calculate remaining driving range of the EV.

To control temperature, thermal management systems are applied. This can be active of passive cooling or heating in case of cold outdoor temperatures. A BMS can maintain temperatures of individual cells to prevent performance degradation as the failure of a single cell can impair the battery performance greatly. Although, BMSs increase the complexity of batteries and consume energy, the benefits far outweigh the downsides.

Managing thousands of cells with a single BMS controller is not reasonable and will be more complex. Thus the battery pack is divided into small battery groups each has its own BMS sub-controller as shown in Fig. 4.10(a). The BMS sub-controller measures current and voltages of all cells and temperature, then report the measured data to BMS main control unit closed as shown in Fig. 4.10(b). BMS sub-controller may have a cell balancer circuit to equalize the cell SOCs using a special algorithm. If BMS main controller detects any dangerous condition; such as over temperature, short circuit or over current during charge and discharge, it should

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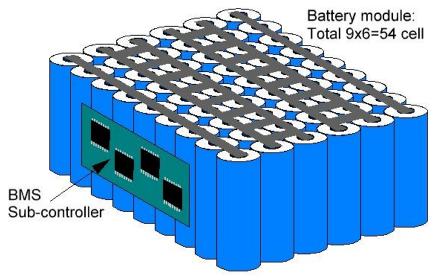
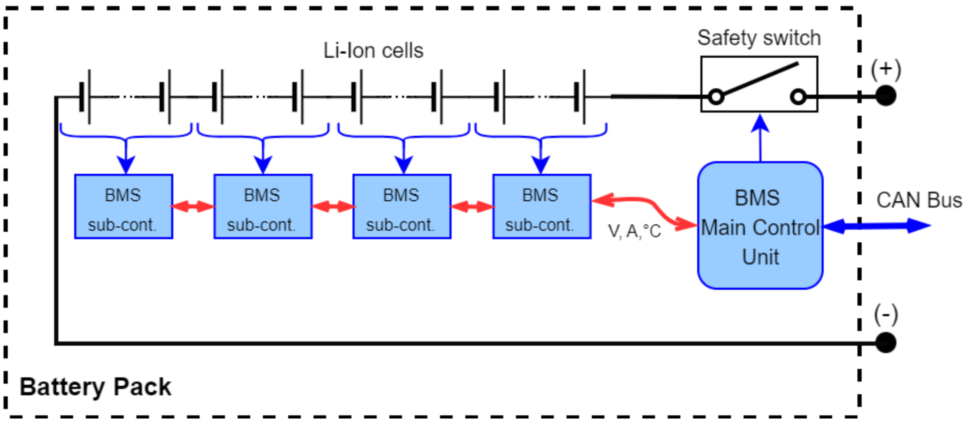
disconnect the battery from the load or charger. For this requirement, a BMS controller always has a series safety switch which is normally closed as shown in Fig. 4.10(b)

Finally a complete battery pack with built in BMS controller is covered with metal frame, equipped with a cooling system, and fuses and busbar connectors are added. The final battery pack is usually placed under the car between front and rear axles for better drive dynamic.



(a)



(b)

Fig. 4.10

4.4 Recycling and reusing

Li-ion is still a new technology in terms of recycling and there is no infrastructure that can manage the waste generated by consumer goods and EVs. Theoretically, it is possible to recycle most of the batteries, including 96% of the copper of electrodes. Still, recycling requires chemicals, a great amount of energy and it is more expensive than mining. In the EU, target rates for recycling of lead-acid batteries is 65%, for nickel-cadmium is 75%, and 50% for other types of batteries.

Reusing old batteries from EVs to provide additional stability and redundancy to the electricity grids is a promising alternative. Batteries at the end of their life span, when they are no longer able to be charged over 80% of the rated capacity, are used to build packages. These batteries do not have the original capacity and stability which is essential for EVs but not for other applications. They can be deployed to increase decentralized and renewable energy penetration of the grid, to improve local renewable energy consumption, or to provide other behind-the-meter services in our homes.

4.5 Safety of EV batteries

Safety issues of BEVs are managed by ISO6469 standard. The standard consists of 3 main parts:

- On-board electrical energy storage, i.e., the battery
- Functional safety means and protection against failures
- Protection of persons against electrical hazards.

BEVs can have different issues compared to ICVs, like fire or smoke from rapid battery discharge. Still, modern BMS, packaging and cooling technologies provide reliable and safe cars. The integrated BMS can calculate SOC, DOD, SOH (State of Healthy) or the energy efficiency of the battery and therefore, provide a wide range of diagnostic options for car mechanics and electricians.

4.6 Lithium-Ion Battery Hazards

Fire hazards happen as batteries have high energy density and electrolytes are flammable. These two factors, compressed in a battery cell make it challenging to use, to store, and to handle batteries. Physical damage, short circuits, overcharging and exposure to high temperature can cause thermal runaways [7].

Thermal runaway: A swift self-heating from an exothermic reaction that may result in a chain reaction.

Manufacturing defects or contaminants can cause thermal runaways. During the reaction, the organic electrolyte vaporizes and the pressure in the cell casing grows. If the case cannot keep the pressure anymore, the flammable and toxic gases are released. The harshness of thermal runaways is partially because of the pressure release from the cell. There are cell structures that are designed to release the pressure through pressure relief vents or by having a soft case. As a result, cell structure defines the severity of battery incidents [7].

The outcome of a thermal runaway can be a rapid venting of thick smoke or similar to a road flare, a steady burn, a fireball or an explosion. Besides the cell case, the battery size, chemistry and the SOC is an important factor for the outcome. Thermal runaway is producing aerosols, vapors, liquids, toxic gases, flying debris, sustained burning of electrolyte or the case [7].

Venting consist of mostly electrolyte constituents like carbon dioxide, carbon monoxide, hydrogen and hydrocarbons. Most of these gases are flammable, they pose hazard of fire or explosion [7].

When a battery is burning, the electrolyte and the gases are on fire produce carbon dioxide and water vapor. In the meantime, fluorine is liberated from the lithium salt which reacts with water and hydrofluoric acid (HF) is produced. Hydrofluoric acid is acidic, corrosive, and is a powerful contact poison that can irritate eyes, skin, nose, throat, burn skin, cause pulmonary edema and bone damage. Symptoms of exposure to HF may not be obvious. Despite the irritating odor, HF can reach dangerous levels in the air without an obvious odor, therefore, cause more severe injuries [8].

4.7 Capacity Preservation: Storage and Use Practices

Degradation happens in battery because of the following physical processes:

- Loss of lithium inventory
- Loss of active material
- Mechanical stress

Proper battery handling [7]:

- Always purchase batteries from reliable sources.
- Do not use batteries or cells that were shipped without packaging.
- Inspect new batteries.
- Keep away from fire.
- Keep away from combustible materials.
- Separate fresh and depleted cells (or keep a log).

- Store batteries in a metal storage cabinets.
- Visually inspect battery storage areas at least weekly.
- Use chargers or charging methods designed to safely charge cells or battery packs at the specified parameters.
- Disconnect batteries immediately if, during operation or charging, they emit an unusual smell, develop heat, change shape/geometry, or behave abnormally.
- Handle batteries and or battery-powered devices cautiously to not damage the battery casing or connections.
- Keep batteries from contacting conductive materials, water, seawater, strong oxidizers and strong acids.
- Do not place batteries in direct sunlight, on hot surfaces or in hot locations.

Taking care of an EV [7]:

- Ideally, keep batteries (and the car) at temperatures between 5°C - 20°C.
- Minimize time spent at 100 % state of charge.
- Minimize time spent at 0 percent state of charge.
- Charge batteries to approx. 50% of capacity at least once in every six months.
- Avoid using fast charging (AC or DC as well).
- Avoid discharging more quickly than it is needed. (Ludicrous mode in Tesla)

4.8 Summary of technical parameters

Some of the battery technical parameters are listed below.

Battery generally [9]:

- *Cell, modules, and packs:* EVs have a high voltage (HV) battery pack that consists of modules and cells organized in series and in parallel.
- *Cell*: the smallest, packaged form a battery, usually between 1-6 Volts.
- *Module*: consists of many cells connected in series or parallel.
- *Battery pack*: is assembled by connecting modules together, in series or parallel.
- *Battery Classifications*: Batteries can be classified as high-power or high-energy, but not both. Additionally, a battery can be designed for high durability, with increased life span (often with lower energy and power).

- *C-rate, E-rate*: Discharging current and Discharging power
- *Secondary and Primary Cells*: Primary cells are non-rechargeable, secondary cells are rechargeable.

Battery condition [9]:

- *State of Charge (SOC) (%):* The actual battery capacity in percentage. 100% is the good state.
- *Depth of Discharge (DOD) (%):* The depth of discharge (DoD) affects the total number of charge cycles that a battery can accommodate over its life span. DoD is used to show a battery's state, similarly to SOC. When DoD increases, SOC decreases. DoD is often indicated in Ah or % (for example 0 Ah is full, 100Ah is empty, or 0% is full and 100% is empty) The DoD can be higher than 110% as the real capacity of a battery can be higher than the nominal value.
- *Terminal Voltage (V):* Voltage between battery terminals when load applied. It varies with SOC and charge current.
- *Open-circuit Voltage (V):* Voltage between battery terminals without load applied.
- *Internal resistance:* Resistance within the battery that varies with charging and discharging. The higher the internal resistance, the lower the efficiency and thermal stability as more energy is converted into heat.

Battery Technical Specifications [9]:

- Nominal Voltage (V): The reference voltage of the battery.
- Cut-off Voltage: The minimum voltage, that defines the empty state.
- Capacity, Nominal Capacity (Ah): The total capacity, ampere-hours available when the battery is discharged at a given discharge current from SOC 100% to Cut-off Voltage.
- Energy, Nominal Energy (Wh): The total energy available in Watt-hours when battery is discharged at a given discharge current from SOC 100% to Cut-off Voltage.
- Cycle Life: The number of discharge and charge cycles possible when the battery can perform and meet specific performance criteria. It is affected by the rate and depth of discharge, temperature and humidity as well. The higher the DOD, the lower the life cycle.

- Specific Energy (Wh/kg): Nominal energy per unit mass. Sometimes it is called gravimetric energy density. The value depends on the battery chemistry and packaging.
- Specific Power (W/kg): Maximum available power per unit mass. The value depends on the battery chemistry and packaging.
- Energy Density (Wh/L): Nominal energy per unit volume. Sometimes referred to as volumetric energy density. The value depends on the battery chemistry and packaging. In case of EVs, this value determines the size of battery needed to reach a given driving range.
- Power Density (W/L): Maximum available energy per unit volume. The value depends on the battery chemistry and packaging. In case of EVs, this value determines the size of battery needed to reach a given performance target.
- Maximum Continuous Discharge Current: The maximum current at which a battery can be discharged continuously. Manufacturers define this value to prevent excessive discharge rates. Maximum Continuous Power and Maximum Continuous Discharge Current define the top sustainable speed and acceleration of an EV.
- Maximum 30-sec Discharge Pulse Current: The maximum current at which the battery can be discharged for pulses of up to thirty seconds. It is defined by the manufacturer. Peak power and this value define the acceleration performance (0-100 km/h time) of the vehicle. This value is to prevent excessive discharge rates.
- Charge Voltage: The voltage of the battery when it is charged until full capacity. See charging schemes and chargers before.
- Float Voltage: The voltage maintained after being charged to 100% SOC to maintain that capacity by compensating for self-discharge of the battery.
- (Recommended) Charge Current: The ideal current to charge the battery until it reaches constant voltage (see Charge/Discharge rate).
- (Maximum) Internal Resistance: The resistance within the battery.

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PART B:

INSTALLATION

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5 EV CHARGING SYSTEMS

Electric vehicles have onboard battery pack and therefore, they need charging equipment. The charger systems must be safe and also guarantee a proper charge for EV battery pack without degrade its lifetime. Moreover, it is preferred to be efficient, reliable and low cost. Moreover, the EV charging infrastructure is essential for the increasing EV penetration and the comfortable use of vehicles. Most of the chargers are private chargers while there are more and more public chargers available around the World.

All rechargeable EVs have on-board charger equipment. Therefore, an EV can be charged by simply connecting it to existing single- or three-phase utility power infrastructure via special plugs and sockets. However, the power of on-board charger is challenging for EV manufacturers in terms of space and weight restrictions of power electronics converters; therefore, they prefer to keep its power as low as possible. On the other hand, standard sockets for domestic grid connection provide maximum 32 A current. Consequently, the standard domestic single phase 230 V and three phase 400V grid allows up to 7.4 kW and 22kW charging powers, respectively. For this reason, the power output of on-board chargers is usually between 3.7kW and 22 kW, and it is called as AC charging. AC charging is most widely accessible way to charge EVs as it can be connected to the existing power infrastructure of offices and private houses.

Advantages of AC charging:

Simple installation

- Use standard AC electricity socket directly, and no need extra inverter or converter
- AC charging equipment are cheaper

Disadvantages of AC charging:

- Charging is much slower than DC

If more charging power is needed, external charger equipment should be used. In this case, DC voltage is provided to the EV, and then this type of charging is called as DC charging.

During DC charging grid power is passing through an AC/DC converter on the station before it is supplied to the EVs battery. DC charging bypasses the limitations of on-board chargers and charges the battery directly. DC charging allows up to 400 kW charging power which provides very low charging times for EVs. DC charging allows EVs to charge to 80% in one hour or less.

DC charging stations need much higher investments than AC. With DC, an inverter needs to be installed, and due to higher losses in the form of heat, heat management of the station is also necessary.

Advantages of DC charging:

- Charging is very fast, with power up to 400 kW
- No need for on-board charger

Disadvantages of DC charging:

- Charging equipment is expensive
- Heat management is needed because of high-power
- Fast charging allows up to roughly 80% of full capacity

EV chargers can also be categorized considering the charging speed. The three categories for charging speed (naming and categorization may vary by source): slow, fast and rapid.

<u>Slow charging:</u> Slow charging is from 3 kW to 6 kW, usually happens at home and used for charging overnight in 6-12 hours.

<u>Fast charging:</u> Fast chargers are rated from 7 kW to 22 kW (single or three-phase 32A). A 7 kW charger will charge a 40 kWh battery in 5-6 hours while a 22kW charger in 1-2 hours. Fast chargers are found in car parks, petrol stations, supermarkets, shopping malls.

<u>Rapid charging:</u> Rapid chargers are often placed next to highways. Rapid DC chargers are around 50kW, while ultra-rapid DC chargers have even higher rated power (up to 400kW). Tesla superchargers have charge power up to 150 kW. Rapid AC chargers can provide 43kW (three-phase, 63 A) if the on-board charger of EV is suitable.

Besides the conductive charging, there is also wireless charging method for EVs. This technology removes the cables and sockets between the EVSE and EV on charge. The power is transferred via electromagnetic induction. However, it is still developing as future technology. Furthermore, wireless chargers require custom onboard hardware for EV and therefore, may be costly. The charging technologies are summarized in Fig. 5.1.

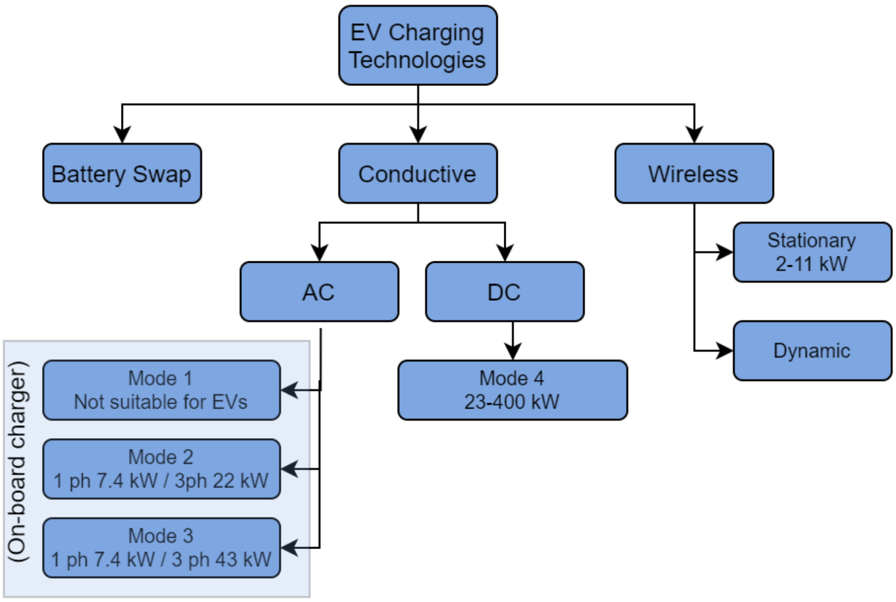

Fig. 5.1

5.1 Battery Charge Capacity

The energy stored in a battery can be expressed in Wh. However, battery terminal voltage significantly varies with the operating conditions (charge or discharge) and temperature. Therefore, energy count of a battery does not precisely indicate the state-of-charge of battery, and then error can be unacceptably high. Instead, Amp-hours counting (i.e., Coulomb counting) are preferred since the Coulombic efficiency of a specific battery is nearly constant. It mostly depends on the temperature as given previously in Fig. 4.5.

For standardization, 10 hours discharge capacity of a battery at room temperature is assumed as nominal capacity of that battery, and denoted as C_{10}. Mostly the subscript of 10 is omitted, and only C letter is preferred. For example, if a battery has C=50Ah capacity, it means that it can provide 5A for 10 hours. It should be remembered that, this capacity is valid only for 5A discharge current with 10 h discharge time at 25°C temperature. For other discharge (or charge) rate and temperature conditions, the capacity changes too.

The working current of a battery is generally specified by referencing its C capacity. For example, if 100 Ah battery has 20 Amps discharge current, the discharge rate can be expressed as 20/100=0.2C. Similarly, if it is charged by 40Amps, its charging rate will be 40/100=0.4C. This

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notation is a little bit confusing, but frequently used in practice. In this notation 0.1C discharge rate corresponds to 10 h discharge time of nominal capacity C_{10}.

For fast charging of battery, the charging rate should be as high as possible. For example, to reach <15 minutes charging time >4C charging rate is required. Table 5.1 shows the charge and discharge rates for lithium battery types, in which only LTO type (Li4Ti5O12) battery can provide fast charging option down to 6 min at 10C. For other types 1C (1 hour) and 2C (30 min) charging is suitable as fast charging. Since fast charging also reduces the lifetime of battery, it may be better not to use it frequently [1].

Table 5.1 Charge and discharge rates for lithium batteries [1]

Cell type	Discharge rate	Charge rate
LTO	5 to 10C	5 to 10C
LFP	3C	1C
NMC	2 to 3C	1C
NCA	2C	0.5C

Furthermore, there is relationship between charging current rate and battery full charge state of charge (SOC) level as shown in Fig. 5.2. It is seen that, fast charging prevents the full charge of battery. We know that the temperature also affects the battery capacity (see Fig. 4.5). Therefore, in combination of fast charging and low temperatures together, the battery capacity can reduce to 50% even within the temperature range allowed by the manufacturer. The extreme temperature range for European countries can be as low as -15°C in winter and more than 40°C in summer. Therefore, in order to guarantee the battery pack capacity against ambient temperature variations, heating and/or cooling options for a battery pack should be considered. Moreover, the vehicle nominal battery capacity for a desired driving range should be selected carefully by taking into account the capacity reduction due to the fast charging and extreme temperatures.

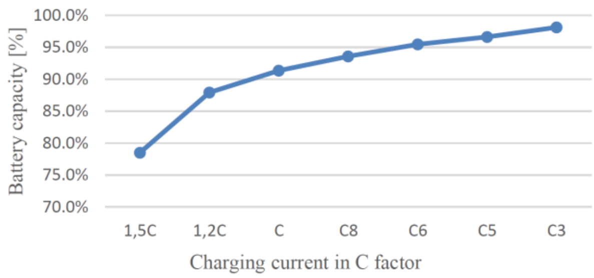

Fig. 5.2 Charging rate vs SOC level [1]

Fast charging of LTO batteries creates extra heat in battery pack, and then they need to have cooling systems, especially in the summertime. LTO may be equipped with heating against lower temp too. For LFP battery, fast charging is moderate speed, i.e., 1C rate, and therefore, not much heat is generated and cooling is not needed. It can operate down to -20C and then heating is also not needed. The NMC and NCA types require heating system due to operating temperature for charging not allowed below 0°C. If the temperature closes the minimum or maximum end, the charging and discharging current must be reduced in order to control the battery temperature. This control is governed by battery management system (BMS) of the car battery.

5.2 Lithium-ion Battery Charging Characteristics

Various charging methods have been proposed for Li-ion batteries. The method of constant current constant voltage (CC-CV) is by far the most common one, as conceptually shown in Fig. 5.3. CC-CV charging method for Li-ion batteries starts with pre-charge constant current phase. If a Li-ion battery is deeply discharged, a pre-charge phase is needed. This phase prevents the cells from overheating until to reach the CC phase. In reality, this phase is rarely needed because BMS circuits shuts down the battery while there is still some charge left in the battery. If the battery terminal voltage is lower than 3V/cell, the pre-charge phase is employed with reduced current, which is generally around 0.1C. When the terminal voltage reaches to 3V/cell, pre-conditioning charge phase is ended and the charging current is increased substantially. During this time if the temperature of the battery cells increases up to a certain level thermal regulation phase is inserted and the charging current is reduced to a safe level. This prevents battery from overheating, capacity loss or possible damage. This phase may be seen in ultrafast chargers. For example, if CC phase current is 2C (i.e., ~30 min fast charger), the charging current will be 20 times higher than the pre-charge phase, and an active cooling may be required. After thermal regulation phase ending, charging current is kept constant at desired level determined by charger setting. During CC phase, the battery voltage increases gradually, and once the voltage reached up to 4.2V/cell, the charger switches to the CV phase. In CV phase, the battery voltage is kept constant at 4.2V/cell [3] and then the charging current starts to decrease exponentially. The charger continuously monitors the charging current in CV phase. When the charging current drops below 0.1C, the charger stops the charging process

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and enters the float phase where the charging voltage is reduced to 3.9V/cell. It should be remembered that the voltage levels given above can vary slightly with respects to cell material used in the battery, but the charging procedures are same for all types.

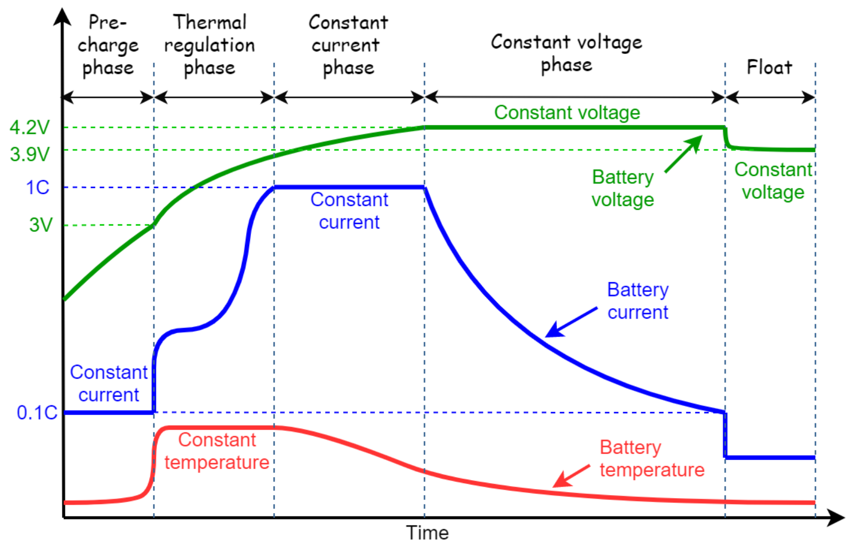


Fig. 5.3

The CC phase can increase the battery SOC up to nearly 75% to 80%. The remaining charge is completed during the CV phase. As we noticed from the experimental curve of Li-ion battery shown in Fig. 5.4 that the CV phase requires more than half of CC phase time despite adding relatively small charge capacity, which is about 20%. This situation prolongs the total charging time considerably. For this reason, fast charging of EV cars generally consists of only CC phase, and therefore, after fast charging, the battery cannot be fully charged by 100%, it stays at 80% roughly.

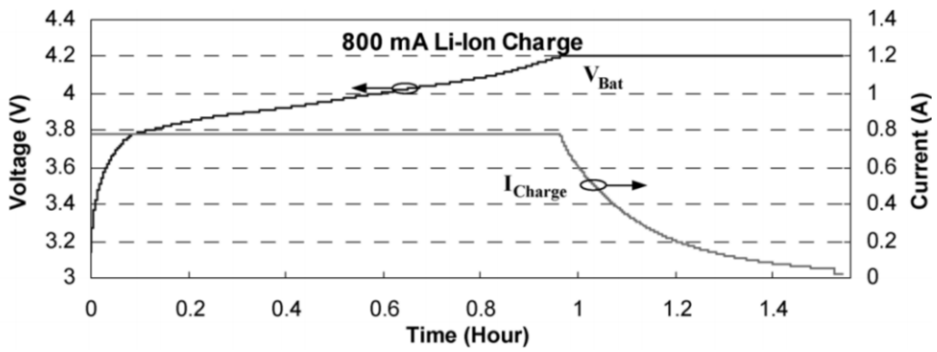


Fig. 5.4 Experimental Li-Ion battery charge curve [2]

5.3 Charging Modes

The charging of EV battery can be realized at small power in long time or at high-power quickly. The EV owners decide the charging power according to their own charging requirements and their grid capacity. For safe operation, various standards have been defined by standard organizations that classify the chargers with respect to power level, safety features, communication, control and maximum current level etc.

The IEC 61851-1 defines 4 charging modes which describes the power and voltage levels, and also the communication protocols between charger station and EV to avoid overcharging, as follows;

- Mode 1, slow charging: non-dedicated outlet
- Mode 2, slow charging: non-dedicated outlet with 'in cable' RCD protection
- Mode 3, slow/fast charging: dedicated outlet
- Mode 4, fast charging: rapid, DC charging

A similar classification has been defined by another standard organization SAE in North America. SAE J1772 standard divides the charge stations into 3 levels according to the charge power level on charger outlet;

- Level 1: slow charging (AC charge)
- Level 2: Semi-fast charging (AC charge)
- Level 3: Fast charging (DC charge).

These two standards have a lot of common points. Therefore, they will be summarized together in the next section of charging modes in detail.

5.3.1 Mode 1

The Mode 1 corresponds to the Level 1 in SAE J1772. In this mode, the EV is connected to standard domestic electricity power through non-dedicated regular wall outlet. This outlet should be single phase in Mode 1. Its voltage can be 110Vac/60Hz (i.e., in USA) or 230Vac/50Hz (i.e., in Europe). The maximum current is limited by the switchboard limit of home which is mostly 16A.

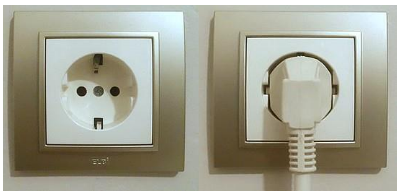
The Mode 1 is slow charging mode, and therefore, the charging time is very long. Thus the cables and sockets operate at maximum current for several hours that may result in high temperature on sockets and cables. Therefore, the electrical installation must comply with safety regulations. It must have an earthing system, an RCD and circuit breaker to protect against electric shock, short circuit, fire and earth leakage. More details about them will be given in the later sections.

The regular outlet at homes, such as NEMA-5-15 or Schuko as shown in Fig. 5.5, can be used in Mode 1. If the maximum socket current is taken as 16A, then the maximum charging power for Mode 1 can be calculated as follows,

For 120Vac grid: $120V \times 16A = 1.92\,kW$

For 230Vac grid: $230V \times 16A = 3.68\,kW$

NEMA 5-15, In=15A [17]



Shuko In=16A

Fig. 5.5

These are very small power for EV charging. If we assume the EV battery capacity is 24 kWh, roughly 24 kWh/3.68 kW≅6.5 hours is needed for full charge in European grid. This is very long time. If battery capacity increases, the charging time increases proportionally. Therefore, Mode 1 charging is suitable for overnight charging at home garage for owner who use their EV rarely in short distances, or for PHEVs since their battery capacity may considerable be lower than BEVs. If we assume that average energy consumption per kilometer for an EV is 200 Wh/km, one hour charging at Mode 1 stores approximately 18 km drive range to the battery as calculated below,

$$\text{Drive range} = \frac{(3.68\,kW)(1h)}{(0.2\,kWh/km)} = 18.4\,km$$

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The cable connection for Mode 1 is illustrated in Fig. 5.6, while one end of cable is household socket; the other end is dedicated charge socket for EV approved by IEC 61196-2 which will be described later.

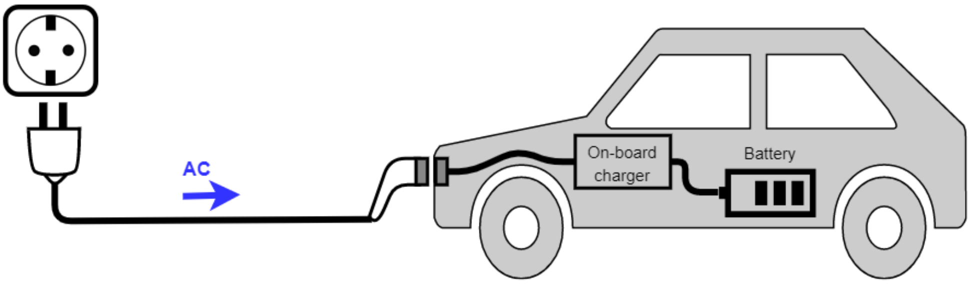


Fig. 5.6 Mode 1 charging cable

There is no power control in Mode 1; therefore, the on-board charger may operate at an excessive current for the cables in the electrical installation of home. Moreover, the EV has big metal surface area, and then any leakage from EV may result in serious electric shock. If the home earthing system, residual current breakers and circuit breakers do not work properly; serious electric shock and fire risk are inevitable. For this reason, Mode 1 is not used for EV charging, it may be used for small carriers, such as scooters, electric bicycle etc.

Mode 1 charging is not advised (or prohibited) for EVs in most of the countries for safety concerns!

5.3.2 Mode 2

The most important difference of Mode 2 from Mode 1 is that the Mode 2 contains a protection device between the utility grid and EV as shown in Fig. 5.7. This equipment, which is called as portable EVSE (Electric Vehicle Supply Equipment), must have an RCD protection according to IEC 62752:2016, and have some communication features for limiting the power. Due to safety reasons, the portable EVSE has to be within 300 mm from the utility socket. The cable is similar to Mode 1 except protection equipment. The most of EVs have this portable EVSE as a standard accessory with suitable cable and sockets.

Fig. 5.7 A portable EVSE [14]

In Mode 2, the charger input power can be taken from single phase (120Vac/230Vac) or three phase (208Vac/400Vac) utility grid with maximum current from 16A up to 32 A. The cable connection is shown Fig. 5.8. For utility side, in addition to standard household sockets (i.e., NEMA 5-15 or Shuko), standard industrial sockets, such as NEMA 14-50 or IEC 60309, that can carry maximum continues charging current up to 32A, can be used (See Fig. 5.9). Therefore, the maximum charging power for single- and three-phase at Mode 2 are obtained as follows,

For single phase:

120Vac grid: $120V \times 32A = 3.84kW$

230Vac grid: $230V \times 32A = 7.36kW$

For three phase:

120Vac grid: $\sqrt{3} \times 208V \times 32A = 11kW$

230Vac grid: $\sqrt{3} \times 400V \times 32A = 22kW$

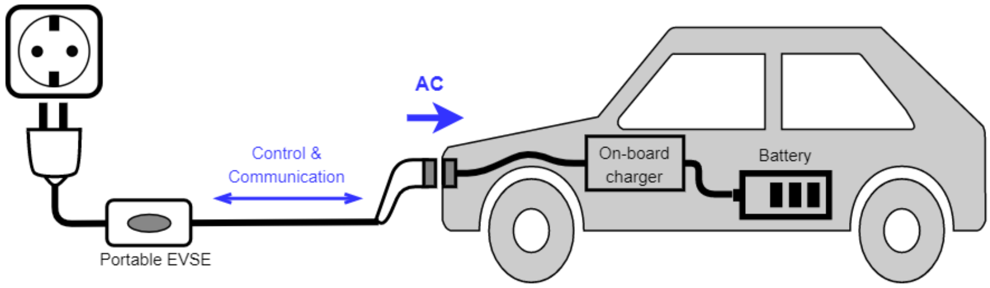


Fig. 5.8

NEMA 14-50 [59]

IEC 60309 [58]

Fig. 5.9

The maximum power in Mode 2 is 6 times higher than Mode 1. Therefore, the full charging time for a 24 kWh battery pack takes roughly 1.1 hours (24 kWh/3.68 kW=1.1 hrs) in 230Vac grid. This is relatively fast charging speed, but it should be remembered that most of BEV battery capacity is higher than 24 kWh. If battery capacity increases, the charging time increases proportionally. If we assume that average energy consumption for an EV is 200 Wh/km, one hour charging at Mode 2 with 22 kW stores approximately 110 km drive range to the battery. This range is sufficiently longer than daily usage of most EV users.

Because of space and weight restriction, some EV manufacturers use single converter both for traction motor driver and charge controller purposes. Since the traction motor is not needed during parking, its DC-AC driver topology can be transformed into AC-DC rectifier topology, and used as a battery charge controller. Moreover, the winding inductance of the electric motor can be used as filter inductor in the power converter. One example schematic for this application is seen in the Fig. 5.10 where three phase full bridge motor driver is converted to three phase interleaved PFC boost converter in which the motor winding are used as inductance. In normal operation, the motor windings is separated from the rectifier (and therefore, from the grid) by a proper mechanical relay switch.

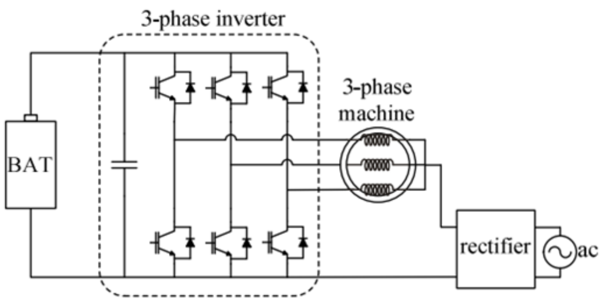


Fig. 5.10: On-board charger using motor driver [53]

All EV's have on-board charger for Mode 2, but its maximum power varies from vehicle to vehicle up to 43 kW. The Mode 2 is intended for mostly home users because it takes energy from household sockets and needs long connection time that is more suitable for overnight charging. For faster charge times, Mode 3 is proposed.

5.3.3 Mode 3

Mode 3 is more costly than Mode 2 since it uses a dedicated charging device which is named as Electric Vehicle Supply Equipment (EVSE) as seen in Fig. 5.11. The EVSE has a built-in protection for safe operation and provides fast charging power for EVs. Some of EVSEs may have advanced power control options like vehicle-to-grid (V2G) communication. The Mode 3 is mostly corresponds to the Level 2 charging of SAE J1772.

Fig. 5.11 Vestel AC wall charger (Courtesy of VESTEL)

The maximum charging current in Mode 3 is generally up to 32 A as similar to Mode 2. However, if the switchboard is suitable, it can rise up to 63A. Then the maximum charging power for three phases at Mode 3 can reach up to,

$$\sqrt{3} \times 400V \times 63A = 43kW$$

According to current and voltage conditions, there are generally 5 charging levels used in Mode 3 for 230Vac grid (power levels for 120Vac grid can be obtained as well.):

- 3.7 kW (16A, Single-phase – 230V AC)
- 7.4 kW (32A, Single-phase – 230V AC)
- 11 kW (16A, Three-phase – 400V AC)
- 22 kW (32 A, Three-phase – 400V AC)
- 43 kW (63A, Three-phase – 400V AC)

5.3.4 Signaling and Communication Protocols

What will happen if EV requests more power than EVSE capacity? Most likely, the EVSE will protect itself and stops the charging. Therefore, the EV on-board charger must know the EVSE's maximum current capacity in order regulate charging process properly. SAE J1772 developed a communication standard between the EVSE and the EV. This is well adopted by IEC 61851-2 and become standard protocol in AC charging of EVs. Therefore, all the IEC 62196-2 compatibles plugs (i.e., Type1 and Type2 plugs) have extra two pins in the socket for this communication, such as Control Pilot (CP) and Proximity Pilot (PP). These pins are used to control the charging process to be safe and under control. The circuit part inside the plugs does not have integrated circuit or microcontroller. All the circuit is based on resistors and switches. It is very simple, robust and can be operable in temperature between -40°C to +85°C.

5.3.4.1 Proximity Pilot signal

According to J1772, the Proximity Pilot circuit uses PP and PE (power earth) pins, and it has two functions. These functions will be explained below.

<u>**PP function #1:**</u>

Proximity pilot signal allows the EV to detect whether it is plugged in, so that it prevents car movement while connected to a charger. Proximity Pilot (PP) circuit for this function has two parts; one part is placed inside the plug and the other part is placed in the vehicle inlet as shown in Fig. 5.12.

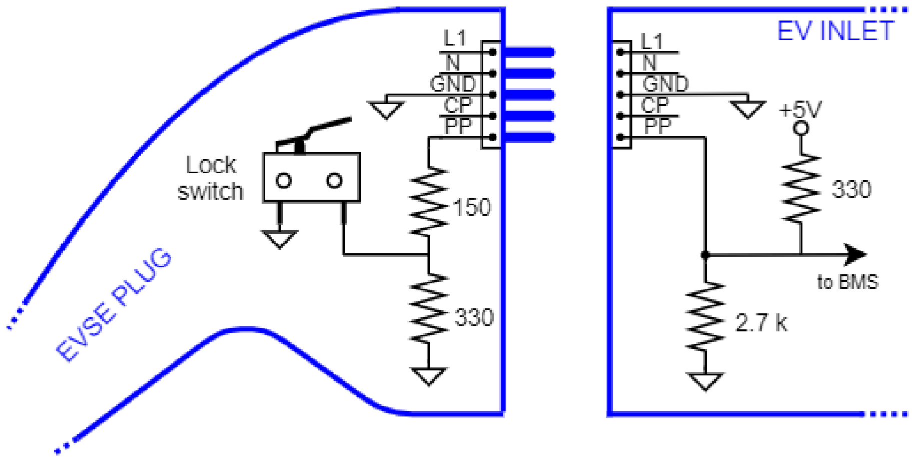
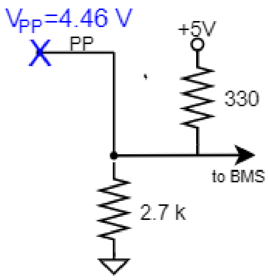


Fig. 5.12. Proximity pilot equivalent circuit

A 5V voltage is applied to the circuit from EV side, and then EV determines the plug status by measuring the voltage at PP pin. There are 3 possible conditions;

***Condition #1, EVSE is not present*:**

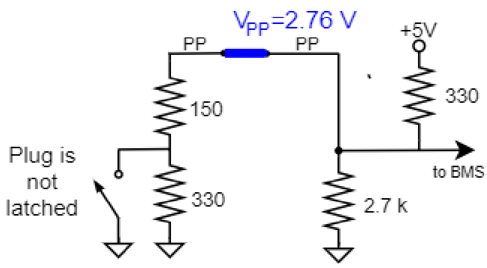
If EVSE is not present; there is no plug connected to inlet, so that the equivalent circuit will be a simple voltage divider as shown on the right. In this case the EV measure the voltage as,



$$V_{PP} = \frac{5V \cdot 2.7k\Omega}{330\Omega + 2.7k\Omega} = 4.46V$$

***Condition #2, EVSE is present but plug is not latched*:**

If EVSE is present and plug is not locked, equivalent circuit will be as shown on the right. In this case the lock switch do not bypass 330 Ω resistor, then measured voltage reduces to,

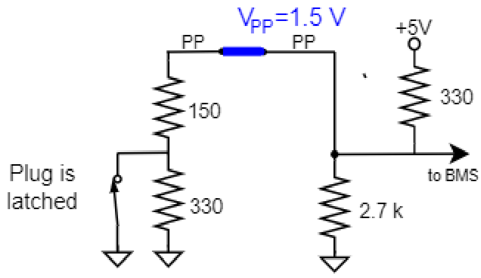


$$V_{PP} = \frac{5V \cdot \left(2.7k\Omega \,||\, \left(150\Omega + 330\Omega\right)\right)}{330\Omega + \left(2.7k\Omega \,||\, \left(150\Omega + 330\Omega\right)\right)}$$

$$= \frac{5V \cdot \left(407\Omega\right)}{330\Omega + \left(407\Omega\right)} = 2.76V$$

***Condition #3, EVSE is present and plug is latched*:**

If EVSE is present and the plug is latched, the equivalent circuit will be as shown on the right. In this case, the lock switch bypasses the 330 resistor, and the EVSE side resistor 150 Ω is in parallel to 2.7 kΩ, and then the EV measures the voltage of,



$$V_{PP} = \frac{5V \cdot \left(2.7k\Omega \,||\, 150\Omega\right)}{330\Omega + \left(2.7k\Omega \,||\, 150\Omega\right)}$$

$$= \frac{5V \cdot \left(142\Omega\right)}{330\Omega + \left(142\Omega\right)} = 1.5V$$

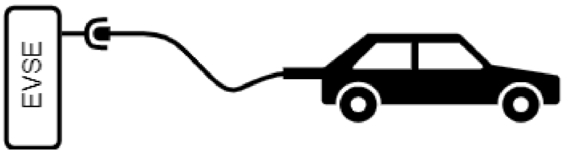
If the charging cable is unplugged during current flows through it, an arcing will occur. The PP signal is used to prevent arcing. When plug is latched and in locked position, lock switch is closed. If the user releases the locking mechanism, the switch will be open and EV side voltage will jump from 1.5V to 2.76V. Then EV controller detects this voltage change, and realizes that it will be unplugged soon, and then suddenly decrease the charging current to 0A (or near to zero). Therefore, there will be no current in the cable when it is unplugged.

PP function #2:

The PP pin can be used also to define the maximum current capacity of cable, so that EVSE do not solicit the charging current more than the cable ratings. This is very important function for safety operation of charging cable. There are three possible cases for cable arrangement in EV charging as follows;

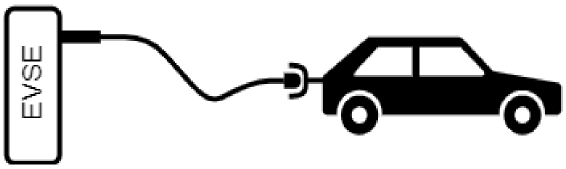
Case #1:

EV side of cable permanently attached. In this case, the cable current capacity is suitable for on-board charger maximum power, so no risk for the cable.



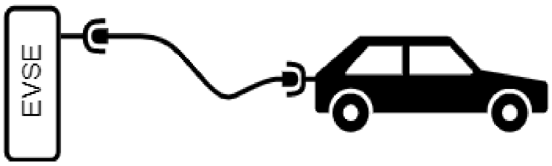
Case #2:

EVSE side of cable is permanently attached. The cable is sized for maximum current of EVSE. So, no risk for the cable.



Case #3:

Both sides of cable have detachable plugs. In this case, there is possibility to use weak cable at high-power. So that PP pin should be used to set the cable current rating.



There is no connection between the PP pins in both ends of the charging cable. The PP pin of EV side plug is used for proximity and latch information functions. The EVSE side of PP pin can be used to code the rated current capacity of the cable to the EVSE. For this purpose a fixed resistor is connected between PP and PE pins inside the plug of EVSE side as shown in Fig. 5.13.

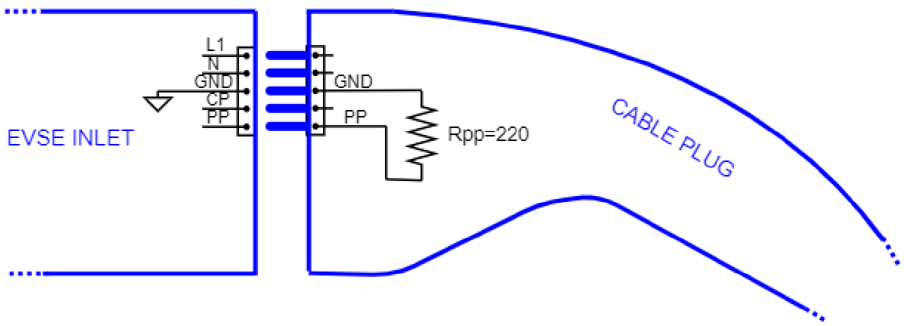


Fig. 5.13

The value of R_{pp} resistor determines the maximum current capacity of that cable as seen in Table 5.2. For example, the resistor value of 220 Ω means that the maximum current for the cable is 32A. Furthermore, the cable resistances have +/- 3% tolerances, so if the resistance falls outside of those tolerances the EVSE must not provide current since the current capacity of the cable is uncertain. As another example, if 22kW Mode 3 charger is used with a 20A cable (Rpp=680 Ω), then the EVSE reduces to output current to 20A, i.e., 13.8 kW, to protect the cable from burning. This is very important feature against possible fire or damage, because the charging of EV takes many hours at maximum power, which may strain the cables and connectors significantly.

Table 5.2: PP pin resistance values for coding cable current rating

Resistance between PP and PE pins	Maximum current of cable	Conductor Size
Open	6A	0.75 mm^2
1500 Ω	13A	1.5 mm^2
680 Ω	20A	2.5 mm^2
220 Ω	32A	6 mm^2
100 Ω	63A	16 mm^2
50 Ω or <100Ω	80A	25 mm^2

5.3.4.2 Control Pilot signal

The Control Pilot (CP) signal is designed to manage the charging status between EVSE and EV. Additionally, the EVSE can limit the maximum allowable charging current by using PWM signal on CP pin. The charge controller of EV continuously watches the PWM signal on CP pin, and do not exceed the allowed current limit. The CP signal may also be useful for power adjustment or power distribution among the EV cars in a charge station.

The CP equivalent circuit is shown in Fig. 5.14. In this circuit, the EVSE provides 12V DC voltage or 1kHz PWM signal according to the charging status. The PWM signal has +/- 12V magnitude, and its duty cycle sets the maximum charging power.

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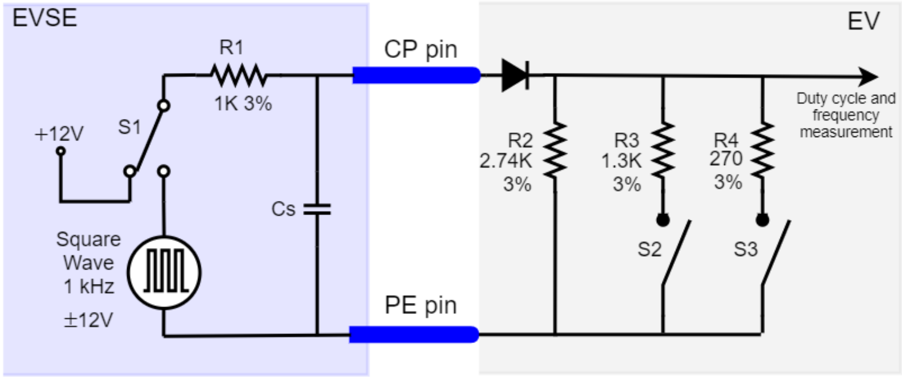


Fig. 5.14

Table 5.3 Charger statuses for control pilot functions

Status	Definition	Resistance between CP-PE	Voltage between CP-PE
Status A	Stand-by	Open	+12 V
Status B	EV connected (Ready)	2740Ω	+9±1 V
Status C	Ready (charging)	882Ω	+6±1 V
Status D	With ventilation	246Ω	+3±1 V
Status E	No power (Shut off)		0 V
Status F	Error		-12V

Charger statuses for control pilot function are listed in Table 5.3 and charge sequence is described below in detail.

***Status A – "Stand-by"*:**

The EV is not plugged in; therefore, no resistor is connected on the EV side as shown in Fig. 5.15. Then V_{CP}= 12V dc voltage is measured. The EVSE is in stand-by position and wait for an EV plug.

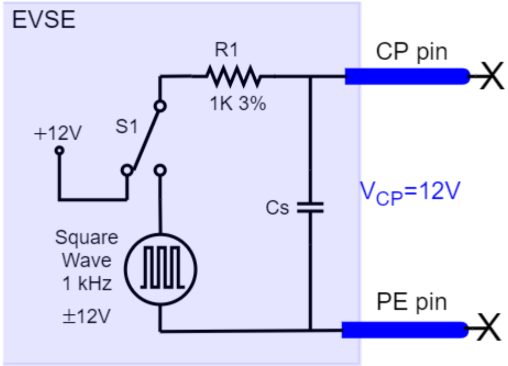


Fig. 5.15

***Status B – " Vehicle detected"*:**

(Step 1)

The vehicle is plugged and the CP circuit is connected to the EVSE side. Since S2 and S3 are normally open, the resistors R3 and R4 are discarded. Then R2 and the diode are connected to the EVSE as shown in Fig. 5.16 and the measured V_{CP} voltage is

$$V_{CP} = \frac{12V \cdot 2.74k\Omega}{1k\Omega + 2.74k\Omega} + V_{diode} \cong 9V$$

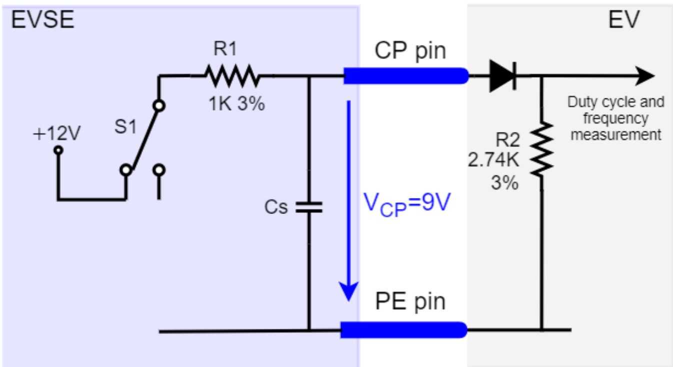


Fig. 5.16

(Step 2)

After checking the 9V is present on V_{CP}, the EVSE changes the position of S1 and put 1 kHz square wave signal on the PP pin through R1 as shown in Fig. 5.17.

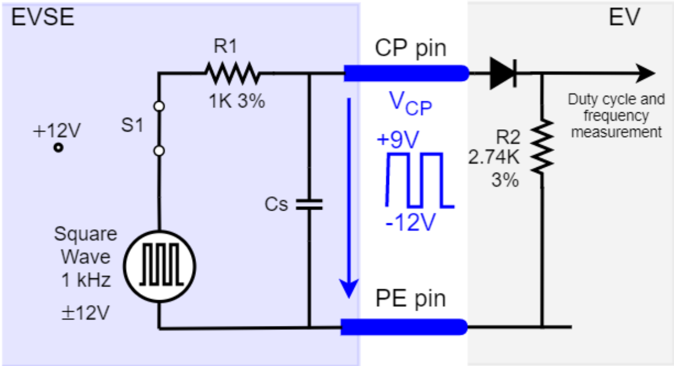


Fig. 5.17

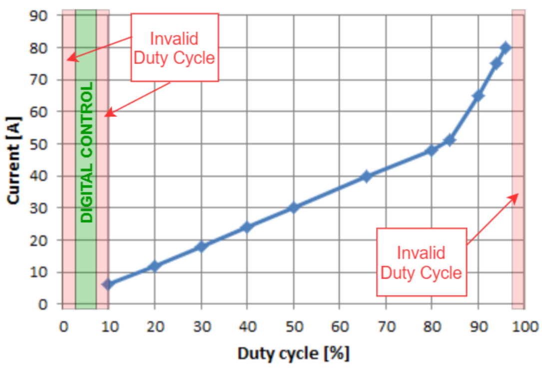
Duty cycle of PWM is adjusted to correspond to the EVSE's maximum charge current according to following formulas:

$$Duty = \frac{Current}{0.6}$$ *(For current between 6A to 51A)*

$$Duty = \frac{Current}{2.5} + 64$$ *(For current between 51A-80A)*

The plot of PWM vs. current according to the formulas above is shown in Fig. 5.18. For 32A charging current, duty ratio should be 53%. If EVSE want to communicate to EV digitally (e.g. Power Line Communication PLC etc.), puts a duty value between 3%-7%. This area is shaded with green color in Fig. 5.18.

Invalid duty cycles, i.e., duty<3% and 7%<duty<10% and duty>96% mean charging is not possible. It is noticed that, PWM duty cycle is controlled by the EVSE, whereas the positive peak voltage of the signal is controlled by the EV.



PWM [%]	Current [A]
10	6
20	12
30	18
40	24
50	30
66	40
80	48
84	51
90	65
94	75
96	80

Fig. 5.18

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Status C– " EV charge":

When the BMS of EV detects the duty cycle, learn the maximum charging current of EVSE, and then sends a charge ready signal by closing S2 which connects the R3 in parallel to R2 as shown in Fig. 5.19. Then, the V_{CP} voltage becomes;

$$V_{CP} = \frac{12V \cdot \left(2.74k\Omega \,||\, (1.3k\Omega)\right)}{1k\Omega + \left(2.74k\Omega \,||\, (1.3k\Omega)\right)} + V_{diode} \cong 6V$$

After that the EVSE detects the +6V positive peak voltage of PWM signal, then close the power relay to give power on the line.

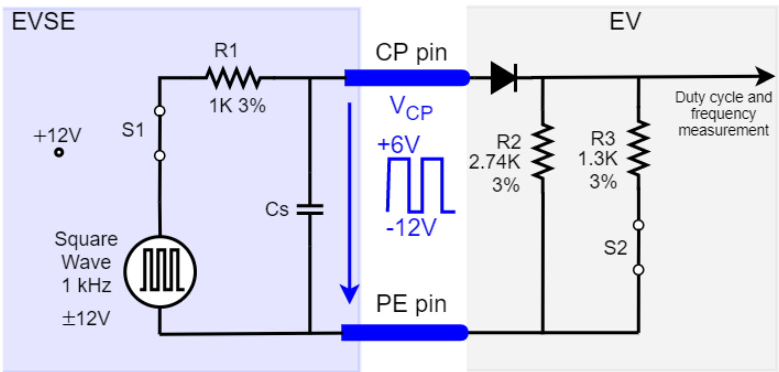

Fig. 5.19

Status D – "EV charge with ventilation":

Some battery types, such as lead-acid, may have harmful and explosive gas emissions during charging. Therefore, the room needs to be ventilated. Even lithium-based batteries do not have gas emissions; IEC 61851-1 standard has this mode for being compatible for all battery types. Therefore, if the charger needs ventilation in the room, then it closes the switch S3 and opens the switch S2, so that only 270 Ω is connected in parallel to R2. So the V_{CP} voltage is,

$$V_{CP} = \frac{12V \cdot \left(2.74k\Omega \,||\, (270\Omega)\right)}{1k\Omega + \left(2.74k\Omega \,||\, (270\Omega)\right)} + V_{diode} \cong 3V$$

When the EVSE detects this voltage, then it starts to operate ventilation equipment if it is installed. However, generally this mode is not used today because all battery types for EVs are lithium-based.

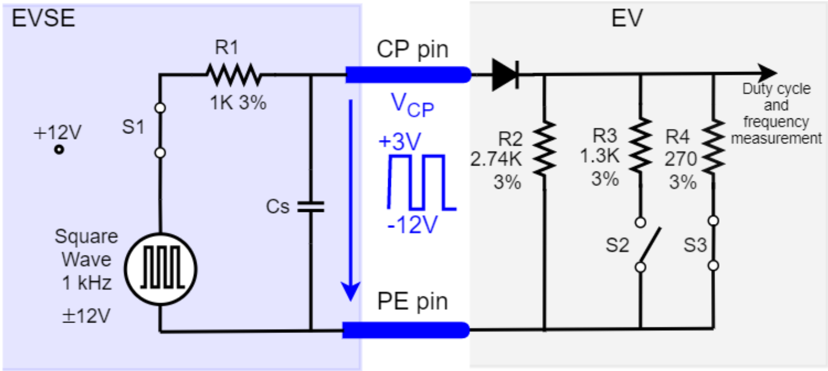

Fig. 5.20

5.3.5 *Mode 4*

Mode 3 can be used up to 62A for AC charging that corresponds to 43 kW maximum. To get even faster charging time, the charging power should be increased further. However, on-board charger weight and size limits the maximum power capacity of Mode 3. Therefore, an external charger, i.e., off-board charger, is required. Since the off-board chargers are stationary and do not have size and weight restrictions, the charge power can be increased up to 400 kW, but in reality, it is restricted by the charging power limit of battery pack.

The Mode 4 is frequently called as DC charger, since the off-board charger is connected to battery DC terminals directly through protections devices as shown in Fig. 5.21. This mode corresponds to the Level 3 charging in SAE J1772.

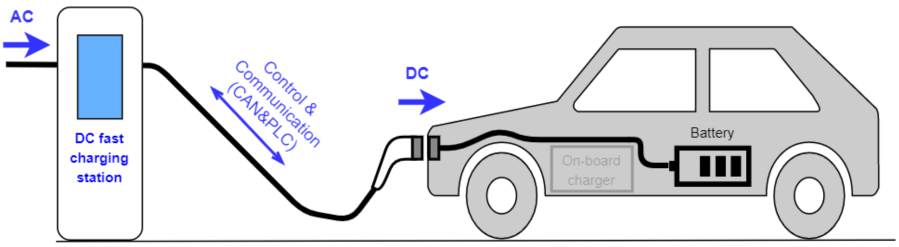

Fig. 5.21

As mentioned before that, the battery can be charged up to almost 80% of capacity in constant current (CC) mode (This is called as "80% rule"). The remaining 20% of charge realized in constant voltage mode and it takes almost half of the time that CC mode takes as seen from Fig. 5.4. For this reason, fast chargers cannot fully charge a battery up to 100% in a short time. The fast charging concept covers only CC mode and can charge the battery up to around 80% SOC.

Fast chargers can able to charge an EV battery under 60 min. Its power capacity is usually at least 50kW or more. For example, if a fully empty 24 kWh battery is connected to a 50 kW fast charger, the charging time will be (0.8)*(24kWh)/50kW=0.38 h (or 23 min). It should be remembered that the charging time can be longer in cold weather due to battery characteristics. In some systems, 50 kW modules are connected in parallel as modular method to increase the total power, but the maximum charge current of battery must not be exceeded for safety.

DC chargers have (+) and (-) terminals for connection to EV battery. Type1 and Type2 connectors, which are used for AC charging, are not suitable for DC chargers. A dedicated connector to withstand for high DC current and voltage is needed. For this purpose, Combined Charging System (CCS), which includes dedicated pins in the sockets for both AC and DC charge together, have been developed. These sockets are also called as Combo sockets, i.e., Combo 1 for CCS1 and Combo 2 for CCS2. While CCS1 is mostly used in USA, the CCS2 is mostly used in European countries. Apart from that, the CHAdeMO and GB/T sockets are used in Japan and Chine for DC charging, respectively. More information about the sockets will be given in the next section.

The maximum charging power of a DC charge station can be between 25kW and 400 kW. Since the on-board charger is bypassed in Mode 4, charging process must be controlled by DC charger according to the battery characteristics. The BMS control systems of EV battery pack supervise the charging process, and the battery voltage and current should be precisely controlled. Otherwise battery lifetime can considerably be reduced. Therefore, a robust and fast digital communication is needed between EVSE and EV as shown in Fig. 5.21. The Power Line Communication (PLC) and CAN bus are widely used protocols for this purpose. IEC61851-24 defines the standard for communication between charging station and electric vehicle in DC charging. The PLC protocol generally uses “control pilot, CP” pin (for CCS1 and CCS2) as a communication medium. In other words, data signal is transmitted by superimposing it on the

CP pin signal. However, some of the charger's socket may have extra 2 pins dedicated for CAN Bus communication in the socket (ex. CHAdeMO).

Battery voltage and capacity varies from EV to EV. So if a DC charger would support only a single charging voltage, it would charge very small number of EV types in the market. However, in a charging station, the DC charger should serve as much EVs as possible for being profitable. For this reason, most of the DC chargers can adjust its output voltage in wide range between 100V and 500V in order to be compatible for most of EVs in the market. The voltage setting is managed by BMS controller and send to the EVSE through the communication between EVSE and EV.

DC chargers can have very high charging power up to 400 kW. In order to efficiently use of this power capacity, most of the DC chargers have more than one charging sockets in order to charge two or more EVs at the same time by sharing power among them as illustrated in Fig. 5.22.

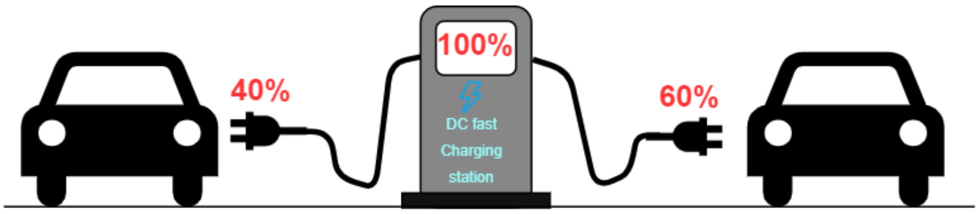

Fig. 5.22 Power sharing function of DC charger

If an EV charge station includes more than one DC charger equipment, it needs very high-power from the utility grid. Therefore, a dedicated utility grid connection with a suitable power transformer is needed for fast charger stations. Domestic or corporate electricity network cannot supply it without new agreement with Distribution Company.

5.4 AC Charging Plugs

Domestic sockets are not designed to energise the high-power devices, such as EVs. EV chargers draw excessive current for a long time that pushes the domestic electric cables and plugs to their limits. A short circuit or any fault in cables/plugs/sockets could easily results in fire or electrical shock. On the other hand, the household plugs can be pulled out by children or someone and that may cause electrical hazard. Therefore, it is not advisable to charge EVs from household sockets due to safety concerns. The EV charging sockets are designed for high-power and maximum safety. For example, charging plug is locked in socket, therefore, no one can take it out. Even if someone rips the cord from the socket accidentally, the charging system will shut down in a safe way and so that people and devices are protected.

On the other hand, household socket does not permit controlling or scheduling the charging power which are very important features for EV charging. For this reason, dedicated charging connectors have been developed for AC and DC charging requirement.

5.4.1 Type 1 EV charging plug

Originally designed by the manufacturer Yazaki and first published in SAE J1772. It is also called as "Yazaki connector" and mostly used in USA because it is designed to connect EVs in Mode 1 standards [4]. IEC 62196-2 is called this plug as "Type 1" and its pin definitions is shown in Fig. 5.23 and explained below;

- 3 power pins; phase (L1), neutral (N) and power earth (PE) for single phase operation. Neutral line can be second phase (L2) for high voltage two phase operation.
- Control pilot (CP) function according to IEC 61851-1 Annex A.
- Proximity pilot (PP) function using auxiliary switch (No current coding for cable).
- IEC 62196-2 defines an operating current up to 32A. The maximum current is 80A in USA
- Lock mechanism to hold plug in place

Fig. 5.23 Type 1 AC plug [6]

5.4.2 Type 2 EV charging plug

This plug is developed for charging in Mode 2 and Mode 3 as a three-phase AC plug. Because the original design is made by the manufacturer Mennekes, it is also known as "Mennekes connector". It has round housing with one side is flattened for making the orientation easy as shown in Fig. 5.24. IEC 62196-2 calls this plug as "Type 2", and its pin definitions shown in Fig. 5.24 explained below;

- 5 power pins; phase 1 (L1), phase 2 (L2), phase 3(L3), neutral (N) and power earth (PE) for single phase or three phase operation.
- Control pilot (CP) function according to IEC 61851-1 Annex A.
- Proximity pilot (PP) function using auxiliary switch and current coding for cable according to IEC 61851-1 Annex B.
- Operating current up to 63A. The maximum current is 70A for single phase operation only.
- When it is inserted in the socket, the lock mechanism in the socket can lock the plug.

IEC 62196-2 defines an operating current up to 63 A, and allows a maximum current of 70 A (single-phase). By regulation, all EV chargers in the European Union need to have Type 2 socket outlet or Type 2 connector. This connector is mostly favoured by German and European car manufacturers. Private chargers usually have 22 kW rated power. Most of the public chargers in Europe are equipped with Type 2 plug with a charging power up to 43 kW (400V, 63 A, AC). Type 2 allows single-phase, two-phase or three-phase charging.

Fig. 5.24 Type 2 AC plug [7]

5.4.3 Type 3 EV charging plug

Originally designed by the manufacturer Scame, and then it is also called as "Scame connector". It can be used in Mode 2 and Mode 3. IEC 62196-2 calls it as "Type 3" plugs and it has two versions: Type 3A for single-phase up to 16A and Type 3C for three-phase up to 63A as shown in Fig. 5.25. It has a shutter to prevent accidental touching which can be important requirement for some countries. However, Type 2 socket is also improved and a shutter is added to it [5]. Type 3 EV plug has,

- 3 or 5 power pins; L1, N and PE for single phase or additional L2, L3 for 3 phase operation.
- Control pilot (CP) function according to IEC 61851-1 Annex A.
- Proximity pilot (PP) function using auxiliary switch and current coding for cable according to IEC 61851-1 Annex B.
- Operating current in single phase up to 16A without control pilot, 32A with control pilot, and up to 64A in three phase charging.
- When it is inserted in the socket, the lock mechanism in the socket can lock the plug.

Type 3 plug is developed and mostly used in Italy, and not seen in Europe Union frequently. Type 2 socket is widely adopted in European countries.

Type 3A male plug (4 pins,250V/16A)

Type 3C male plugs (7 pins, 480V/63A)

Fig. 5.25 Type 3 AC plugs [8]

5.4.4 *GB/T AC charging plug*

In China, Guobiao standard GB/T 20234.2-2015 for AC-charging specifies cables with Type 2-style male connectors (See Fig. 5.28) on two ends, and a female inlet on the EVs. This is the opposite gender used by the rest of the world. Also, different control signals are in use.

Fig. 5.26 GB/T AC plug [9]

5.5 DC Charging Plugs

DC fast chargers have DC output and therefore, Type 1, Type 2 and Type 3 connectors are not suitable for DC power. For this reason, either new plug should be developed or existing AC plugs need to be improved. Both methods are seen in practice; for example while CHAdeMO plug is designed specifically for DC charging, the CCS1 and CCS2 plugs are an extension version of Type1 and Type 2 plugs, respectively. IEC 62196-3 describes vehicle connector for DC charging of electric vehicles in Mode 4. The specific designs are grouped into several configurations.

5.5.1 CHAdeMO

CHAdeMO is a Japanese standardized charging protocol developed by CHAdeMO organization which allows charging power up to 62.5 kW (500V, 125 A, DC). CHAdeMO 2.0 (revised) allows 400 kW (1000V, 400 A, DC). The connector can be found in IEC 61851 and in IEC 62196.

CHAdeMO is using CAN bus protocol to perform safety interlock, to transfer SOC, stop signal, voltage, battery capacity, etc. Communication between EVSE and EV is realized based on CAN bus protocol using pin 8 and pin 9 of the plug. Pin 7 (PP) is stands for the proximity detection as seen from Fig. 5.27 . CHAdeMO is the first DC standard to facilitate V2X (V2G) via 1.1 version of protocol, and there are numerous pilot projects running around the World to test its capacities.

CHAdeMO is the most widely used charging standard promoted by Nissan-Renault and several Japanese brands like Mitsubishi, Toyota, Honda, etc.

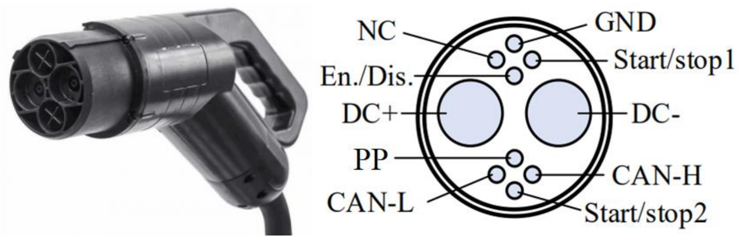

Fig. 5.27 CHAdeMO plug [11] and pin descriptions

5.5.2 GB/T

GB/T DC charging plug is developed and used in China as a competing standard. The view and pinout of GB/T plug is shown in Fig. 5.28. The maximum voltage and current of this plug are

750V (or 1000V) and 250A, respectively. The maximum 185 kW charging power is allowed. The communication between the EVSE and EV is realized by using CAN bus protocol as like CHAdeMO. GB/T plug has pins to charge the low voltage auxiliary battery, and also two proximity pilot pins.

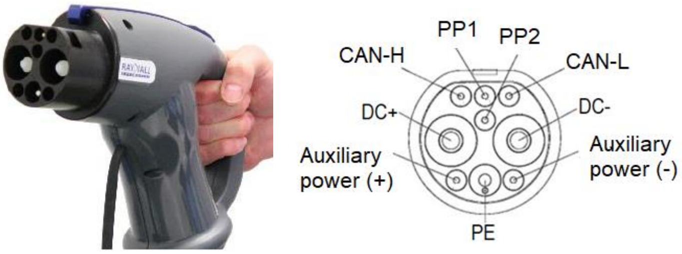

Fig. 5.28 GB/T Plug and pin descriptions [12]

5.5.3 CCS 1

This plug is obtained by placing two pins for DC connection at the bottom of Type 1 AC plug as shown in Fig. 5.29. Since this socket is suitable for both AC and DC charging, it is named as Combined Charging System 1 (CCS1) connector, or COMBO 1 connector. This plug is single phase and mostly used in USA. There are no dedicated pins in CCS1 connector for communication between the EVSE and EV. The communication is realized using Power Lines Communication (PLC) protocol through CP&PE pins according to IEC 61851-24 Annex C and ISO 15118-3. The maximum charging current for CCS1 is 200A with maximum 500V, and the maximum power is 80 kW. Latest standard supports current up to 500A which corresponds to 250kW. It should be remembered that, high current requires large cable-cross-sections and probably may need cooling of cable.

Fig. 5.29 CCS 1 DC charging plug and pin descriptions [10]

5.5.4 CCS 2

It is obtained by similar way as CCS 1. The CCS 2, it is also called as COMBO 2, combines DC connector with Type 2 connector as shown in Fig. 5.30. It should be noted that, 4 power pins, e.g., L1, L2, L3 and N pins, are removed from the plug in CCS2, since these pins are not needed in DC charging. They are required for only AC charging. This plug is standard for DC charging in European Union countries. CCS 2 plug can be used either for single phase, three phase and also DC charging modes. It can use PP, CP and PE pins for proximity pilot and charge pilot functions. AC power pins are not used in this plug. The communication is realized using Power Lines Communication (PLC) through CP&PE pins according to IEC 61851-24 Annex C and ISO 15118-3 as similar to CCS1. The maximum charging current for CCS1 is 200A with maximum 1000V, and the maximum power is 200 kW. Later edition of standards supports currents up to 400A for future charging infrastructures, However, such a high current requires high cable cross sections and leading to heavy and stiff cables, and also requires cooling system for cables and connectors due to ohmic resistances of cable and contacts.

Fig. 5.30 CCS 2 Charging plug and pin descriptions [10]

5.5.5 EV inlets

Each AC and DC plugs have a dedicated inlet on EV as described in Table 5.4. CCS1 inlet is suitable for Type 1 AC plug also. Similarly, CCS2 inlet is suitable for Type2 AC plug. The Type1 and CCS1 are popular in USA, and Type2 and CCS 2 are popular in European Union. CHAdeMO connector is also seen in USA and European Union in charging stations.

However, Type 1 and Type 2 are completely compatible for single phase and a simple adapter can connect the two plugs. Type 3 plugs are mainly used in Italy, but it is electrically compatible to Type 1 and 2. CCS 1 & CCS 2 are compatible with AC and DC charging modes and therefore, most of the automobile manufacturers support CCS connectors and place the CCS inlet on their automobiles.

Table 5.4: Charging connectors and EV inlets

Charging mode	Plug	Compatible EV inlets
1 Phase AC charging Mode 2&3 3-7 kW	 Type 1 Female [6]	  Type 1 Male [18] CCS1 Male[18]
1 or 3 Phase AC charging Mode 2&3 3-43 kW	 Type 2 Female Plug (Mennekes) [7]	  Type 2 Male [18] CCS2 Male [18]
	  Type 3A and Type 3C Male plugs [8]	  Type 3A Female and Type 3C Female [8]
	 GB/T Male AC Plug [9]	 GB/T Female AC Inlet [18]
DC charging (USA) Mode 4 Up to 350 kW	 CCS1 Female Plug [10]	 CCS1 Male Inlet [18]
DC charging (EUROPE) Mode 4 Up to 350 kW	 CCS2 Female Plug [10]	 CCS2 Male Inlet [18]

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DC charging (JAPAN) Mode 4 Up to 350 kW	 CDAdeMO Male Plug [11]	 CHAdeMO Female Inlet [11]
DC charging (CHINA) Mode 4 Up to 250 kW	 GB/T Male DC Plug [12]	 GB/T Female DC Inlet [18]

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6 EV CHARGING LOCATIONS

The EVs can be recharged at residential homes, at workplaces, at parking places or at charging stations as well. All these charging options have their own pros and cons. Home charging takes long time to full charge of battery, but it is cost effective. In contrast, DC fast chargers are capable to charge the EV up to 80% in less than 30 min, but they are most expensive charging option. So the charger should be selected for best fit to owner's needs with minimum investment. Although the chargers in residential areas or in workplaces are dedicated to some limited owners, the public chargers can serve to all EV owners.

The EV chargers can generally be divided into 4 separate categories. These are residential home, workplaces, parking lots and commercial stations. The main parameter that separates these groups from each other is the difference in charging times that is determined by the charging power. Let's take a closer look at these 4 categories of charging systems each has different properties.

6.1 Residential Homes

For private houses, it is relatively easy to find a charging place. The car probably has a dedicated parking area or a garage. On the other hand, for an apartment, several factors should be considered before installing a charging station. First of all, it is necessary to own the parking area or get permission for usage from the owner. If parking areas are in shared use, no conflict should arise in regarding to ownership or usage of charging station. The owner must agree with the apartment management association regarding the suitable location for the charging station. For new apartments, there may be reserved places for EV chargers in parking lots. But in old apartments it may not be easy to find a suitable place, or in some cases it may be impossible.

For private houses, the electricity is supplied to charger from the owner's electricity meter. But for apartments the situation is not simple as like that. If the ownership belongs to the person who will install the charging station, then it is appropriate to get the electricity from his/her own energy meter. In this case the installation has the same procedure as for a private house. Alternatively, a shared meter of common utilities can be used if it is suitable and get permission.

In either case, the electric installation should be done according to the national codes for residential electricity as like installation of air condition or lighting outlet. Enclosed parking garages can be hazardous locations, and so that national electric code for installing electric equipment in those areas should be followed [1].

The EV chargers, i.e., EVSE, can be wall mounted with tethered cable or just only socket as shown Fig. 6.1. If charging station is in safe area against thief, tethered cable version can be practical. Otherwise, cable needs to be removed from the charger every time. In wall chargers, the Type 2 socket is mostly used in Europe; Type 1 is preferred in USA. The EV is usually parked overnight and connected to the charger all night. Overnight charging has the advantage of being the cheapest period for charging in most cases. The owner can find the EV as ready with full battery in the morning.

Fig. 6.1 Wall mount EVSE with un-tethered (left) and tethered cable (right) (Courtesy of VESTEL)

The EV charger takes power from the same switchboard with home electrical appliances; such as refrigerator, washing machine, dishwasher, oven, cookers, TV, lighting, ironing etc. So if the total current is more than the circuit breaker trip current, home will be de-energized. Hence, the charging power should be selected carefully in order to prevent power loss at home.

The EVSE, with Mode 2 or Mode 3, are the best fit for these places with single phase (230V) or three phases (400V) electricity options. In the market, the maximum power of EVSEs in Mode 2 & Mode 3 is generally 3.7kW&7.4 kW and 11kW&22 kW for single-phase and for three-phase, respectively. A suitable one among them can be selected by evaluating the home electric consumption.

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The small power EVSEs, i.e., 3.7kW (for single phase) or 11 kW (for 3 phase), may seem suitable for home chargers. But in this case, full charging time will be very long, and the EV may not be ready with full battery in the morning. As we have learned that, the charging power can be adjusted by EVSE using control pilot (CP) function, therefore, it is also possible to use 7.4kW or 22 kW EVSEs. But in this case, the EVSE power should be reduced so as to reserve some power for home appliances, and then the maximum power of EVSE cannot be utilized effectively.

Best solution for this case is the "Dynamic Power Management" feature. As seen in the Fig. 6.2, a power optimizer meter is placed into the home energy main flow path to measure the instantaneous power consumption of the home. When home power usage increases, power optimizer sends a signal to EVSE through PLC or any other communication methods, so that the EVSE decreases the charging power, and consequently the total power will be kept always below the switchboard limit. However, this feature may increase the cost of EVSE considerably since an extra power management device is required.

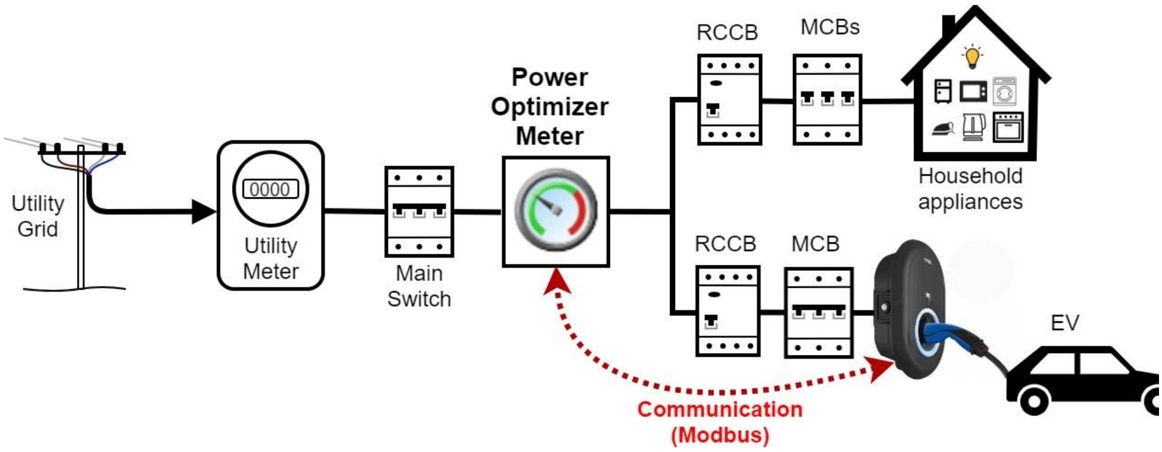

Fig. 6.2 Dynamic power management block diagram

Some of the EVSEs in the market have built-in power scheduling feature. This feature is a simple but cost-effective alternative to dynamic power management and can be useful in private houses. In these EVSEs, the charging power can be programmed by the user with respects to time throughout the day like as shown in Fig. 6.3. In this example, EVSE charging power is maximum during the nighttime when the home electricity consumption at the lowest value. For other times of the day, the EVSE reduces the charging power to a safe value. It is important to note that, this power levels and switching times are fixed, and not adjusted automatically.

These values can be set by the user by considering the possible peak power consumption of home.

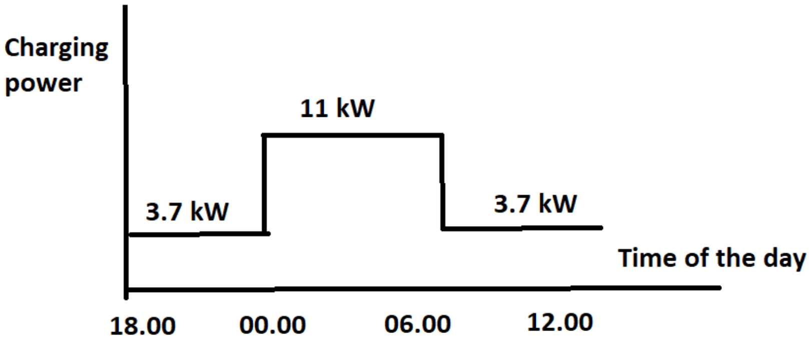

Fig. 6.3 Example power scheduling for home charging

For reducing the installation cost, portable charge equipment as shown in Fig. 5.7 can also be used. The owner should ensure that the portable device has certification for IEC 62752:2016, built-in RCD and communication feature with the EV. The non-standard devices may cause fire or electric shock risk.

6.2 Workplaces

Charging power requirement for an EV in the case of workplaces is generally low, since the employees have a predictable work schedules. For example, if we assume that the average power consume of an EV is 200 Wh/km and employees drive from 50 km away in average, the required energy to be charged is only 10 kWh. Even a 3.7 kW charger can supply this energy less than 3 hours. This time is considerably lower than the daily standard working hours of 8 h. Therefore, the EVs will be fully charged before the workplace closing time.

However, there may be a lot of EVs in the workplace to be charged at the same time. In this case, the peak electric power can reach to very high level, and circuit breakers can be tripped. Scheduling of charge operations can fix this problem. As mentioned in previous sections, the communication between the EVSE and EV permits the power adjusting. Therefore, a power optimizer meter (POM) device can control the maximum charging power of individual EVSE, and implements a load control strategy. The POM can manage the all EVSEs in the workplace so as to limit the maximum power to a desired level. This is called as dynamic load management and some of the chargers have compatibility with this feature built in via power line communication (PLC) as shown Fig. 6.4.

Although, 3.7 kW or 7.4 kW chargers in Mode 3 seems good choice for workplaces, one or more fast chargers may be required for company service cars, since daily driving range of service cars may be high and need fast charging overnight, to be ready for next day. The switchboard power rating is considerably higher in industrial facilities than a home. Therefore, it is possible to charge many cars together with load management feature.

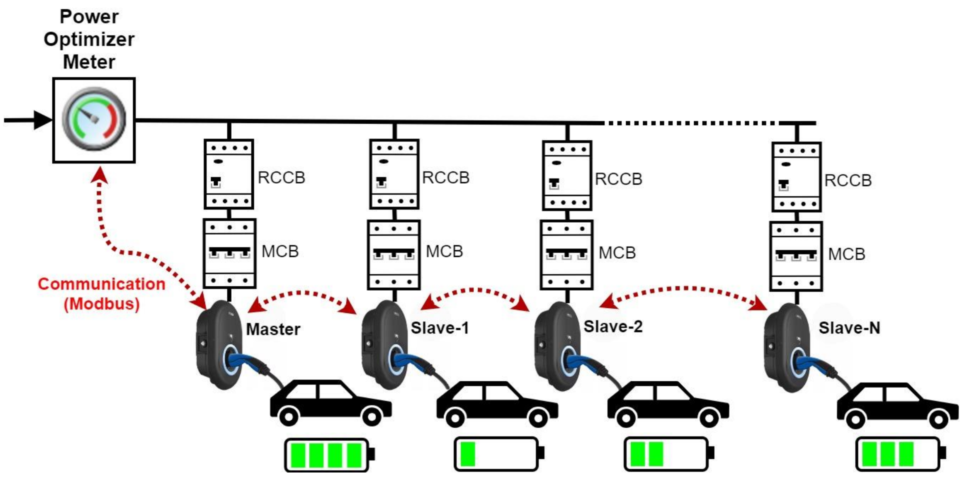

Fig. 6.4. Dynamic load management

6.3 Parking Places

Public or private parking areas are very suitable places for EV charging. Hotels, shopping centers, government buildings, airports and city parking areas are providing more and more charging points for EVs. Today, we see that generally less than 3 charging points in these areas, but in near future, when the EVs become widespread it will increase considerably. Hotels and shopping centers may want to install EV charge point to meet customer/visitors requirements who own an EV. In these areas, fast charging is not essential since hotel customer or shopping center visitor will have at least one hour charging time. Moreover, credit card or some service fee collection mechanism should be provided. The Mode 3 chargers can fulfill all these requirements.

It should be noted that, EV needs long time, i.e., up to several hours, to be fully charged. Then, the parking lots which contain EV charger can be reserved for EV owners in order to balance parking places between conventional fossil fuel cars and EVs as shown in Fig. 6.5. Moreover, in order to share one charging station as much EV as possible, the charging time may be restricted to 1h or 2h maximum.

It may be advantageous to place EV charging station near to the places where the customer can spend time, such as restaurants, shopping mall, sport centers etc. While customer do activities, their EVs store back the drained battery energy. Additionally, public transportation, parks etc. may be helpful for EV owners to prefer EV parking and charging place.

Fig. 6.5 [3]

6.4 Commercial charging stations

The main difference of commercial charging stations from hotel or shopping center parking places is that it is dedicated only to charge EVs commercially as shown in Fig. 6.6. These charging stations should be placed near to the potential customer location. Additionally, to increase visibility of the station, wayfinding signage, mobile app portal or membership of some EV charging organizations will be helpful.

Fig. 6.6 [4]

Commercial charging stations, most probably, has one or more DC fast charging option and a lot of AC charge port as many as possible. Since its charging power requirement is very high, mostly a special contract is needed with the utility grid through a private transformer. Sufficient distance between distribution transformer and EVSE should be given as described by the local electrical installation guide. Because the power rating of these station is very high, the customer should stay in safe distance to transformer against fire, explosion etc.

DC fast chargers are mostly needed on highways for intercity travel in order to charge the EV battery less than 30 min. These chargers reduce the range anxiety and provide long range driving for EV cars. For this purpose, frequently used travelling routes should be covered with DC fast charger infrastructure.

In the planning phase of any DC fast charging station, it is important to make a projection regarding the number of EVSEs for future expansion. Always it is less expensive to add additional conduits and power panels during system installation than to modify it in future.

Some additional considerations for EV charge stations are listed below;

- The EVSE and the associated parking area should be as close as to the electricity distribution transformer that will reduce the losses of systems. Remember charging power is very high, and takes for hours.

- The power cord of EVSE should not be placed on pedestrian walkway. The cable insulation may be damaged due to crushing, friction and impact, and the protection equipment may cause false trip.
- Evaluate the risk of vandalism and take proper precautions. Use security lighting, security cameras, locked enclosure for equipment
- Aesthetic view of charging station may be important for some customer. For this purpose, landscaping, wall painting and hiding some equipment by wall may help.

6.5 Effects of EV chargers on the utility grid

By 2030, it is expected that the EVs will consume electricity between 550 to 1000 TWh globally. In Europe, EVs will count for more than 4% of total electricity consumption (Source: IEA). However, today, the EVs are charged after work when the energy consumption is at the peak level, thanks to home appliances. If the power requirement increases too much due to EV charging in a relatively short period of time, a great pressure on electricity grids would occur. Some of the possible results of the future load caused by EVs:

- Potential blackouts
- Transformer system overload
- Voltage and frequency drop
- Increased CO_2 emission by peak power plants
- Lower renewable energy penetration
- etc.

The Norwegian Water Resources and Energy Directorate released assumptions about the necessary investments in the electricity grid due to increasing EV penetration by 2040. There are 3 scenarios visible on the figure:

1. EVs are charged at night, when batteries are controlled to charge outside of peak periods.
2. EVs are charged when it is necessary (every 2-3 days when the battery is low).
3. EVs are charged every day, in peak hours, which is the case in Norway according to surveys made.

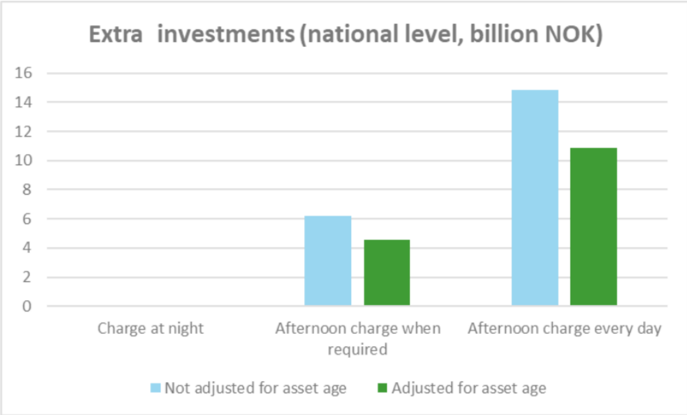

Fig. 6.7 [5]

6.5.1 *Smart Charging, V1G*

Smart charging, or V1G, covers the ability to dynamically modify the charge rate/charge time. V1G partially provides solution for the load issue that is caused by EVs in the future. As seen on the Fig. 6.8, charging is scheduled for off-peak times; therefore, several of the negative effects listed above are solved or minimized. Also, charging costs can be decreased in case of time of use (ToU) electricity pricing.

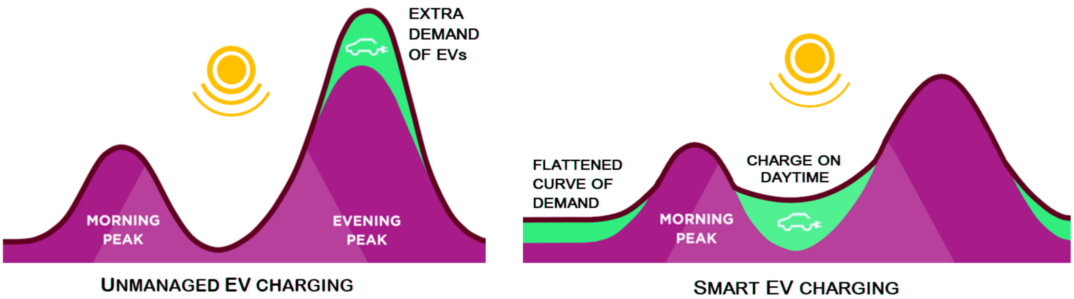

Fig. 6.8 [6]

6.5.2 *Vehicle-to-grid, V2G*

As of today, EVs are mainly charged in the evening, partially covering the peak electricity consumption period. Vehicle-to-grid (V2G) optimization of EV charging has a great potential to charge in off-peak periods and to discharge in peak periods.

I. On the Fig. 6.9, the electricity demand profile and the EV charging demand profile is shown. The effect of charging EVs traditionally after working hours - in peak times - is visible on the first graph. Without any control, peak load is increased, which puts a burden on the electrical grid.

II. The second graph shows the potential of controlling charging. By introducing control of charging, EVs can charge in off-peak and reduce load in peak times. This covers the functionality of V1G.

III. The third graph in the evolution shows the case when not only charging times are controlled, but EVs discharge and provide generation resources to the grid. This type of control is called Vehicle-to-Grid.

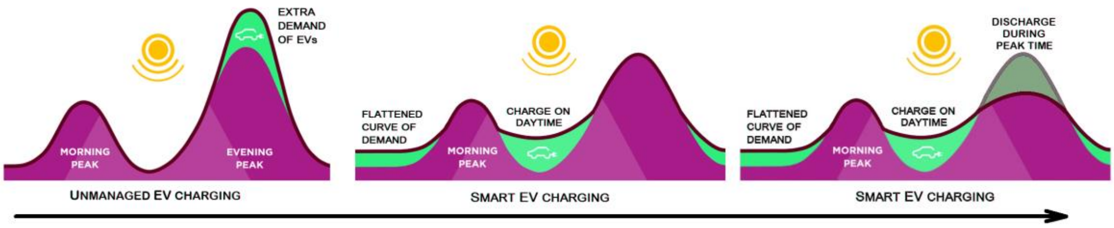

Fig. 6.9 [6]

EV owners doing V2G have the ability to be the supplier and the consumer in the same time. With V2G it is possible to use the battery as an energy asset, it can both charge (consume) and discharge (supply).

As an energy asset, the EV's battery is a valuable asset for many parties. EV batteries can build up the discharge rate in less than a second, they can be controlled remotely by a DSO, an aggregator or Electric Mobility Service Provider (eMSP) and EV batteries have a long lifespan and can resist cycling. Thanks to the controlled charging, Smart Charging, EVs can be charged in off-peak times, cheaply.

What is possible with V2G?

- Frequency balancing
- Voltage control
- Grid balancing
- Delaying grid investments
- Peak shaving

- Energy trading
- Tariff optimization
- Demand response
- TOU tariff
- Demand Charge Management
- Renewable energy integration

6.6 Photovoltaic Energy Integrated EV Charge Station

It is mentioned in Section 1 that, if the charging power of EV does not come from renewable source, the carbon emission of EVs will stay at high level. Only difference, the emissions shifted from combustion car to the power plant. In order to obtain green transport system, the charging power must come from renewable sources, such as photovoltaic and wind power etc. Typical system topology for solar energy integrated EV charging station is shown in Fig. 6.10. The system has two power sources; utility grid and PV arrays. Utility power is connected to the AC bus which is usually 400V/50 Hz three phase AC voltages. On the other hand, the solar power is connected to DC bus which is generally 400Vdc. The EV charger can use power from both sources. Notice that, the utility power is bidirectional, which means if solar power generated is more than required; the excess energy can be transferred into the grid via AC-DC bi-directional converter. Moreover, excess energy can be stored in battery. Battery can be used also for power scheduling for smart grid purposes.

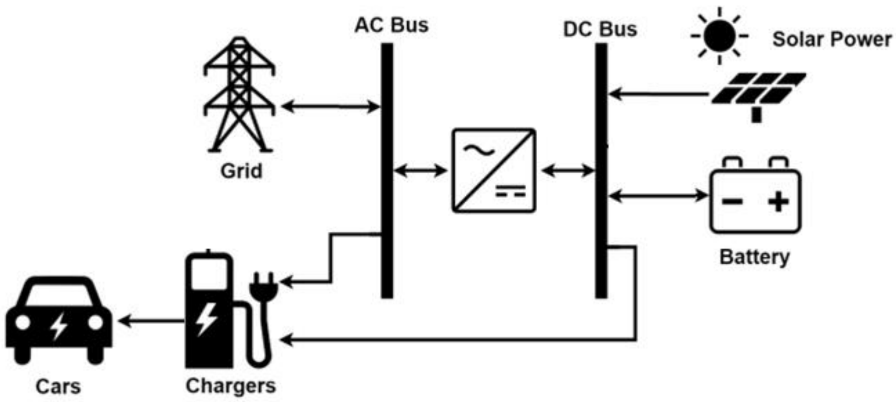

Fig. 6.10

Fig. 6.11 shows the solar integrated charging station for 25 EVs in main campus by Oak Ridge National Laboratory. The systems consists of a solar canopy having 47 kWp total power, 2 kW

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per parking space. The battery can be charged during nigth from grid and also stores excess power from solar. The system connection diagram is shown in Fig. 6.12. 125 solar integrated EV charging stations similar to this one are installed in Tennessee by Oak Ridge and it is obtained that a non-linear control algorithm can offset the EVSE load on the grid by up to 70.7% during typical operating conditions at ORNL [2].

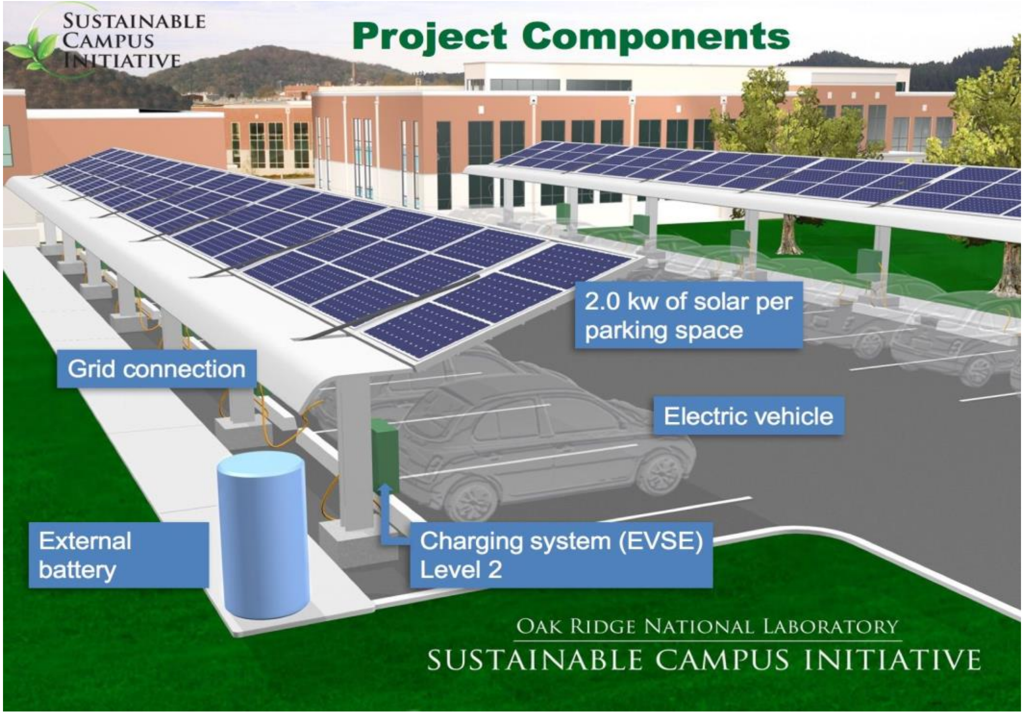

Fig. 6.11 [2]

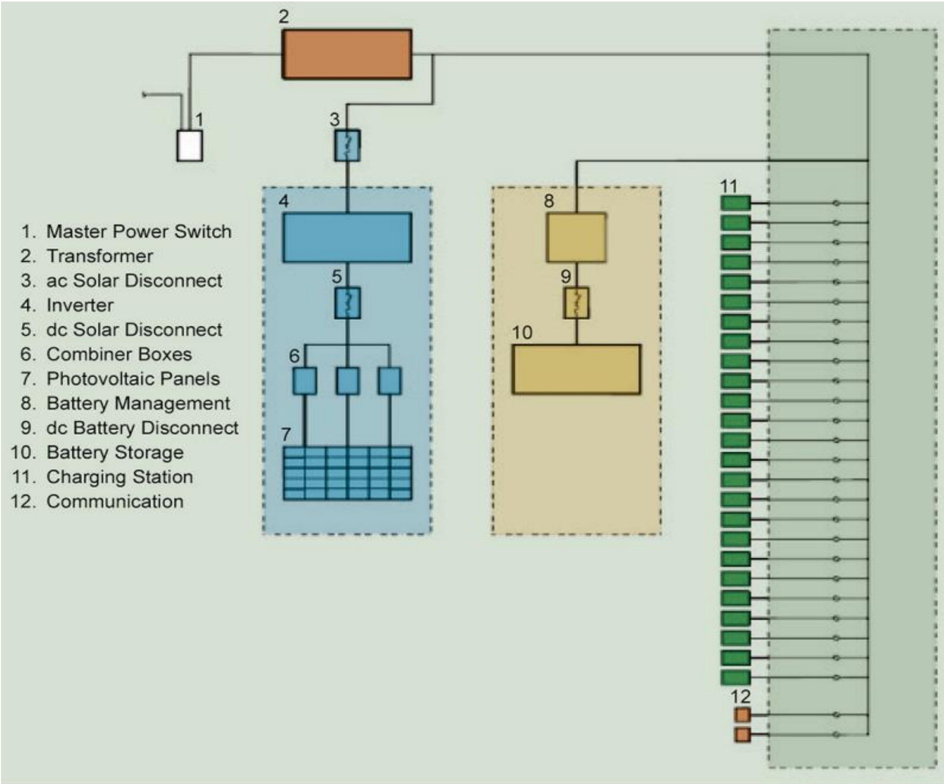
1. Master Power Switch
2. Transformer
3. ac Solar Disconnect
4. Inverter
5. dc Solar Disconnect
6. Combiner Boxes
7. Photovoltaic Panels
8. Battery Management
9. dc Battery Disconnect
10. Battery Storage
11. Charging Station
12. Communication

Fig. 6.12 [2]

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7 INSTALLATION OF EV CHARGERS

The IEC 60364-5-52 Ed.3 defines the standards for Low Voltage Electrical Installation; e.g. methods of installation and current carrying capacities etc. However, national electricity codes may have differences and thus national standards must be followed during installation. In this chapter, the general parameters that should be considered during EV charger installation are summarized.

7.1 Selection of EV Charger Point

When selecting suitable places for EV charger, the following factors should be considered.

- Power availability: Placing the EV charger near to the utility power meter will reduce the installation cost and installation time. Long distance requires long cables which constitutes the main cost of installation. If the reserve power capacity of the switchboard is enough for EV charger, then no need to upgrade the service power in switchboard. Otherwise, some investment should be needed to have new connection from the utility distribution company. In this case the cost will increase substantially.
- Construction requirement: In order to get power from switchboard to the EVSE, generally wall installation is needed. However, sometimes trenching may be required. In this case, softer grounds (grass etc.) are preferable instead of hard rock or concrete ground.
- Mounting: The EVSE can be mounted on a wall or a pole as shown in Fig. 7.1. Placing the EVSE on a wall is cost effective and faster way than pole mounting option. Pole mounting needs construction to fix the EVSE pole into ground and increase the cost and workmanship. If the site has a suitable wall area, wall mounting option is often preferred.

  On the other hand, dual EVSE mount with single power connection lowers the installation cost. Therefore, if additional EVSE will be installed in the same place in future, keeping the installation power of connection is high will reduce the installation cost and time.

- Environmental concerns: Charging equipment can be installed indoors or outdoors. If it is outside, EVSE should be prevented from exposure of the Sun since it affects the thermal behavior of EVSE. On the other hand, the measures should be taken against heavy rain and floods. Moreover, the EVSE should be places at least 0.5m to 1.0m above the ground to prevent car hitting.

Pole mounting

Wall mounting

Fig. 7.1 (Courtesy of VESTEL)

After determining the EV location, electrical power connection should be extended to that point from the nearest switchboard through cables.

7.2 Electric Cables

An electric cable consists of one or more conductor in the centre, a PVC or XLPE insulating layer around all the conductors, bedding and an outer sheath to isolate and to protect the conductors from environmental conditions, as shown in Fig. 7.2. Some cables have armour around the cable to protect it from mechanical stress.

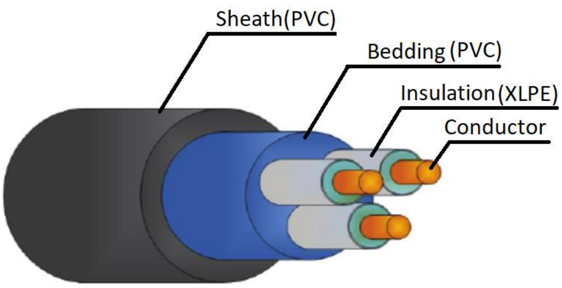


Fig. 7.2 [12]

Current flowing through a conductor creates joule heat losses on the conductor and this thermal energy increases the temperature of conductor material. Although the conductive metal itself can withstand very high temperatures, for example the melting temperature of copper metal is approximately 1084 °C, the maximum temperature limit of the insulation material surrounding the conductor is relatively very low. If the insulation material starts to melt, safety hazardous situation occurs as the insulation layer being loosed, such as, electrical short circuits or electric shock. Hence, the current carrying capacity (i.e., Ampacity) of a conductor is the result of placing an upper limit on the conductor temperature. The definition of Ampacity is expressed as *"The maximum current, in Amperes, that a conductor can carry continuously under the conditions of use without exceeding its temperature rating"* in the *"National Electricity Code (NEC) Article 100 – Definitions"* document. The temperature rating value in the description represents the maximum permissible temperature value of the conductor. Since the insulator is the material which has generally the lowest temperature limit value in a conductor, the temperature limit value is based on the upper temperature limit of the insulation material.

The insulation provided on each conductor of a cable by mainly PVC (Poly Vinyl Chloride), XLPE (Crosslinked Polyethylene) or RUBBER (Various Types of Rubber). The insulating material determines the maximum operating temperature of cable as shown in Table 7.1. As the operating temperature increases, the cable ampacity increases correspondingly as mentioned above.

Table 7.1 Maximum operating temperature of insulating materials

Insulation Material	Maximum Operating Temperature
PVC TYPE A	75˚C
PVC TYPE B	85˚C
PVC TYPE C	85˚C
XLPE	90˚C
RUBBER – EPR IE-1	90˚C
RUBBER – EPR IE-2, EPR IE-3, EPR IE-4, SILICON IE-5	150˚C

IEC 60446 defines the colour codes of wiring in a cable as shown in Table 7.2. Most European countries adopt this standard, but it should be checked for each country whether it is strictly valid.

Table 7.2 Color codes of wiring in a cable

Function	Label	Color, IEC	Visual
Single Phase Cables			
Protective earth	PE	green-yellow	
Neutral	N	blue	
Line	L	brown	
3-phase Cables			
Protective earth	PE	green-yellow	
Neutral	N	blue	
Line, 3-phase	L1	brown	
Line, 3-phase	L2	black	
Line, 3-phase	L3	grey	

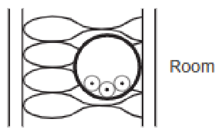
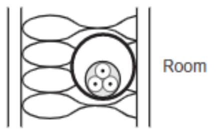
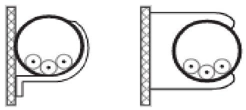
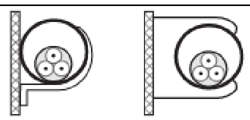
7.2.1 Cable Ampacity

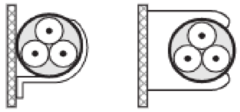
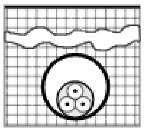
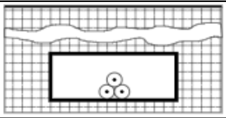
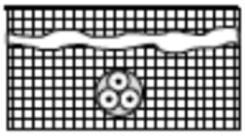
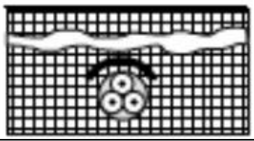
Maximum current value that a conductor can safely carry, in other words ampacity, depends on many parameters, and therefore, it is necessary to obtain mathematical models of all these parameters to keep the accuracy high in calculations. These parameters can be listed as follows;

- Cross-sectional area and geometry of the conductors
- Maximum temperature limit of the conductor’s insulating material, and all terminal materials in the circuit from beginning to end of current flow.
- Conductor material (copper, aluminium etc.)
- Length of the conductor (voltage drop).
- Number, geometry and location of other current-carrying conductors in the conduit
- The ambient temperature (air or ground)
- Whether direct sunlight falls on the cable or not
- Conductor heat storage capacity and thermal resistances
- The air flow rate circulating around the cable
- Operating voltage,

The list can be expanded further. However, considering so many parameters require a very complex modelling which takes too much time and big effort. For this reason, IEC or similar organizations publish the maximum current carrying capacity of the conductors in a table for certain installation methods. These tables allow the designer to easily select the conductors without complex calculations. IEC 60364-5-52 defines many installation methods, but most common are listed in Table 7.3.

Table 7.3: Typical installation methods according to IEC 60364-5-52

Installation Method	**Illustration**	**Reference Methods**
Insulated conductors or single-core cables in conduit in a thermally insulated wall		A1
Multi-core cables in conduit in a thermally insulated wall		A2
Insulated conductors or single-core cables in conduit on a wooden, or masonry wall		B1
Multi-core cable in conduit on a wooden, or mansonry wall		B2

Single-core or multi-core cables: - fixed on a wooden, or mansonry wall		C
Multi-core cables in conduit or in cable ducting in the ground		D1
Single-core cable in conduit or in cable ducting in the ground		D1
Sheathed single-core or multi-core cables direct in the ground -without added a mechanical protection		D2
Sheathed single-core or multi-core cables direct in the ground -with added a mechanical protection		D2

In low voltage applications, the PVC and XLPE insulated copper cables are frequently used, therefore, the current carrying capacities of PVC and XLPE cables for two and three loaded copper conductors are given in Table 7.4,

Table 7.5, Table 7.6 or Table 7.7.

Table 7.4: Current carrying capacities in [A] for methods of installation in Table 7.3, PVC insulation/two loaded copper conductors, conductor temperature 70°C, ambient temperature 30°C in air, 20°C in ground.

Conductor nominal cross- sectional area [mm²]	Current-carrying capacities in [A] for methods of installation in Table 7.3						
	A1	A2	B1	B2	C	D1	D2
1.5	14.5	14	17.5	16.5	19.5	22	22
2.5	19.5	18.5	24	23	27	29	28
4	26	25	32	30	36	37	38
6	34	32	41	38	46	46	48
10	46	43	57	52	63	60	64
16	61	57	76	69	85	78	83
25	80	75	101	90	112	99	110
35	99	92	125	111	138	119	132
50	119	110	151	133	168	140	156
70	151	139	192	168	213	173	192
95	182	167	232	201	258	204	230
120	210	192	269	232	299	231	261
150	240	219	300	258	344	261	293
185	273	248	341	294	392	292	331
240	321	291	400	344	461	336	382
300	367	334	458	394	530	379	427

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Table 7.5: Current carrying capacities in [A] for methods of installation in Table 7.3, XLPE or EPR insulation/two loaded copper conductors, conductor temperature 90°C, ambient temperature 30°C in air, 20°C in ground.

	Current-carrying capacities in [A] for methods of installation in Table 7.3						
Conductor nominal cross- sectional area [mm²]	**A1**	**A2**	**B1**	**B2**	**C**	**D1**	**D2**
1.5	19	18.5	23	22	24	25	27
2.5	26	25	31	30	33	33	35
4	35	33	42	40	45	43	46
6	45	42	54	51	58	53	58
10	61	57	75	69	80	71	77
16	81	76	100	91	107	91	100
25	106	99	133	119	138	116	129
35	131	121	164	146	171	139	155
50	158	145	198	175	209	164	183
70	200	183	253	221	269	203	225
95	182	167	232	201	258	204	230
120	210	192	269	232	299	231	261
150	240	219	300	258	344	261	293
185	362	329	449	384	506	343	387
240	424	386	528	459	599	395	448
300	486	442	603	532	693	446	502

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Table 7.6: Current carrying capacities in [A] for methods of installation in Table 7.3, PVC insulation/three loaded copper conductors, conductor temperature 70°C, ambient temperature 30°C in air, 20°C in ground.

Conductor nominal cross- sectional area [mm²]	Current-carrying capacities in [A] for methods of installation in Table 7.3						
	A1	**A2**	**B1**	**B2**	**C**	**D1**	**D2**
1.5	13.5	13	15.5	15	17.5	18	19
2.5	18	17.5	21	20	24	24	24
4	24	23	28	27	32	30	33
6	31	29	36	34	41	38	41
10	42	39	50	46	57	50	54
16	56	52	68	62	76	64	70
25	73	68	89	80	96	82	92
35	89	83	110	99	119	98	110
50	108	99	134	118	144	116	130
70	136	125	171	149	184	143	162
95	164	150	207	179	223	169	193
120	188	172	239	206	259	192	220
150	216	196	262	225	299	217	246
185	245	223	296	255	341	243	278
240	286	261	346	297	403	280	320
300	328	298	394	339	464	316	359

Table 7.7: Current carrying capacities in [A] for methods of installation in Table 7.3, XLPE or EPR insulation/three loaded copper conductors, conductor temperature 90°C, ambient temperature 30°C in air, 20°C in ground.

Conductor nominal cross- sectional area [mm²]	Current-carrying capacities in [A] for methods of installation in Table 7.3						
	A1	**A2**	**B1**	**B2**	**C**	**D1**	**D2**
1.5	17	16.5	20	19.5	22	21	23
2.5	23	22	28	26	30	28	30
4	31	30	37	35	40	36	39
6	40	38	48	44	52	44	49
10	54	51	66	60	71	58	65
16	73	68	88	80	96	75	84
25	95	89	117	105	119	96	107

35	117	109	144	128	147	115	129
50	141	130	175	154	179	135	153
70	179	164	222	194	229	167	188
95	216	197	269	233	278	197	226
120	249	227	312	268	322	223	257
150	285	259	342	300	371	251	287
185	324	295	384	340	424	281	324
240	380	346	450	398	500	324	375
300	435	396	514	455	576	365	419

The correction factors for cables installed in the air are given in Table 7.8, and in ground are given in Table 7.9. If the design temperature is different than 30°C for air and 20°C for ground, the current values must be multiplied by the correction factors shown in Table 7.8 and Table 7.9, respectively.

Table 7.8 Correction factors of cables for ambient air temperatures other than 30°C

Ambient Temperature [°C]	PVC Insulation	XLPE or EPR Insulation
10	1.22	1.15
15	1.17	1.12
20	1.12	1.08
25	1.06	1.04
30	1.00	1.00
35	0.94	0.96
40	0.87	0.91
45	0.79	0.87
50	0.71	0.82
55	0.61	0.76
60	0.50	0.71
65	-	0.65
70	-	0.58
75	-	0.50
80	-	0.41

Table 7.9 Correction factors of cables for ambient ground temperatures other than 20°C

Ground Temperature [°C]	PVC Insulation	XLPE or EPR Insulation
10	1.10	1.07
15	1.05	1.04
20	1.00	1.00
25	0.95	0.96
30	0.89	0.93

35	0.84	0.89
40	0.77	0.85
45	0.71	0.80
50	0.63	0.76
55	0.55	0.71
60	0.45	0.65
65	-	0.60
70	-	0.53
75	-	0.46

In practice, the cable length is very important and sometimes causes larger cable to be used. Because long cables may cause considerable voltage drop and the voltage at the load end can become out of the limits. Therefore, the voltage drop should also be taken into account.

7.2.2 Voltage Drop

When current flows through the cable a small voltage drop occurs between both ends of the cable according to the Ohm's Law, i.e., V=IR. As the voltage drop increases, the load gets lower operating voltage, and in turn, it may cause dim or flickering of lights, hot running of motors or devices may stop operation to protect itself from low or fluctuating voltages. On the other hand, more voltage drop means more dissipated power in the cable that increases the temperature of the cable conductor, which reduces the current carrying capacity of cable. As the cross-section area of cable increases, its ohmic resistance decreases that result in lower voltage drop and lower power dissipation. However, increasing the size of cable also increases the weight, volume and cost of cabling. Therefore, optimum cable size is important for an electrical installation.

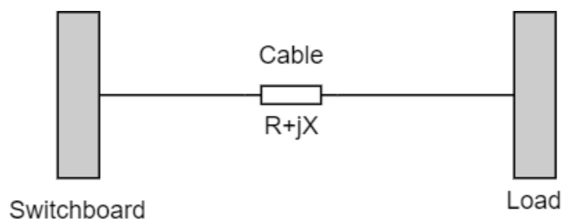

Fig. 7.3

The voltage drop occurs on the cable impedance which includes resistance R and reactance X as shown Fig. 7.3. If we assume that the Us is the source voltage and Ur is load voltage, the phasor diagram of voltage drop can be illustrated as shown in Fig. 7.4. The load power angle ϕ is inductive. The voltage drop in the cable can be expressed as following formula:

$$\Delta V = I\left(R\cos\phi + X\sin\phi\right) + U_s - \sqrt{U_s^2 - \left(IX\cos\phi - IR\sin\phi\right)^2}$$

where I is the current passing through the cable impedance. However, this formula can be simplified more for hand calculations since the last two term of the formula has small effect on the result.

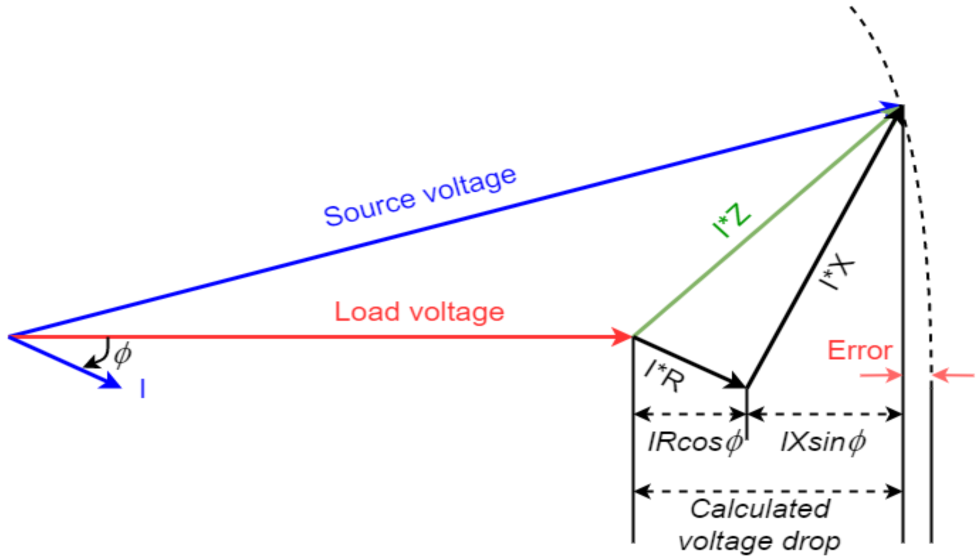

Fig. 7.4

Therefore, the following formula is obtained,

$$\Delta V = I\left(R_c\cos\phi + X_c\sin\phi\right)$$

The simplification error in voltage drop calculation is indicated in Fig. 7.4 which is very small. The percent voltage drop can be obtained by dividing ΔV to the nominal line voltage,

$$e(\%) = \frac{\Delta V}{U_s}$$

The cable resistance R and reactance X values can be obtained from the manufacturer datasheets. Generally, they are given as per Ω/km like an example shown in Table 7.10. The conductor resistance varies with operating temperature and the following equation can be used for conversion,

$$R = R_{ref}\left[1+\alpha\left(T-T_{ref}\right)\right]$$

where α is the temperature coefficient of wire, which is α=0.00393 for copper and α=0.00403 for aluminium conductors.

Table 7.10: Copper cable resistance and reactance values in Ω/km at 80°C

Cable Size, S (mm2)	Single Core Cable @ 80°C		Multi Core Cable @ 80°C	
	R(Ω/km)	X (Ω/km)	R(Ω/km)	X(Ω/km)
1.5	14.8	0.168	15.1	0.118
2.5	8.91	0.156	9.08	0.109
4	5.57	0.143	5.68	0.101
6	3.71	0.135	3.78	0.0955
10	2.24	0.119	2.27	0.0861
16	1.41	0.112	1.43	0.0817
25	0.889	0.106	0.907	0.0813
35	0.641	0.101	0.654	0.0783
50	0.473	0.101	0.483	0.0779
70	0.328	0.0965	0.334	0.0751
95	0.236	0.0975	0.241	0.0762
120	0.188	0.0939	0.191	0.074
150	0.153	0.0928	0.157	0.0745
185	0.123	0.0908	0.125	0.0742
240	0.0943	0.0902	0.0966	0.0752
300	0.0761	0.0895	0.078	0.075

If the resistance is unknown, the approximated value can be found according to Annex G in IEC 60502-1 using the following equation;

$$R_c = \frac{0.0225L}{s} \quad \Omega / km$$

where L, is length of cable in km and s, is the cross-section area of the cable conductor in mm^2.

It is seen from Table 7.10 that, the reactance X is greater for small size cables. However, the effect of X decreases due to decrease of R/X ratio in small sized cables. On the other hand, for large size cables, reactance gets smaller and becomes saturated at a certain value. Despite its

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small value, its effect is significant; therefore, IEC 60502-1 assumes reactance constant for all cables at low voltage as following value.

$$X_c = 0.08 \ \Omega / km$$

7.2.2.1 Voltage drop calculation in single phase circuits

The maximum load current in single phase load can be calculated using

$$I = \frac{P}{U\cos\phi}$$

where P is load maximum active power, cosϕ is load power factor. The voltage drop is calculated as follows,

$$\Delta V = I(2L)(R_c\cos\phi + X_c\sin\phi)$$

The cable length is multiplied by 2 since both phase and neutral conductors cause voltage drop. The unit of L is in km. The percent voltage drop is then calculated using the following formula,

$$e(\%) = \frac{\Delta V}{U}\times 100 = \frac{2IL(R_c\cos\phi + X_c\sin\phi)}{U}\times 100$$

Example:

Find the voltage drop on a 2 core 6 mm^2 PVC cable with length of 25m distance installed between the switchboard and the EVSE. The EVSE operates at unity power factor and needs 7kW maximum power at single-phase. The cable AC resistance and reactance per km at 80° are R=3.78 Ω/km and X=0.0955 Ω/km, respectively.

Solution:

First, the EVSE maximum current is calculated.

$$I = \frac{P}{U\cos\phi} = \frac{7000}{(230)(1)} = 30.4A$$

Then the voltage drop can be found as follows

$$\Delta V = I(2L)(R_c \cos\phi + X_c \sin\phi)$$
$$= (30.4)(2)(0.025)((3.78)(1) + (0.0955)(0)) = 5.75V$$

The percent voltage drop is

$$e(\%) = \frac{\Delta V}{U} \times 100 = \frac{5.75}{230} \times 100 = 2.5\%$$

7.2.2.2 Voltage Drop Calculation in Three Phase grid

In three phase systems, the maximum phase current can be calculated using maximum load power of P, as follows

$$I = \frac{P}{\sqrt{3} U_{LL} \cos\phi}$$

where U_{LL} is the line-line voltage and $\cos\phi$ is load power factor. The voltage drop can be expressed as,

$$\Delta V = \sqrt{3} IL(R_c \cos\phi + X_c \sin\phi)$$

The unit of L is in km. The voltage drop is multiplied by √3 to make ΔV correspond to phase-phase voltage. Therefore, percent voltage drop is,

$$e(\%) = \frac{\Delta V}{U_{LL}} \times 100$$

Example:

A 4 core PVC cable 25 mm² is selected to feed a 3-phase/400V/65 kW load at distance 50m. The load power factor is 0.85. Calculate the voltage drop in Volts and express it as percent of rated voltage.

Solution:

The load is balanced and thus the maximum phase current is,

$$I = \frac{P}{\sqrt{3} U_{ll} \cos\phi} = \frac{65000}{\sqrt{3}(400)(0.85)} = 110.4A$$

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The cable resistance and reactance can be taken from Table 7.10 as R=0.907 Ω/km and X=0.0813 Ω/km. Then the voltage drop can be found as,

$$\Delta V = \sqrt{3}(110.4)(0.050)\left[(0.907)(0.85)+(0.0813)(0.527)\right] = 7.78V$$

The percent voltage drop is

$$e(\%) = \frac{\Delta V}{U}\times 100 = \frac{7.78}{400}\times 100 = 1.95\%$$

7.2.3 Cable Selection

Insufficient cable can result in the risk of electric shock, fire or equipment damage, and it may also prevent fuses and other safety equipment from working properly. Oversizing the cables significantly increase the installation costs. Therefore, optimum selection of cable size is essential part of electrical installation.

Considering the safety and cost factors, there are two important parameters when selecting the cable cross-section: Current carrying capacity and voltage drop. The selected cable must fulfil both of these conditions as shown in Fig. 7.5.

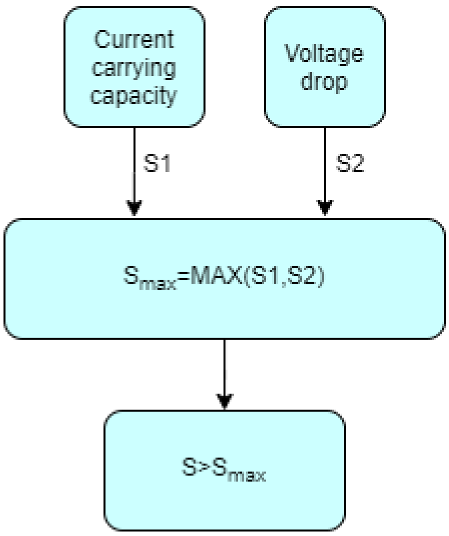

Fig. 7.5

The first step of cable selection is determining the maximum current (I_{load}) that will flow through the cable as worst case. As mentioned before in Section 7.2.1, the mechanical installation of a cable is very important in selection process. The ampacity of a cable depends on the installation method, thus the installation method which best fit the application should be determined from Table 7.3. After that, the ampacity of cable can be selected from corresponding ampacity tables, such as the Table 7.4,

Table 7.5, Table 7.6 orTable 7.7. The ampacity of the cable must be higher than the load maximum current.

The stress on the cable is maximum at short circuit, therefore, the selected cable must withstand to this current safely before the circuit breaker breaks the current. In generally, the miniature circuit breakers (MCB) are used in EVSE installation, and they break the circuit when current reach $>1.45xI_n$. Since the power cables can withstand 1.45 times of its ampacity value, the MCB protects the cable from the short circuit. But it should be remembered that, for proper operation, the MCB nominal current should be selected lower than the cable ampacity value.

The second step of cable selection is to calculate the voltage drop. The maximum permitted voltage drop may vary from one country to another. Typical values for IEC 60364-5-52 is given in Table 7.11. In low voltage applications, the total voltage drop from the distribution system to anywhere in the installation should be kept below 5% of the full line voltage for power applications. This value can be increased by 0.005% per meter beyond 100 meters provided that they are not greater than 0.5%. If the voltage drop calculated is higher than these limits, then conductor cross section should be increased.

Table 7.11: Typical voltage drop limits

Type of installation	Lighting circuits	Other uses (heating and power)
Low voltage installation supplied directly from a public low voltage distribution system	3%	5%
Low voltage installation supplied from private LV supply	6%	8%

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For example, in residential EVSE installation, 3% of voltage drop may be suitable from the energy meter to the EVSE installation point. Hence, 2% of voltage drop is reserved from distribution point to home energy meter, and total drop becomes 5% as suggested by IEC 60364-5-52. If the installation starts from private distribution transformer, in this case, the total voltage drop can be up to 8%.

If there is a risk of explosion, i.e., presence of explosive materials or dust, in the installation area, the current-carrying capacity of cable should be reduced by a certain factor described in standard IEC 60079.

Example:

A single phase 7 kW Level 1 EV charger will be installed in a parking lot. The nearest switchboard distance is 75m away and the PVC cable in conduit ducting underground needs to be used. Unity power factor is assumed for the EVSE. The Ground temperature is taken as 25 °C. Determine the suitable cross-section for the cable by providing 3% voltage drop maximum.

Solution:

The nominal load current should be calculated first, as follows;

$$I = \frac{P}{U\cos\phi} = \frac{7000}{(230)(1)} = 30.4\,A$$

The design temperature is different than 20°C of ground installation. Therefore, temperature compensation should be done using Table 7.9. For 25°C the compensation coefficient is obtained as 0.95, therefore, cable ampacity value must be at least

$$Ampacity = \frac{30.4}{0.95} = 32\,A$$

The installation type is D1 is found from in Table 7.3. Since the PVC cable has more than two cores, then from the column D1 in Table 7.6, the minimum cross-section that can carry the load current of 32A is found as 6 mm2. But 3% voltage drop requirement must be checked before deciding the cable cross-section. The 6 mm2 cable AC resistance and reactance per km at 80° are found as R=3.78 Ω/km and X=0.0955 Ω/km from Table 7.10. Then the voltage drop is

$$\Delta V = I(2L)(R_c \cos\phi + X_c \sin\phi)$$
$$= (30.4)(2)(0.075)\left[(3.78)(1) + (0.0955)(0)\right] = 17.4V$$

As a percent voltage drop,

$$e(\%) = \frac{\Delta V}{U} \times 100 = \frac{17.4}{230} \times 100 = 7.56\%$$

This value is considerable greater than the 3% limit. Therefore, cable of 6 mm^2 is not suitable and the larger cross-section should be preferred. Let's select the next larger cross-section which is 10 mm2. Its AC resistance and reactance values are found as R=2.27 Ω/km and X=0.0861 Ω/km from Table 7.10. Then the voltage drop is

$$\Delta V = I(2L)(R_c \cos\phi + X_c \sin\phi)$$
$$= (30.4)(2)(0.075)\left[(2.27)(1) + (0.0861)(0)\right] = 10.4V$$

As a percent voltage drop,

$$e(\%) = \frac{\Delta V}{U} \times 100 = \frac{10.4}{230} \times 100 = 4.5\%$$

This value is still greater than the 3% limit. Therefore, the next larger cross-section which is 16 mm2 should be checked. Its AC resistance and reactance values are found as R=1.43 Ω/km and X=0.0817 Ω/km from Table 7.10. Then the voltage drop is

$$\Delta V = I(2L)(R_c \cos\phi + X_c \sin\phi)$$
$$= (30.4)(2)(0.075)\left[(1.43)(1) + (0.0817)(0)\right] = 6.52V$$

As a percent voltage drop,

$$e(\%) = \frac{\Delta V}{U} \times 100 = \frac{6.52}{230} \times 100 = 2.83\%$$

This value fulfils the 3% voltage drop limits, and therefore, the EVSE can be connected to the grid via 3x16 mm^2 underground PVC cable.

In Table 7.12, the maximum cable length for 3% and 5% voltage drop limits are listed for various charging power and cable conditions as a reference value. For this table, the cable impedances given in Table 7.10 are used and the EVSE power factor is assumed as unity. As seen from the table, the cable size needs to be increased for long distances due to the voltage drop requirement, even the ampacity of cable is enough. For this reason, it is important to install the charging station close to the power grid in order to keep installation cost and labour requirements at low level.

Table 7.12: Maximum cable length for various installations

AC grid	Max. Charging Power/Current	Cable size (copper)	Max. cable length for 3% voltage drop [m]	Max. cable length for 5% voltage drop [m]
Single phase 230V/50Hz	3.7 kW/16 A	2.5 mm^2	22	37
		4 mm^2	36	61
		6 mm^2	55	92
	7.4 kW/32 A	6 mm^2	27	45
		10 mm^2	45	76
		16 mm^2	72	121
Three phase 400V/50Hz	11 kW/16 A	2.5 mm^2	41	68
		4 mm^2	64	108
		6 mm^2	99	165
	22 kW/32 A	6 mm^2	49	82
		10 mm^2	82	137
		16 mm^2	131	218

When installing the charge station indoors, the EVSE should be located close to EV in order to keep the charge cable as short as possible. Some of EVSE has some fixture to wind up the cable if it is long (See Fig. 6.1). In order to avoid long cables, pole mount option near the EV parking area can be considered. The EVSE mounting height should be between 0.5m and 1.5m to protect EVSE from car hit.

The EVSE should not be placed near faucet, especially if puddle can occur under the EVSE. Water may cause serious hazards in electrical installation.

Some of the EVSE needs ventilation. Therefore, if the EVSE is installed in a garage, proper ventilation equipment should be installed permanently. The ventilation should take fresh outdoor air inside. However, the ventilation system increases the installation cost. For this reason check the EVSE user guide if it is need a ventilation system. For outdoor installing no ventilation is required.

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7.3 Fuses and Circuit Breakers

In an electrical circuit, the current may increase to extremely high value (mostly to kA level) when a fault is occurred. Such a high current causes high-power dissipation in the cable that creates extremely high heat in the cable and may melt the cable conductor or even cause a fire. In order to reduce the stress on the cable and on insulating material, this fault current must be removed as fast as possible. The fuses and circuit breakers limit the dissipated power in fault section of the electrical installations, and protect the equipment and cables in a safe way.

7.3.1 Melting type fuses

In order to protect the equipment from a high current fault stress, a short thin wire is added to the current flow path as shown in Fig. 7.6(a). The wire conducts normal operating current without interruption. But excessive current melts the thin wire, and it becomes open circuit, and thus clears the fault current very fast. This is the basic operating principles of melting fuses. The fuses should be inside of an enclosure to prevent melting particle to spread around which may damage closer objects or may create fire. For this reason, a fuses is never be replaced by a simple wire. Additionally, the melting current level of a conductor is strongly depends on the environmental condition (temperature and humidity). Therefore, the housing of fuse provides suitable environmental conditions for proper operation, and thus it operates as close as design specifications of fuse.

IEC 60269 defines technical standards for low voltage power fuses. Standard identifies two digit application category code as follows;

1st digit

a: Fuse is designed for short-circuit protection only and generally acting very fast. It cannot be used for overload. Additional device is required for overload protection.

g: Fuse is designed for both overload and short-circuit protection. It is considered general-purpose fuses for protection of wires.

2nd digit

G: General purpose protection of wires and cables
M: Motors
PV: Solar photovoltaic arrays as per 60269-6
R, S: Rectifiers or semiconductors as per 60269-5
Tr: Transformers

For example, the aR and gR markings belongs to fast acting fuses for semiconductor devices; aR protects for only short-circuit protection, gR for full protection. aM and gM fuses are slow type and for protection of motor loads in the same manner. gG fuses are for general purposes like as power cable protection. There are also special purpose fuses, such as gPV for solar photovoltaic array protection, gTr for protection power transformers etc. Mostly seen fuse types in electrical circuits are shown in Fig. 7.6 (b) and (c); such as cartridge type and NH type, respectively.

(a) (b) (c)

Fig. 7.6 Fuses a) fuse structure b) glass type, b) NH type

A typical time-current characteristic of a melting fuse is shown in Fig. 7.7. It is seen that the fuse can operate at rated current I_n continuously. If the current increases beyond the trip current, the fuse breaks. The breaking time reduces significantly as current increases since the melting energy (I^2t) is proportional to square of fuse current. As the current increases, the melting energy increases rapidly. For fast blowing fuses, time required for melting is considerable lower than slow blowing fuses.

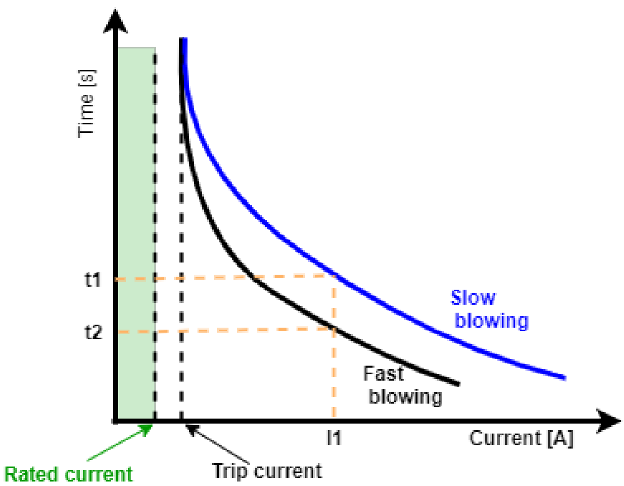

Fig. 7.7 Typical time-current characteristic of a fuse

7.3.2 Miniature Circuit Breaker (MCB)

The MCB is electro-mechanical device that protect the equipment in electrical installation from over current and short circuit stress as similar to fuses. The main advantage of MCBs is that they can be used many times by resetting it via lever (See Fig. 7.8). They are much safer to use and operate since all conductors are isolated by plastic housing.

The most of the MCBs have two different operating characteristics; thermal and magnetic. These MCBs are called as thermal-magnetic MCB. In thermal characteristic, a bimetal is used to trip the breaker. As current increases, the bimetal heats and bends more and more. When it reaches to rated current, the displacement of bimetal is enough to mechanically trip the breaker mechanism. In magnetic characteristics, there is a coil in the MCB which works as like an electromagnet. The main current pass through the coil, and when it reaches a certain value, the electromagnet attract a mechanical trigger which trips the breaker mechanism. Magnetic response of an MCB is significantly faster than the thermal response. Therefore, thermal characteristics covers overload protection and magnetic characteristics covers short circuit protection in an MCB.

There are 5 types of MCBs according to the short circuit tripping characteristics (e.g. magnetic characteristics) as listed in Table 7.13. The thermal characteristics of all MCB types are same, but the magnetic characteristics are different among the MCB types. Type A MCB immediately cut off the circuit if the current is higher than 3 times of rated current. Type B is used in domestic applications. Type D has the highest current tripping level and then it is preferred for motor applications since the initial start-up current for motors can be very high. The time-current curves of MCB types are shown in Fig. 7.9. All three types of MCBs provide tripping protection within one tenth of a second. Red lines in the graph show the thermal characteristics of the MCB which are same for all types.

Table 7.13

Type	Thermic breaker		Magnetic breaker	
	Trip current	**Tripping time**	**Trip current**	**Tripping time**
A	1.13...1.45*In	<1h	2...3*In	<0.1s

B			3...5*In	
C			5...10*In	
D			10...20*In	

Fig. 7.8 [13]

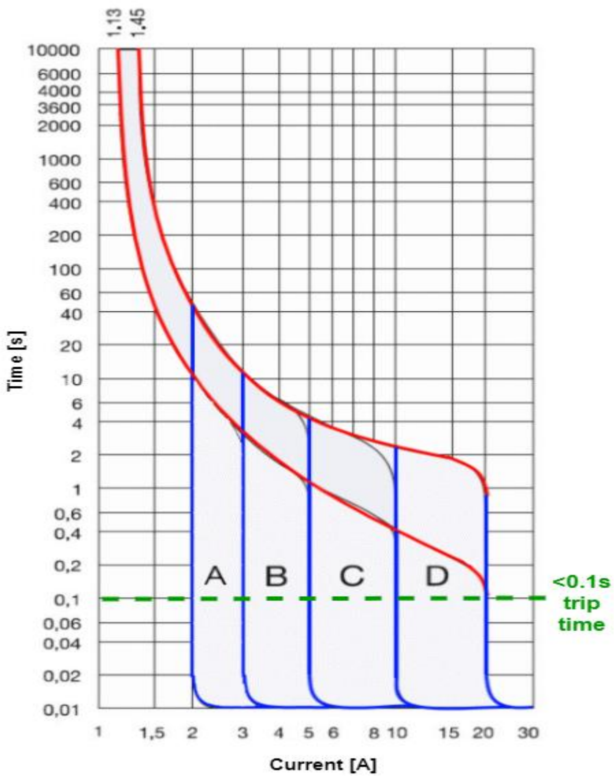

Fig. 7.9

7.3.3 Residual Current Circuit Breaker (RCCB)

An RCCB, or RCD (Residual Current Device), is a protection device against electric shock and fire. It continuously monitors load current, if it detects electricity flowing down an unintended path, such as through a person who has touched a live part, or through any leakage path, the RCCB will quickly disconnect all live conductors including the neutral, which significantly reduces the risk of death or serious injury or fire. Trip level for leakage current in an RCCB is 30 mA for residential applications. It should be noted that an RCCB are unable to detect or respond to overcurrent or short circuit. Therefore, an RCCB together with an MCB (Miniature Circuit Breaker) protect people, equipment and building against overcurrent, short circuit and earth leakage problems. Today there are devices in the market which provide the combined function of both RCCB and MCB.

Operating principle of RCCB is shown in Fig. 7.10(a) where the toroidal core has 3 windings; two identical main coils and one search coil. The current must be in a loop in an electrical circuit, therefore, I_p and I_n must be equal to each other in normal operation. In this case, the magnetic fields created by the main coils cancel each other since their current directions are opposite, hence the net magnetic field in the toroid is zero, and no voltage induced in the search coil. Therefore, trip coil is not energized and load is supplied with AC power.

If any earth leakage current present in the circuit as shown in Fig. 7.10(b), in this case a net magnetic fields remain in the core which is detected by search coil and main contacts is turned-off and then the leakage path is interrupted. If the current difference of $\Delta I=I_p-I_n$ is higher than the trigger level of 30 mA, the RCD breaks the circuit. An RCD is also trigger if the operating current exceeds the $5I_n$ for more than 40 ms to protect the load and its internal wires.

An RCCB must trip in 300 ms at its rated sensitivity, i.e., 30 mA. When the leakage current is 5 times higher than the rated sensitivity, it should trip in 40 ms. Moreover, a 10mA RCCB must always trip within 40 ms regardless of the test current.

In all RCDs, there is a test button to check whether the RCD operates properly. By pushing the test button, a resistor is connected between L and N, but one end is connected before the toroid, and other end is connected after the toroid as shown in Fig. 7.10(c). Thus test resistor creates a current difference between the main coils that triggers the main contact without need a real leakage current.

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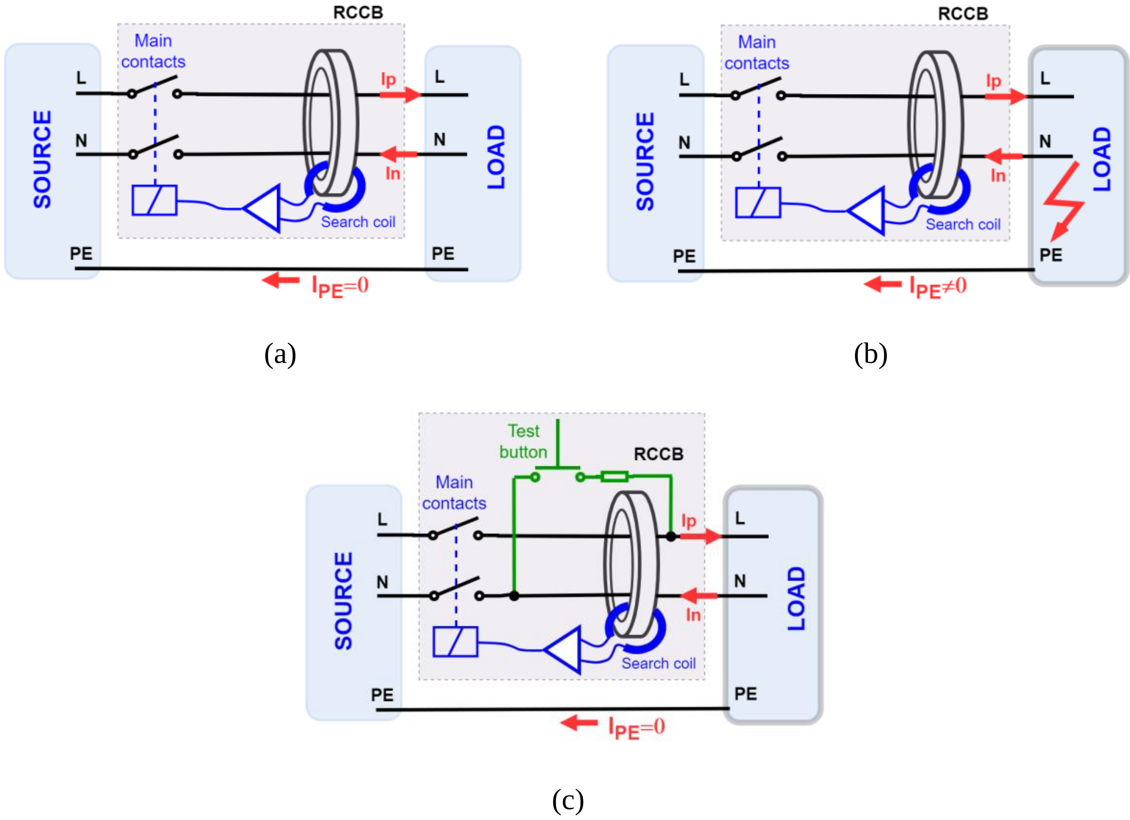

Fig. 7.10 RCD operation circuit a) normal operation, b) earth leakage c) test

A front view of a typical RCCB is shown in Fig. 7.11. The RCCB devices are classified as Type AC, Type A, Type F and Type B as listed in Table 7.14. These types should not be confused with MCBs of type A, B, C and D which are related to time-current characteristics of MCB. The RCCB classifications are made as follows according to the leakage current waveform that can be detected by the device:

- **Type AC** is tripping for AC residual currents only,
- **Type A** is tripping for AC and pulsating DC residual currents,
- **Type F** is tripping additionally mixed frequency residual currents 10Hz< 1kHz for loads with single-phase inverters and similar high frequency domestic/industrial equipment.
- **Type B** is tripping for AC, pulsating DC, high frequency AC and Smooth DC (6 mA) leakage currents.

Fig. 7.11 front view an RCD [9]

According to EN 62423, Type-AC RCCB can only detect the sinusoidal AC leakage current. For most of the condition, Type AC is enough in electrical installation, for example residential use and industrial machines etc. However, if there is any possibility of DC leakage current, Type-AC may fail to trip since the DC leakage current can saturate the magnetic core of device. In this case, Type-A RCCB can be used since it can work with superimposed DC residual current up to 6 mA. In addition to the features of Type-A RCCB, Type-F can also detect the high frequency leakage currents caused by the DC-AC inverters with superimposed DC residual current up to 10 mA. In addition to the Type-F features, the Type-B RCCBs can also trip for smooth DC leakage current up to 6 mA.

The EV's on-board chargers generally include an AC-DC high frequency converter, which may cause a smooth DC leakage current. For this reason, IEC 62955:2018 requires RCCB protection for sinusoidal AC, pulsating AC and also 6 mA smooth DC leakage currents, all of which are covered by Type-B RCCB. However Type-B RCCB may increase the installation cost significantly. On the other hand, IEC 61851-1:2019 standard requires RCD Type-B, or RCD Type-A plus appropriate equipment against DC fault current above 6 mA. Therefore, some of the EVSE manufacturers add a 6 mA residual smooth DC current detection circuit inside the EVSE. Therefore, a relatively cheap Type-A or Type-F RCCB, together with the built-in smooth DC leakage detection circuit, fulfils the requirements of IEC 61851-1:2019.

Table 7.14 RCD types

		Type of RCD			
Leakage waveform	Symbol	Type AC	Type A	Type F	Type B
AC 50/60 Hz		*	*	*	*
Pulsating current with DC component			*	*	*
Multi-frequency current, 10Hz< 1kHz				*	*
Smooth DC current					*

Some of the RCDs do not have an internal overcurrent circuit breaker which is called as RCBO. The titles of related standards for RCD products are as follows:

- IEC 61008-1: Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCBs) – General rules
- IEC 61009-1: Residual current operated circuit-breakers with integral overcurrent protection for household and similar uses (RCBOs) – General rules
- IEC 60947-2: Low Voltage Switchgear and Control gear – Circuit Breakers
- IEC 62423 ed.2: Type F and type B residual current operated circuit-breakers with and without integral overcurrent protection for household and similar uses
- IEC 62020: Electrical accessories – Residual current monitors for household and similar uses (RCMs)
- IEC/TR 60755 ed 2: General requirements for residual current operated protective devices
- IEC/TR 62350: Guidance for the correct use of residual current-operated protective devices (RCDs) for household and similar use.
- IEC 62955:2018: Residual direct current detecting device (RDC-DD) to be used for mode 3 charging of electric vehicles

- IEC 61851-1:2019: Electric vehicle conductive charging system, Part 1: General requirements

7.3.4 Arc Fault Detection Device

A gas discharge may occur when air is subjected to strong electric field that is called as arc. Loosening of electrical connections, aging of insulation in cables, break in or damaging a cable, defective wall plugs, rodent biting cables or aging of equipment etc. can cause electrical arcs. If an arc occurs continuously, its internal temperature can reach to 5000-15000 °C which is an important factor causing an electrical fire [1].

The arc fault cannot be detected by traditional overload circuit breakers since the current is lower than trip level. On the other hand, RCDs do not protect against an arc fault too. Therefore, additional dedicated protection device is needed, which is called as Arc Fault Detection Device (AFDD) or Arc Fault Circuit Interrupter (AFCI). The International Electrotechnical Commission (IEC) published the International Standard, IEC 62606 in 2013 titled "General Requirements for Arc Fault Detection Appliances (AFDD)".

The operating principal of an AFDD (or AFCI) is based on signal processing. AFDD detects the current and voltage simultaneously and analyse their waveforms and harmonic frequency components in order to look for inconsistent current waveforms in different half cycles under arc fault conditions. If any arc pattern is recognized the breaker is switched off as shown in Fig. 7.12.

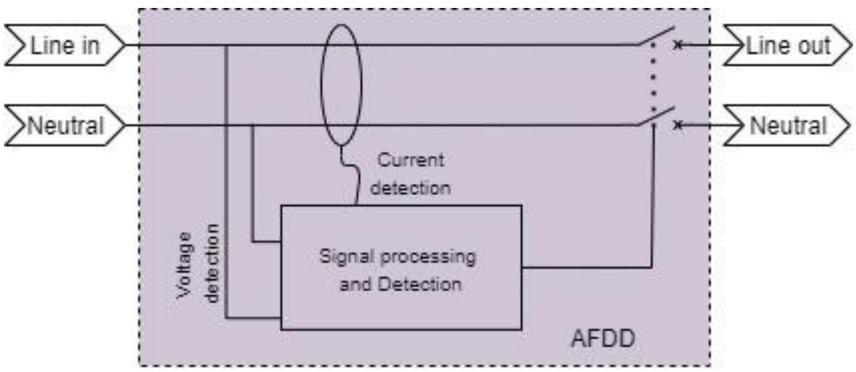

Fig. 7.12

If AFDD is more sensitive, these devices may accidentally break the circuit during normal operation of some loads, such as vacuum cleaners, brushed motors, or during lightning strikes etc. This annoyance may prevent it to be installed in an electrical system. But for maximum safety against electrical fire, an AFDD is important device. For instance, in EV charging case, plugs, sockets and cables are used every day. The cable insulation material may lose effectiveness, plugs and sockets may have bad contact and arcing in time, which are potential factors for electrical fire. Today, some companies have products in which there are MCB, RCD and AFDD at the same time. The protection of these devices are seen in the Table 7.15

Table 7.15

Fault type	**Short Circuit**	**Overload**	**Residual Current**	**Arc Fault**
Line-Line	MCB	MCB	-	-
Line-Neutral	MCB	MCB	-	AFDD
Line-Earth	MCB	MCB	RCD/RCCB	RCD/RCCB/AFDD

7.4 Earthing Systems

Although it is an indispensable part of our daily life, the electric energy can cause severe electrical shock or even death if it is not properly installed or isolated. Earthing system is important to protect people from electric shock or to prevent possible fire.

In any electrical installation of utility grid, the Earth potential is taken as a reference potential due to safety concerns. There are three different earthing methods for low voltage electric circuit today, such as TT, TN and IT. The first letter in the names can be T or I, and indicates whether the neutral point of transformer is connected to earth.

- T (Terra): Neutral point is connected to the ground
- I (Isolation): Neutral point is insulated from ground

The second letter can be T or N, and indicates the connection status of the electrical devices to the ground.

- T (Terra): Bonded to ground
- N (Neutral): Connected to the neutral line

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The protection characteristics are different among the earthing methods, thus the electricity code of all countries defines one of them for a specific application. TT, TN and IT earthing systems are explained in detail in the following sections.

7.4.1 TT Earthing System

In TT earthing system, the neutral point of utility distribution transformer is connected directly to the earth as shown in Fig. 7.13. On the other hand, in consumer side, the PE (protective earth) conductor is separately earthed by a grounding rod or plate as shown in Fig. 7.13. All exposed conductive parts of equipment are connected to the PE.

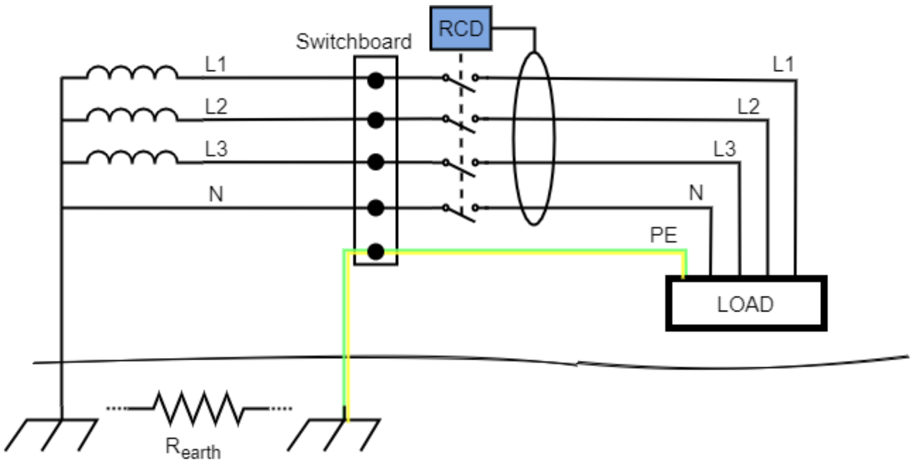

Fig. 7.13 TT earthing system

If any phase-to-phase or phase-to-neutral short circuit occurs in the installation, the very high current starts to flow through the path including fuses (or overcurrent circuit breakers). Then fuse opens the circuit and protects the system. Similarly, when an isolation fault to the chassis occurs in the equipment, same fuses must open the circuit as fast as possible to protect people from electric choke. As can be seen in the Fig. 7.13, any isolation fault causes a current flow through the PE conductor and Earth resistance R_{earth}. If this resistance is not small enough, for example due to corrosion in earthing rod etc., the fault current can become lower than the rated interrupting current of fuse then fault current cannot be interrupted. In order to prevent that there is maximum limits for R_{earth} value.

If the safe voltage level against electrical shock is assumed as 50V and the fuse interrupting current level is I_a, then earth resistance must be lower than the following value,

$$R_{earth,\max} \leq \frac{50}{I_a}$$

If the value of Earth resistance is lower than $R_{earth.max}$ value, the potential of equipment chassis will be lower than the safe voltage level of 50V. Therefore, during the time between fault occurrence and fuse interrupt, this safe voltage level prevents people from serious electric shock. On the other hand, it should be noted that, $R_{earth.max}$ value is not a constant for all applications, it depends on the fuse interrupting current value. For example, the interrupting current value of a Type B MCB is 3 times of nominal current, i.e., if In=16A then Ia=3*In=3*16=48A therefore

$$R_{earth} \leq \frac{50}{48} = 1.04\Omega$$

If Earth resistance is higher than this value, the In=16A fuse may not trigger instantly and protective function doesn't work.

In freshly installed systems, earth resistance can be low enough, but as years passed, the earth resistance can increase. This situation creates serious safety problem. For this reason an RCD is also employed in the TT system as shown in Fig. 7.13. For example, an RCD device opens the circuit when 30 mA leakage current is detected. Therefore,

$$R_{earth} \leq \frac{50V}{30mA} = 1667\Omega$$

is obtained. Therefore, the protection functionality of the TT earthing is increased to a safe level by using an RCD. For this reason, an RCD protection is obligatory for electrical installations, especially for domestic installation, in most of the countries.

However, some loads, which have high leakage current during normal operation, require an isolation transformer or specific RCDs. By installing separate RCDs in series to loads, selective interruption can be obtained.

As a summary, in TT systems, any single isolation fault results in an interruption in supply of power. The leakage fault current must be higher than the circuit breaker nominal interrupting current. For this requirement the $R_{earth.max}$ resistance needs to be very low and it is difficult to

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obtain practically. Therefore, protection is ensured by special devices, such as a residual current device (RCD) which also prevents the risk of fire.

7.4.2 TN Earthing System

In TN earthing systems, the utility side is exactly same as for the TT system. However, all exposed conductive parts of equipment are not directly connected to the earth ground as TT system; but instead it is connected directly to utility earth point via a dedicated conductor. There is no earth resistance R_{earth} in the current path, and therefore, in any isolation fault results in high fault current due to low impedance, and consequently low earth resistance requirement is not needed for TN earthing systems.

There are 3 type of TN systems; TN-C, TN-S and TN-S-C according to the arrangement of the neutral and protective ground conductors. The meaning of letters are C = Combine (combined), S = Separate (split).

7.4.2.1 TN-S Earthing System:

The protective earth conductor is separated throughout the system as shown in Fig. 7.14. However, this system requires extra and long conductor for PE from transformer to the installation point and that increases the installation cost. Therefore, it can be used for short distances if it needed.

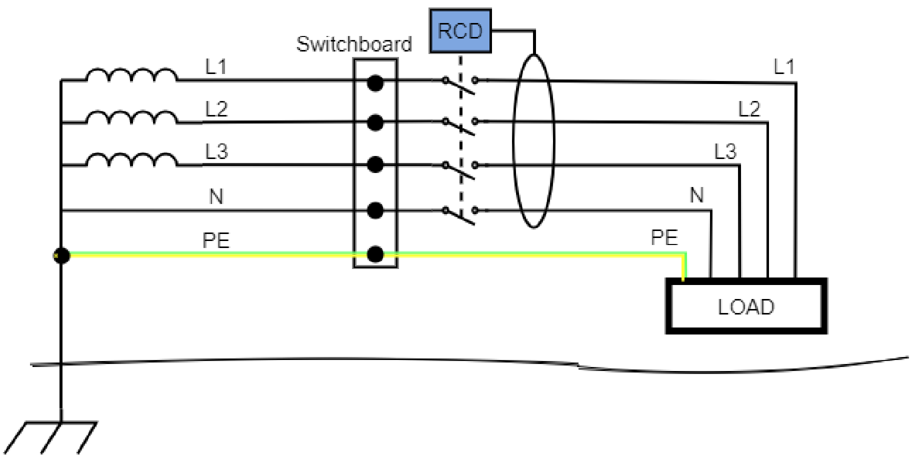


Fig. 7.14

7.4.2.2 TN-C Earthing System:

The neutral and protective earth conductors are combined in a single conductor throughout the system as shown in Fig. 7.15. This conductor is named as PEN. Normally this configuration is used for distribution networks only. It is not suitable for equipment grounding. The TN-C-S earthing system combines TN-C and TN-S as described in the next definition

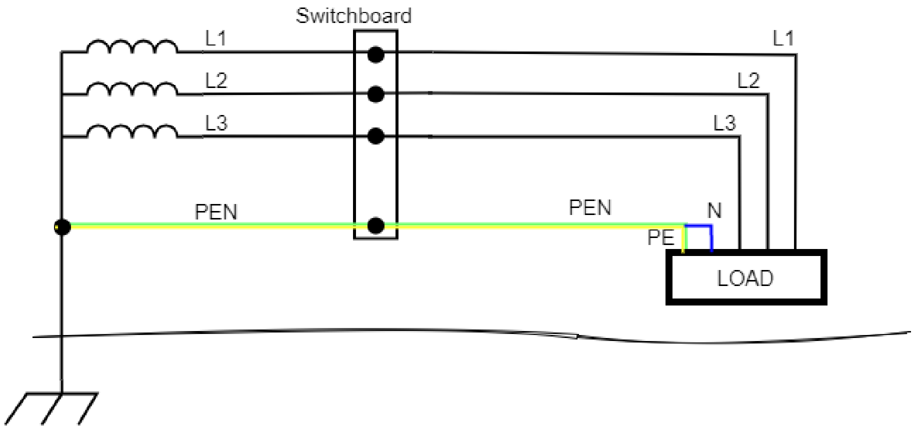


Fig. 7.15

7.4.2.3 TN-C-S Earthing System:

In TN-C-S earthing system, neutral (N) and protective earth (PE) functions are combined in a single conductor, i.e., PEN conductor. The PEN extends from transformer to the building distribution point as in the TN-C system. In the switchboard of building distribution point, it is separated into PE and N conductors similar to a TN-S system as shown in Fig. 7.17. Any isolation fault between one phase and conductive parts of equipment creates high current due to low impedance in the current path. Therefore, the smallest fuse in the circuit is triggered and de-energizes the circuit. But what if there is any disconnection or break in PEN or PE conductors? These are weak points of TN-C-S systems, therefore, it is worth to analyse them in detail.

For example, let's assume that PE conductor is broken and a leakage fault between L1 and chassis of equipment is occurred. The fuse cannot interrupt the circuit in this case since there is no low impedance path for the fault current. In this fault, the metal chassis of equipment will be live, and any touch of a person to chassis will cause electric shock. Adding an RCD before equipment power connection protects people from this dangerous condition, since it detects the leakage current if it is greater than >30 mA then disconnects the circuit.

When the PEN conductor is broken, unfortunately, an RCD cannot prevent from electric shock since the current flows in both the line and neutral conductors and consequently there is no imbalance to cause operation of the RCD. More dangerously, broken PEN causes the chassis of equipment will be live even no isolation fault exists in the installation as shown Fig. 7.17. Therefore, the broken PEN conductor is the most dangerous fault in the TN-C-S systems since the electric shock is inevitable. In this case an additional device, which can detect the broken PEN and disconnects the circuit, is essential. For example, the voltage between protective earth (PE) and real earth (Ground) is greater than 70 V may show the PEN is broken. If the supply voltage is outside of the range 207Vrms < $V_{Line\text{-}Notr}$ < 253V, that can indicate some problems with the PEN conductor. A device checking the above conditions or more continuously can prevent hazardous condition arising from PEN conductor disconnection. Alternatively, an additional earth electrode can be installed in the equipment side, i.e., TT system is obtained.

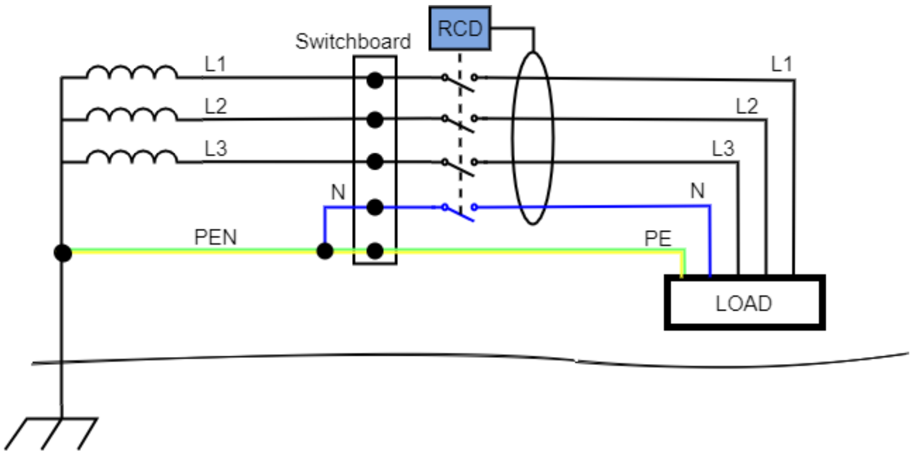


Fig. 7.16

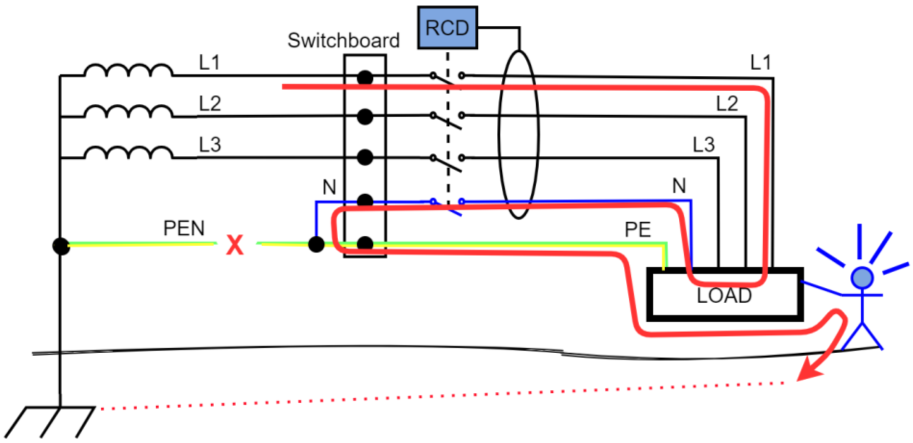


Fig. 7.17

7.4.3 IT Earthing System

The main idea behind the IT system is that a single fault cannot interrupt the power source, i.e., the voltage supply is maintained and therefore, devices connected to the supply is still operating. For this reason, IT earthing systems is used to power the critical areas in a hospital; such as operating rooms, intensive care rooms, premature childbirth rooms, angiography examination etc.

In IT earthing systems, the isolation monitoring device should be used. Overcurrent protective devices and RCDs are permitted. A first ground fault will not cause a fuse or RCD/GFCI to trip. This increases the power availability. A ground-fault monitoring device will detect and signal an impermissible deterioration in insulation. A ground fault should be eliminated as quickly as possible before a second ground fault can occur on a different live conductor, as this would cause the system to fail.

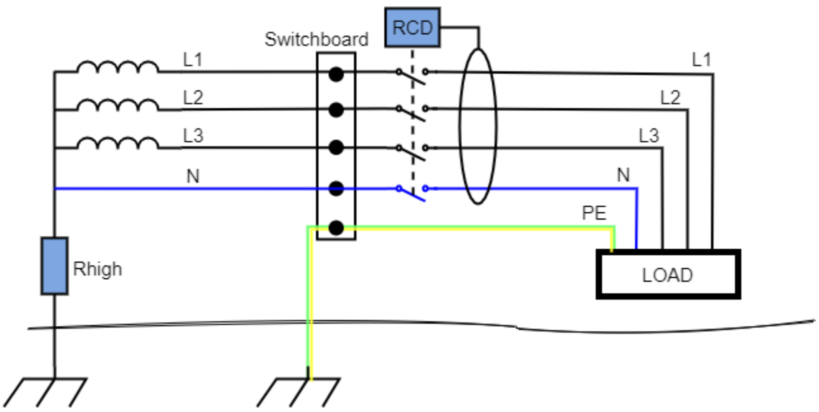


Fig. 7.18

Some advantages of IT system:

- Location the fault during operation
- The system can operate when the first insulation fault is occurred
- There is no risk for dangerous electrical shock due to low fault currents protect.
- The mandatory insulation monitoring devices continuously checks the insulation faults and reduces the risk of fire.

As a conclusion, the charging station must be grounded properly according to earthing system used in the location of station. This is very important requirement for life and fire protection, and never be ignored. The proper earth connection responsibility is belongs the owners. In order to reduce electric shock hazards, earth connection is essential. During operation of station, it is needed to check the earthing system frequently and ensured that it is working properly. National codes may require an RCCB, ask for local authorities.

As an example to electrical installation, the previous example on cable selection can be used. Since the maximum load current is calculated as 30.4 A, , an 32A Type B MCB and an 32A Type B RCCB are added to the system for protection purposes as shown in Fig. 7.19. Moreover, if it is outdoor EV charger, then surge protection devices (SPDs) should be added close to or inside of EVSE.

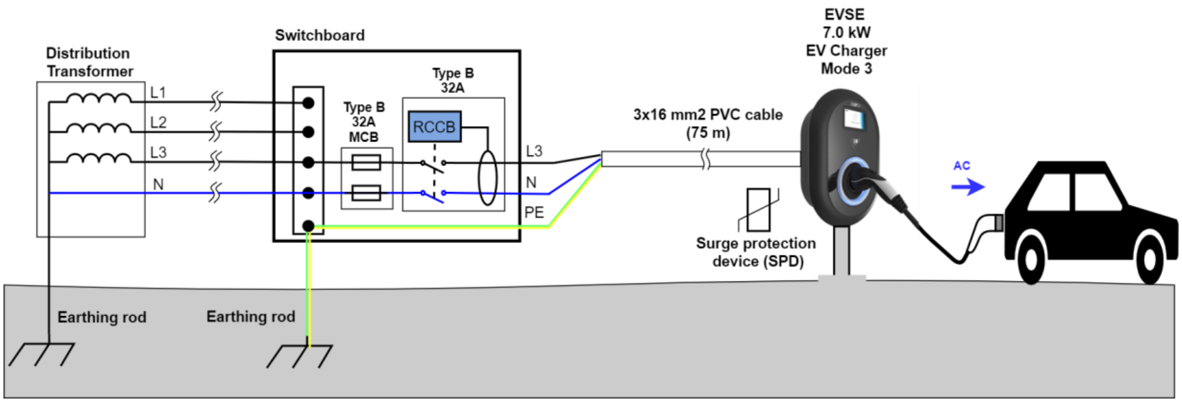


Fig. 7.19 (Courtesy of VESTEL)

7.5 General Safety considerations

7.5.1 Environmental Considerations

In winter, snowing can be heavy and entire ground and even the EV itself may be completely covered with snow. If the charging cable is laid on the ground, it may be covered by snow and may be difficult to locate. Similarly, an EV charged overnight may be completely covered by snow during strong snowfall at night and the charging socket may be invisible. On the other hand, strong fluid may fill the charging zone with water. The charging ports may be frozen and cables may be encrusted with ice. In all these harsh environmental conditions, the charging equipment must be safe to operate. If the charging station is indoor, no worry about weather conditions. But outdoor charging stations should have appropriate precautions against these conditions.

The effect of snowing can be reduced by using a canopy or a simple roof. These structures also offer a large visible area for charging station, making it easy to locate from a long distance. Additionally, solar arrays can be installed on the roof to generate some of the charging power.

Fig. 7.20 [2]

Underground heating is an option to keep the charging area free from snow and ice. However, it is effective on surface only, not on the car surface or charging ports. Moreover, additionally energy (electric etc.) is needed for heating. Alternatively, the charging cable can have a rewind feature and pulled out from a hole placed on a high point. This structure also protects the cable from the harmful effect of sun when it is not used, since it would be rewind into the charging box.

Rainwater should not be allowed to collect in the charging area. If the water level reach the electronics equipment, it can be dangerous for people or protective equipment. Therefore, a water drainage mechanism may be required.

The EVSE should also be protected from heavy rain. Check the IP standards of EVSE whether it is suitable for outdoor installation. Moreover, direct sunlight can be harmful for all sensitive electronic equipment; therefore, it should be protected by proper housing or shadowing. The operating temperature should also be checked for EVSE, generally it is between -20°C and 50°C.

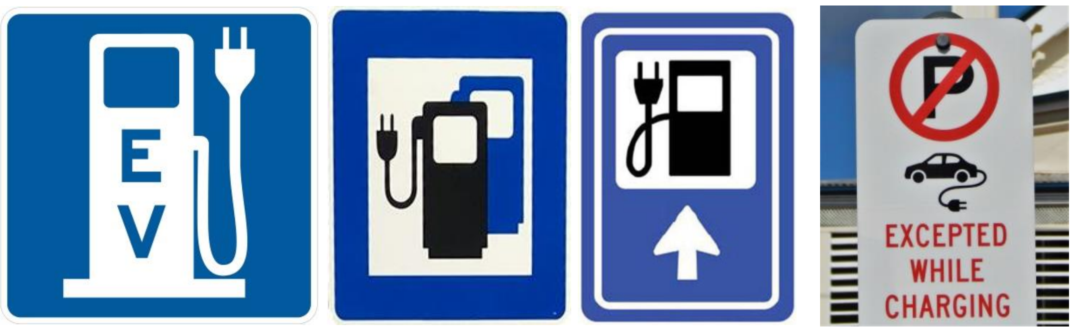
In order to provide accessible operation to EVSE, some barriers, such as bollards, curbing or wheel stops may be required. These barriers also protect the EVSE from vehicle impacts as shown in Fig. 7.21.

Fig. 7.21 [3]

7.5.2 *EV Charging Station Signage*

Most of the EV users will find the charging stations by using their smart phones or car navigation systems. However, the visible signs are also important for users who are unfamiliar to the area. These signs should be placed on clearly visible walls, or elevated point on a dedicated pole. Moreover, if the station is not on the main road, the direction signs on main road turning point may be useful to reach the station easily.

The following signs are frequently seen in charging stations. Some parking lots may be reserved for EV charging, in these cases, service signs may be useful for drivers.



(a) [10] (b) (c) (d) [11]

Fig. 7.22

Fig. 7.23 [4]

Fig. 7.24 [5]

Fig. 7.25 [6]

7.5.3 *Charging station safety devices*

In order to avoid the risk of explosion and electric shock, a Type B RCCB should be installed for each EVSE. The RCCB opens the circuit if any ground fault occurs. RCCB should trip at over 30 mA ground leakage current.

Users are not exposed to dangerous voltages or currents, since connector pins are not energized until the connector is inserted properly in the EV charging socket and communication has been established between the vehicle and the charging station. In addition, the connector is sealed to protect the live components from the weather. Lastly, a locking mechanism (latch) prevents accidental disconnection resulting from a tug on the cable.

7.5.4 *Protection Against Fire*

Three conditions must come together in order to start a fire; i) substance to burn (i.e., solid, liquid, gas and metal flammables), ii) a source such as heat or spark that could start a fire (chemical, biological or physical), iii) adequate amount of oxygen. IEC 60364-4-42 classifies the damages and dangers in electrical installation in four groups;

- Electric shock currents,
- Extreme temperatures causing burning, fire and other damaging effects,
- Accidents caused by mechanical devices driven by electric energy,
- Explosions.

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All the electrical equipment made of non-flammable materials. However, overloading, short-circuit, loose connection, improper component selection can create heat in electrical installations, and start fire in the nearest flammable material.

It is very important to keep the electrical installation away from the explosive materials. IEC 60079 should be reviewed for this purpose. The cable isolation materials and cross-sections should be selected according to the maximum load current by including the environmental temperature derating. On the other hand, RCCB protects against earth leakages higher than 30 mA that prevents also from fire effectively. However, loose connection can create arcs in contact points which is important source for fire start. For preventing this arcing, an Arc Fault Detector (AFFD) can be employed in the system. The AFFD is not a root device; each branch requires a separate AFFD. This may increase the installation cost considerably, therefore, the protection requirements may be determined according to the load type.

7.5.5 Protection against lightning and surge voltages

The installation cost of EV charge stations are very high thus it should be protected against lightning. The power supplies equipment, the EVSE, and communication equipment are susceptible to lightning effects [7]. The damage could mainly result from overhead transmission lines or direct lightning attachment to air-termination systems or equipment. Protection against direct lightning of the charging station should be provided with proper direct lightning protection devices; such as air-terminations rods or conductors. The chargers, which are installed outdoor, should be provided with a metal shelter with roof. If the roof is not metallic, air-termination rods should be installed.

Moreover, Surge Protection Devices (SPDs) should be provided for power and signal lines. The SPDs should be located as close as possible to the device to be protected. Using more SPDs in low voltage side of transformers, at the power input terminal of EVSE and each signal terminal connection increases the protection level against lightning considerably [7].

7.5.6 Standards related to EV electrical Safety

There are large differences on utility grid voltage and frequency in the world. Therefore, it is emerged more than one standard regulations regarding EV charging. The standards defined by IEC (International Electrotechnical Comission), SAE (Society of Automotive Engineers) and GB/T (Guobiao standards) are mostly accepted ones at present, and mainly used in countries of Europe, U.S.A and China, respectively. Some standard names issued by these organizations for EV charging are listed in Table 7.16. They regulate the power level, cords, connectors, communication, topology, safety and charging modes etc. The manufacturers follow these regulations and design suitable equipment for EVs. It should be noted that, the EV industry is still developing and regulations regularly be updated according to market requirements.

Table 7.16 EV charging standards [8]

Standard	**IEC**	**SAE**	**GB/T**	**Others**
Connector	62196-1 62196-2 62196-3 62752:2016	J1772	20234-1 20234-2 20234-3	
Communication	61850 61980-2 61980-3	J2293-2 J2836 J2847	27930	ISO 15118
Topology	61439-5 61851-1 61851-21 61851-22	J2953	18487-1 29781 33594	
Safety	60364-7 60529 61140 62040	J1766 J2894-2	18384-1 18384-3 37295	ISO 6469-3 ISO 17409 NBT 33008

As an example, titles of some IEC standards are given below:

IEC 62196: Plugs, socket-outlets, vehicle connectors and vehicle inlets, Conductive charging of electric vehicles

- IEC 62196-1: General requirements
- IEC 62196-2: Dimensional compatibility and interchangeability requirements for A.C. pin and contact-tube accessories
- IEC 62196-3: Dimensional compatibility and interchangeability requirements for D.C. and A.C./D.C. pin and contact-tube vehicle couplers

IEC 61851 consists of the following parts

- IEC 61851-1: General requirements
- IEC 61851-21-1: Electric vehicle on-board charger EMC requirements for conductive connection to AC/DC supply
- IEC 61851-21-2: Electric vehicle requirements for conductive connection to an AC/DC supply - EMC requirements for off board electric vehicle charging systems
- IEC 61851-23: DC electric vehicle charging station

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- IEC 61851-24: Digital communication between a DC EV charging station and an electric vehicle for control of DC charging

IEC 61980 consists of the following parts

- IEC61980-1: Electric equipment for the supply of energy to electric road vehicles using an inductive coupling - Part 1: General requirements
- IEC 61980-2: Electric vehicle wireless power transfer (WPT) systems –Specific requirements for communication between electric road vehicle (EV) and infrastructure with respect to wireless power transfer (WPT) systems
- IEC 61980-3: Electric vehicle wireless power transfer (WPT) systems –Specific requirements for the magnetic field power transfer systems.

IEC 62752:2016: In-cable control and protection device for mode 2 charging of electric road vehicles.

7.6 Case Study #1: Residential Home EVSE installation

The rated current of main switchboard at home is generally restricted to 16A or 32A by the Distributed Network Operator, which corresponds to 11kW or 22 kW power ratings in three phase network, respectively. Hence, the maximum power for an EV charger in residential homes is usually up to 22 kW. However, it should be remembered that, there are various electricity appliances at home which needs electric power too. Therefore, the maximum power capacity of the switchboard cannot be utilized by the EV charger; some reserved power is needed for home appliances.

For standard wall socket, the maximum current of 10A can be used with Mode 2 in which the charge power becomes 2.3 kW. This is the lowest charging power for domestic applications.

If the EV charger has a dedicated cable directly from the main switchboard, then maximum charge current (16A/32A) can be used, and therefore, 3.7kW & 7.4 kW & 11 kW of charging powers can be obtained. Moreover, a 22 kW charger may also be installed, but its full power may not be used most of the time, since some power needs to be reserved for home appliances.

Table 7.17 shows estimated battery charging times of some EV cars with various charging powers. It is seen that, as the charging power decreases, the charging time increases. Especially

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charging time can be very long for 2.3 kW. Hence, it is very important that the cables in home electricity installation are in good condition and secure, because the cables will stay long time with high stress by rated current.

Table 7.17 Battery capacity and average charging time of some EV models

EV Car Model	Battery Cap. & Driving Range	On-board Charger Power & Plug type	Estimated Charging time (0-100%)			
			Charge station (AC charge)	Home wall box (7.4 kW)	Home wall box (3.7 kW)	Domestic socket (2.3 kW)
Smart EQ Forfour	17.2 kWh 125 km	22 kW Type 2	~0h 47min @22 kW	~2h 9min	~4h 39min	~7h 29min
Renault Zoe	52 kWh & 395 km	22 kW & Type 2	~2h 22min @22 kW	~7h 2min	~14h 03min	~22h.37min
Honda-e Advance	35.5 kWh & 219 km	6.6 kW & Type 2	~5h 23min @6.6 kW	~4h 48min	~9h 36min	~15h 26min
Nissan Leaf	40 kWh & 238 km	6.6 kW & Type 2	~5h 23min @6.6 kW	~5h 25min	~10h 49min	~17h 24min
Tesla Model S	84 kWh & 426 km	22 kW & Type 2	~3h 49min @22 kW	~11h 29min	~22h 42min	~36h 31min

Selection of suitable charger:

The power capacity of charger can be determined by evaluating the battery capacity of EV, daily driving requirements and reserved power for home appliances. It may be good strategy to keep the charging times below 8 hours which may allow overnight charging from evening to morning. The chargers, which have time scheduling function, can be preferable since the cost of energy can be reduced by shifting the charging process to the night time where the electricity price is cheapest. For this reason, at single-phase installation, 3.7kW and 7.4 kW chargers with time-scheduling function may be more suitable for residential homes. On the other hand, three-phase 11 kW and 22 kW chargers with time-scheduling function can also be used effectively, since the decreasing of charging power by the user is always possible. If possible, three-phase chargers may be preferred over single-phase, because the charging power is 3 times high for the same cable current. Additionally, the total power is balanced among the phases, which is important property for grid operators.

Another concern regarding the charger selection is the type of the charging socket of EV. The plug type on the charger cable must be compatible with the socket on the EV, otherwise the

EV cannot be connected to the charger. IEC Type 2 socket is almost attached to the cars sold in Europe for AC charging. Then charger should have Type 2 socket. On the other hand, if the owner want to install a DC charger, should also check the plug-socket compatibility for DC chargers, since the cars may have different sockets for DC charging, such as CCS2, CHADeMO or GB/T.

For this case study, installation details of a single phase 7.4 kW AC charger in a residential home will be explained. Let's assume that the distance between the EVSE and switchboard is 20 meters, the cable will be installed in conduit on the wall surface, and the voltage drop limit is specified as 3%.

Determining the cable size:

The cable size is determined by considering the current carrying capacity and voltage drop properties of the cable. As a first step, the nominal current flowing through the cable is calculated as,

$$I = \frac{P}{U\cos\phi} = \frac{7400}{(230)(1)} = 32A$$

where the power factor is taken as unity by assuming that the on-board charger includes a Power Factor Correction (PFC) circuit. Considering the PVC multi-core cable installed in conduit on the wall (B2), the size of cable is found as 6 mm^2 for 32A current from Table 7.4. However, the voltage drop restriction must also be checked. We conclude from Table 7.12 that 6 mm^2 cable can be up to 27 meters long for a 3% voltage drop at 7.4 kW, that is 7 meters longer than the distance between the EVSE and the switchboard in the case study. Therefore, 6 mm^2 multicore PVC cable is suitable for the case study.

Alternatively, we would prefer to use a XLPE cable, and obtain the cable cross-section as 4 mm^2 from

Table 7.5 for 32 A. It is clear that, XLPE cable needs smaller cable size than PVC for the same current ratings. But we see that, 3% voltage drop distance is just 18 meters which is shorter than the desired cable length of 20m. Therefore, the cable size should be increased to 6 mm^2

which is equal size with the PVC cable. Since the PVC cable is cost effective than XLPE, the PVC is preferred in this case study.

Circuit breaker selection:

Circuit breakers protect the cable and equipment from overcurrent, and therefore, must be selected carefully. If the trip current of circuit breaker is higher than the cable ampacity, it cannot protect the cable. Therefore, MCB trip current must be lower than the ampacity value of 6 mm^2 cable, which is 38A in this case study. On the other hand, the fuse should not be tripped at the load current of 32A. Therefore, the fuse trip current should be selected between 32A and 38 A.

The standard trip current ratings of MCBs in the market up to 100A are 1, 3, 6, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100 A. It is seen that an MCB with 35A trip current are suitable for the case study.

Determining the type of MCB is based on its ability to handle surge currents without tripping (see section 7.3.2). Typically, the surge current is arised from the inrush current of the equipment. For example, Type D MCB is suitable for motors, since the surge current at start-up can rise up to 10 times higher than the rated current. The on-board EV chargers also have inrush current during start-up. The magnitude of the inrush current depends on the design specifications, and therefore, user manual of the EV charger should be checked for precise value. Generally, Type-B MCB is suitable for home installations, which allow the surge current up to 3 to 5 times of rated current. If the MCB type is not selected properly, unwanted tripping of MCB can occur. A Type-C device can be substituted for a Type-B device if unwanted tripping occurs frequently.

RCCB selection:

Two parameters are very important for selection of proper RCCB device. The first one is the Type of RCCB. As mentioned in the Section 7.3.3, only Type-B or Type-F RCCBs can be employed for EVSE installation since they can detect DC leakage currents. The second one is the current rating of the RCCB which must be equal or higher than the MCB current ratings. In this case study, a 2 pole (Phase and neutral), 40A Type-B RCCB can be selected.

Cable installation:

Scraping the wall and making the cables invisible are possible for unfinished wall. But, routing the electric cables on the finished wall can be more challenging than unfinished wall, because it should be done without destroying the wall surface.

First of all, investigate the area and make a cable routing plan which makes the cable length as short as possible. Remember that long cables increase the voltage drop. If possible, run the cables through inconspicuous places for aesthetic concerns. Routing the cable through the corners using PVC cable duct is mostly used for these purposes. While the duct protects the cable from environmental hazards (e.g. direct sun light at outdoor), it doesn't spoil the aesthetic appearance.

The EVSE end of the cable can be connected to an industrial wall socket rated for the maximum charge current, i.e., 16A/32A. Alternatively, the cable can also be tied directly to the power input terminal of EVSE. This method is more preferable in most cases since the socket.

EVSE installation:

Wall mounting of the EVSE is easier than the pole mounting; therefore, it should be preferred when a suitable wall is available. If the EVSE is mounted at low height, the car may hit accidentally, or may be the water can reach to device in a flood, or children may want to play with it. Hence the EVSE should be mounted within 0.75 m to 1.5 meters from the finished floor level for safety as shown in Fig. 7.26. The mounting place on the wall must be away from any flammable, explosive and combustible material.

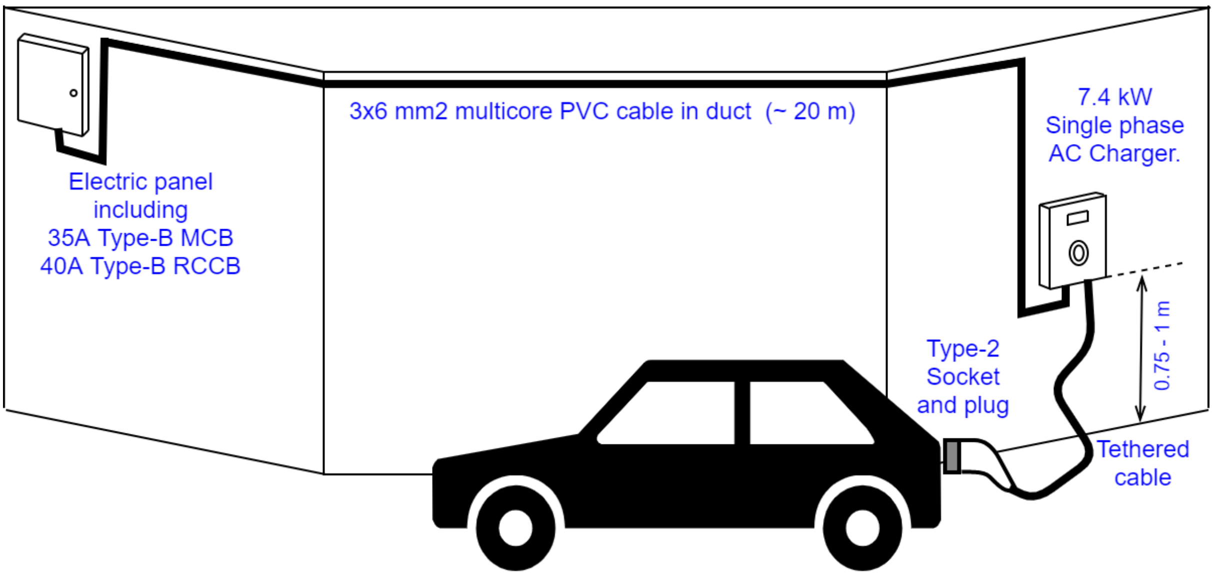


Fig. 7.26

The EVSE, which is designed for indoor, should not be mounted outdoor. Because direct sunlight, raining, extreme temperatures can be very harmful for indoor equipment.

If there is special power socket on the wall at home for EV charging, the EVSE should be mounted on wall next to this socket. Some new homes already have this socket. In this case, no need to run extra cable from the main switchboard. This situation makes the installation process very simple. In any case, the EVSE should be close to the EV so that the charging cable reaches the EV charging socket without any tension.

Having a wireless internet connection in the EVSE location would be advantages, since most of the EV chargers have Wi-Fi connection to remotely monitoring and controlling the charging process.

De-energize the electric system from the main circuit breaker until the wiring is completed. During connection of cable to the terminal, it is important to follow the colour coding as given in Table 7.2. As a summary, green/yellow for power earth, blue for neutral cable and brown/black/grey for lines, as shown in Fig. 7.27. Color coding provides very important function during the maintenance and repairing of electrical installation.

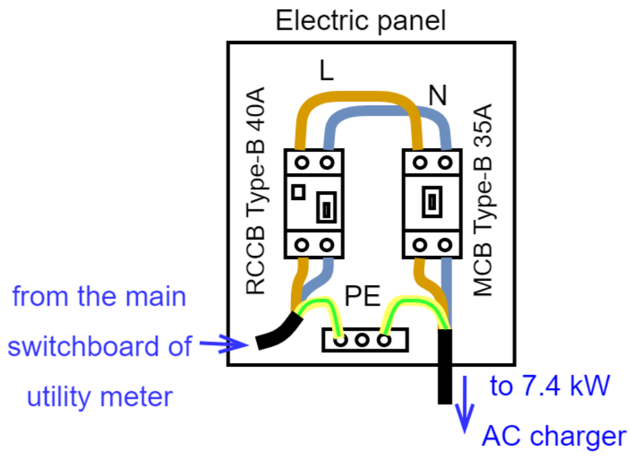


Fig. 7.27

The earthing must be checked if it works properly. Earthing failure can lead to risk of electric shock and fire. This is critical task for all electrical installation. Therefore, high attention must be paid.

7.8 Case Study #2: Parking area EVSE installation

In this case study, installation details of outdoor EV charger in the parking lot of Ege University campus in Izmir, Turkey on December, 17 , 2020, will be given along with photos. The aerial view of the installation area is obtained from Google Map, and given in Fig. 7.28. The electric power is supplied from the distribution transformer house which is 52 meters away from the installation area. The EV charger to be installed is EVC04-AC22 model 22 kW AC charger produced by VESTEL company.

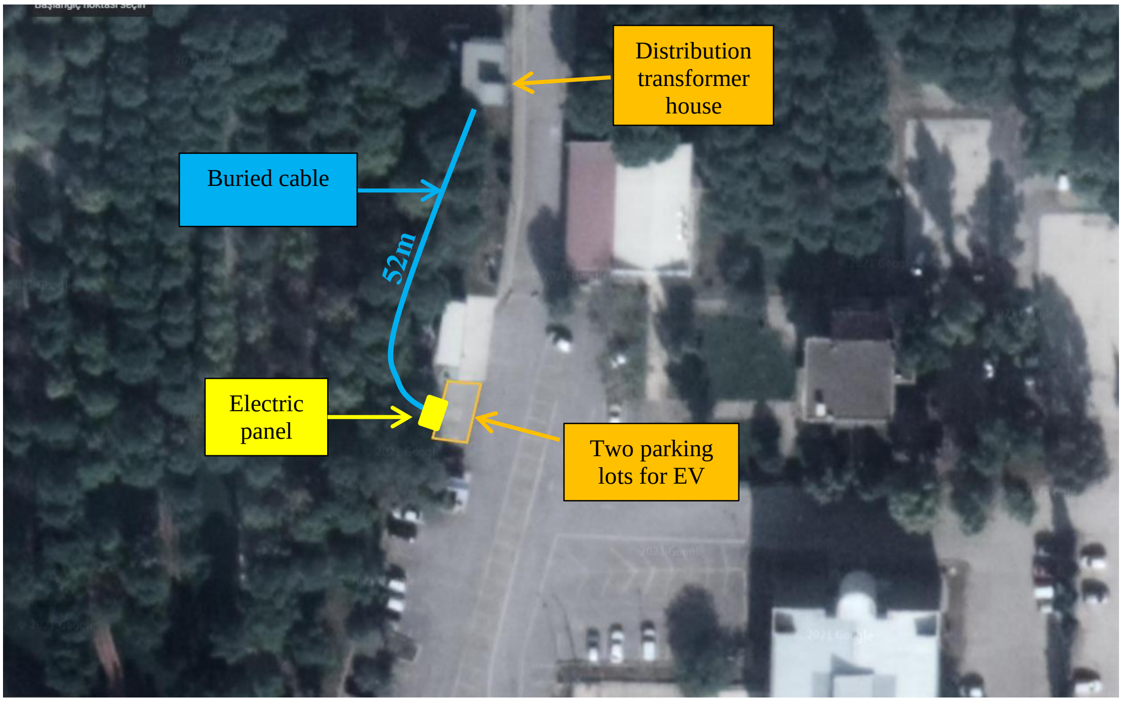


Fig. 7.28 (Courtesy of VESTEL)

Design section:

At first, the size of buried cable is determined. For this purpose, rated current of cable for 22 kW power is calculated as below;

$$I = \frac{P}{\sqrt{3}U_{LL}\cos\phi} = \frac{22000}{\sqrt{3}(400)(1)} = 32A$$

Since two EV chargers will be supplied by the buried cable, the cable size is selected for 2x32 A=64 A load current. However, only one of them is installed in this case study. The other is reserved for future installation.

The cable will be placed in a conduit in the ground, and then the reference method from the Table 7.3 is found as D1. The PVC material is preferred for the cable to keep the cost low. The minimum cross-sectional area for the PVC cable carrying 64A is found as 16 mm^2 from Table 7.6. Since it is very critical size, one step larger size, i.e., 25 mm^2, is selected. The ampacity of 25 mm^2 buried cable is 82A which is fairly enough for powering two chargers.

The cable resistance and reactance for 25 mm^2 PVC cable can be taken from Table 7.10 as R=0.907 Ω/km and X=0.0813 Ω/km. Then the voltage drop can be found using unity power factor load as,

$$\Delta V = \sqrt{3} IL \left(R_c \cos\phi + X_c \sin\phi \right)$$

$$\Delta V = \sqrt{3}(64)(0.052)\left[(0.907)(1)+(0.0813)(0)\right] = 5.23V$$

$$e(\%) = \frac{\Delta V}{U} \times 100 = \frac{5.23}{400} \times 100 = 1.3\%$$

The percent voltage drop is lower than the design requirement of 3%, and therefore, 25 mm^2 multi-core PVC cable is suitable for the installation.

In order to protect the buried cable from overload, a thermal-magnetic circuit breaker whose trip current is 80A is employed. As recommended in the user manual of EVC04-AC22 charger, two protection devices; such as a 4-poles 40A Type-C MCB and a 4-poles 40A Type-A RCCB are added into the electric panel. The cable between the electric panel and EVSE is selected as 5x6 mm^2 PVC multi-core cable. This size is recommended by the user manual of EVC04-AC22 for up to 50m distance.

Installation section:

The installation was started with the preparation of concrete mounting bases for the electrical panel and EVSE as shown in Fig. 7.29.

Fig. 7.29 (Courtesy of VESTEL)

Then, the soil was excavated and cable duct was laid for buried cable from the distribution transformer to the installation site as shown in Fig. 7.30.

Fig. 7.30 (Courtesy of VESTEL)

Finished view of electric panel and 2 EVSE locations are seen in Fig. 7.31. The EVSE location #2 on the right is reserved for expanding the charging capacity for the future.

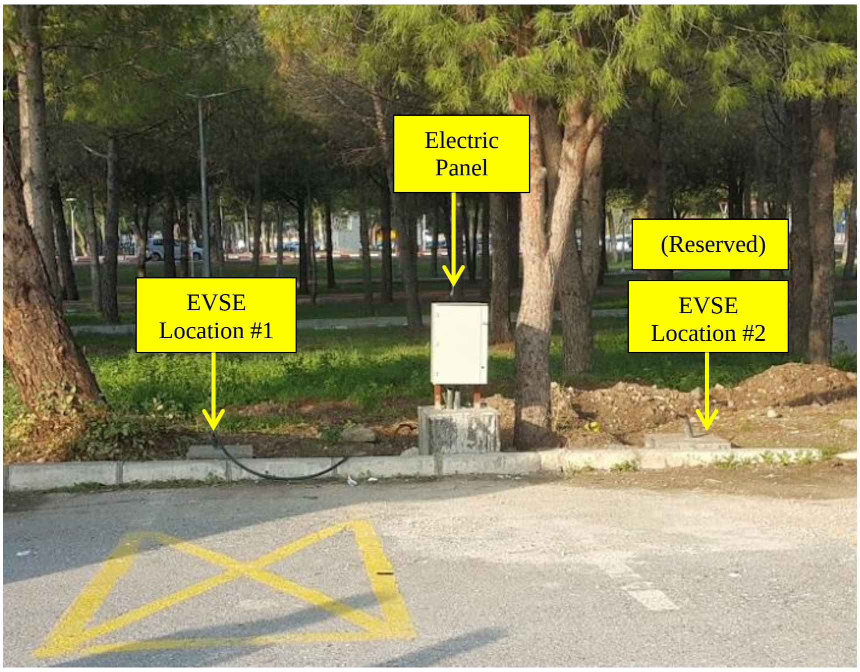


Fig. 7.31 (Courtesy of VESTEL)

The next task was to fix the mounting pole of EVSE to the concrete base. The installation steps are shown in Fig. 7.32. First, the cable was inserted through the pole and mounting holes were marked on the concrete base. Then holes were drilled, and the pole was placed perpendicular to the ground.

(a)

(b)

(c)

(d)

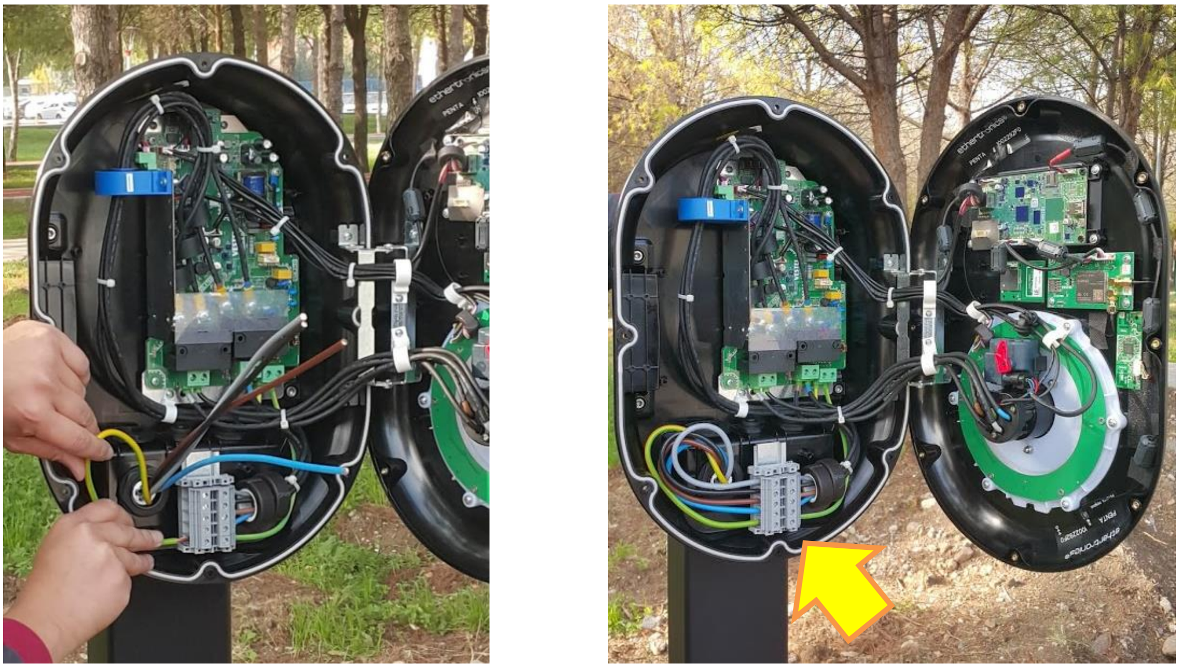
Fig. 7.32 (Courtesy of VESTEL)

The mounting plate was placed on the pole as described in the user manual of EV charger as shown in Fig. 7.33.

(a) (b)

Fig. 7.33 (Courtesy of VESTEL)

After fixing the EVSE on the mounting plate, the power cables were screwed into the input terminals as shown in Fig. 7.34. Attention to the colour coding of cables is very critical in this step. Standard coding is green/yellow for power earth, blue for neutral cable and brown/black/grey for power lines.



(a) (b)

Fig. 7.34 (Courtesy of VESTEL)

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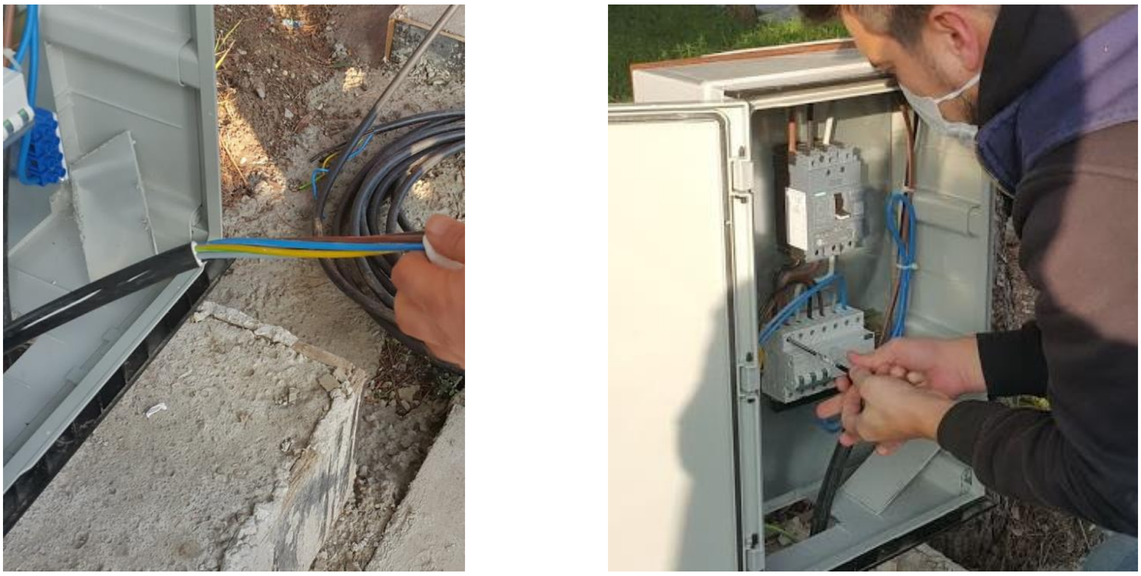
After that, the 5x6 mm^2 multi-core PVC power cable coming from the EV charger was connected to the electric panel as shown in Fig. 7.35 and then the charger was energized by turning on the main circuit breaker.



(a) (b)

Fig. 7.35 (Courtesy of VESTEL)

A number of functional and electrical checks were done just after finishing the installation. The power earth impedance measurement test, RCCB functional test, measuring isolation resistance was realized by Profitest Mxtra. The AC charger functional tests were realized by Vestel EVC tester as shown in Fig. 7.36

(a) (b)

Fig. 7.36 (Courtesy of VESTEL)

After the installation is complete, front view of the 22 kW Pole mount EV charger was like as shown in Fig. 7.37. There is a parking lot in front of the charger. The signage and barriers will be added soon. The AC charger has communication options; such as Ethernet (default), Wi-Fi, Bluetooth and GSM. Any of the communication functions were not activated for now, but can be used in future. Currently charger can only be activated using an RFID card compatible with ISO-14443A/B and ISO-15693.

Fig. 7.37 (Courtesy of VESTEL)

A Tesla Model S car was the first electric vehicle to be charged from the new charging station. The car was connected to the charger via un-tethered IEC Type-2 (also known as Mennekes) cable as shown in Fig. 7.38(a). Despite the maximum power capacity of the charge station is 22 kW, charging power of Tesla car was 10.7 kW as seen from the charger display in Fig. 7.38. The 11 kW is the rated power of on-board charger of this car, therefore, it was charging at rated power. This is a good example to show the power controlling feature of EVs when the charge station power capacity is high. Therefore, for fast charging, not only the charging station, but also on-board charger power must be high.

(a)

(b)

Fig. 7.38 (Courtesy of VESTEL)

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PART C

MAINTANENCE

8 MAINTENANCE

Inspection of the charging facilities should be carried out regularly (for example monthly) in an EV charging station. If repair or maintenance is needed, it should be carried out by registered electrical contractor and registered electrical worker. Unqualified persons can disrupt the electric system, and make charge station prone to hazardous conditions. Keeping the charge station in continuous service is an ultimate goal of the maintenance works.

Additionally, safety of electrical equipment in electrical installation of the charge station is also important because of electric shock and fire risk. There are innovative solutions offered by service providers for charging point operators like preventive maintenance, remote diagnosis, and remote solutions for service cases [1].

From the previous chapters, we know that there are two distinct EV charger types, namely AC and DC chargers. For residential and private charging stations, generally Mode-2 and Mode-3 AC chargers are more convenient. In most cases, the rated power of AC chargers is up to 22 kW and usually doesn't need cooling fan. Therefore, they generally require cleaning and visual inspection as maintenance. On the other hand, the DC charger is the fastest option for EV charging and therefore, requires very high electric power. The preventive maintenance for cooling equipment and electrical devices periodically is essential for DC chargers. For this reason, it is usually suitable for public charge stations.

The maintenance requirements for AC and DC chargers are described below separately.

8.1 Maintenance requirements for AC chargers:

For residential homes, Mode-2 portable chargers need very low maintenance because it simply uses the standard household AC power sockets. The user should perform a visual inspection periodically to ensure that all system components are clean and functioning; for example MCB, RCCD, power cable in electrical installation, and also wall power socket, charging cable and its plug need to be visually checked. If any damage is found, that components must be replaced with a new one, and loose connections should be tightened. High current stress in long time increases the temperature of wall socket, reduces lifetime and makes it much prone for damage. Therefore, it will be good to replace it periodically without waiting for any significant

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damage. It should be kept in mind that, the system must be de-energized before any attempt on electrical components. All repair and maintenance should be done by a qualified technician.

Mode-3 AC charger for residential home requires similar maintenance as Mode 2 portable AC chargers. The Mode-3 AC chargers have dedicated cable for direct connection to the main electric distribution panel, and therefore, the MCB, RCCD, terminal connections should be checked regularly. The time scheduling function should also be tested if it is included in the charger. If it doesn't function properly, the charging time cannot be programmed by the user, or the unit price of charging energy may rise up.

On the other hand, Mode-3 chargers can also be used in corporates, in shopping mall or in public charge stations. In these applications, the number of chargers can be quite high and maintenance task increases proportionally. Hence, it may be appropriate to make a service agreement with a professional service team. A service technician can regularly perform a visual inspection on all equipment to ensure that all system components are clean and full functioning, replace components if needed and prepare regular reports. This preventive maintenance prolongs the equipment lifetime.

Except electrical and mechanical maintenance, Mode-3 charging units may have advanced management features, such as payment system and charging authorization etc. These management parts of system also require periodic maintenance, such as software update, firmware update, and inspection of communication equipment. Having warranty from the system manufacturer or system installer is straightforward way to keep system operational for long time with low cost. In some cases, extended warranties can be advantageous.

8.2 Maintenance requirements for DC chargers:

DC charging units consist of an AC-DC converter whose power is usually from 50 kW up to 250 kW. Although the efficiency of the converter is relatively high (> ~94%), the power losses in the converter is not small enough for using convection cooling, and hence an active cooling system is required for effective power dissipation. Active cooling is usually a forced air circulating with a suitable fan. Some DC chargers operating at very high-power level, and thus they can employ a water-cooling systems. In any case, active cooling systems use a fan and filtering components (e.g. for air or for water). If these components do not operate properly, the semiconductor temperature in the converter can rise and that may result in a fault in the converter or activate a some thermal protection function in the system. For this reason, regular cleaning of filters and maintenance of mechanical parts of cooling system are critically important.

Regular maintenance of DC charger units is very important for public fast DC chargers. If maintenance is not enough, some protection functions of the device may be activated, and in turn, charger may be out of service. This may result in a serious loss of revenue, especially for heavily used fast charging stations. For this reason having a contract with a professional maintenance firms for regular maintenance work should be considered. It should not be forgotten that, the regular maintenance prolongs the lifetime of charge station considerably too.

8.3 Electrical maintenance checklist

Monthly inspection of power circuit is usually recommended by manufacturers. Dirty and dust can cause insulation problems. The coarse dirt, dust and oily parts should be cleaned by vacuum cleaner, dust-absorbent cloths and liquid cleaners, respectively. The more important safety device in the installation is the circuit breakers, and they should be checked during regular maintenance. Therefore, all MCB's, RCCB's and AFFD's should be visually inspected for cracks, melting parts or defects. More importantly, all the cable connections should be checked carefully against loose coupling. Since the connection resistance is high due to loosening of the connection, if high current flows through the connection, the power loss (I^2R loss) increases significantly, and rising temperature will damage the parts or cause melting.

Repairing the MCB and RCCB equipment may cause fatal problems in the system, since they realize critical tripping and protection properties. Hence, always replace the protections devices with a new one. The enclosure of EVSE does not need any maintenance except cleaning it.

After any large fault or short circuit failure occurred in the system, a comprehensive inspection should be carried out in the whole system to ensure that there is no insulation damage in equipment, especially in conductors.

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The technical person should take notes about maintenance details, such as, date, time, checked, tested and replaced parts in the systems etc. After the maintenance, a detailed report should be prepared and then archived.

As an example, basic maintenance checklist is given in the Table 8.1.

Table 8.1: Maintenance checklist

Maintenance checklist	**Action**
Inspect the electric panel visually	• When partial breakage, burning or melting is inspected on some parts (cables, panel door, lamps, displays etc.) , replace it with a new one immediately • Check all terminal connections by eyes one by one. If any damage is found, replace that equipment (and cable if necessary).
Check for any live conductor or exposed circuit parts	• Replace it immediately
If possible, check the cable insulation by an insulator tester.	• Replace the cable if insulation fault is detected.
Inspect the charging zone visually	• If accumulated water is found in the charging zone. Drain the water. Locate the source of water, find the cause and take necessary measures to prevent recurrence • If snow is found in charging zone, clean the snow and add a canopy if possible
Check the switchboard case	• Clean with a slightly wet soft cloth if enclosure is dirty • Replace if enclosure is damaged
Check all manually controlled power switches	• Clean with a dry soft cloth or a vacuum cleaner if it is dirty • Replace if damaged or broken • Replace if emits audible and visible sparks • Check if any colour change is visible on the case of equipment due to high heat or temperature. If yes, replace the switch.
Check the cables	• Clean with a slightly wet soft cloth if it is dirty • Clean the cable ducts with a vacuum cleaner if there is dust • Replace if damaged, broken or crushed

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	• Tighten the loose pins, or replace if needed. • Repair/replace the conduit if damaged • Replace if cable has insulation fault
Check all MCBs	• Clean with a dry soft cloth or a vacuum cleaner if it is dirty • Replace if damaged • Ensure that no obstruction or excessive friction when operates manually while system de-energized • Replace if there is a damaged terminal • Check if any colour change is visible on the case of equipment due to high heat or temperature. If yes, replace the MCB.
Check all RCCBs	• Clean with a dry soft cloth or a vacuum cleaner if it is dirty • Replace if damaged • Ensure that no obstruction or excessive friction when operates manually while system de-energized • Replace if there is a damaged terminal • Check if any colour change is visible on the case of equipment due to high heat or temperature. If yes change the RCCB. • Press the test button in the front face of RCCB. It must be tripped. Otherwise replace the RCCB
Check all AFDDs	• Clean with a dry soft cloth or a vacuum cleaner if it is dirty • Replace if damaged • Press the test button in the front face of AFFD. It will start a self-check function. If test is failed, replace the AFFD
Verify the ratings of MCB and RCCB	• If it is not suitable, replace it with a suitable values.
Check the charging plug and its locking mechanism	• It should be operate successfully and not to be damaged. If not, replace it.
Check the input AC voltage of charger	Grid voltage tolerance is 10% in most of the countries. If the grid voltage is not in the range of 230V ±10%, report it. If the voltage is out of the range recommended by user manual of the charger, shut down the charger, and inform the responsible person immediately.

RCCB and AFFD Test procedure:

The RCCBs has a test button on itself, and its functionality can be verified by using following steps,

- Make sure that the RCCB is in the ON position.
- Press the test button.
- The RCCB must trip immediately.

If it does not trip, the RCCB must be replaced with new one, otherwise the charging station and people are not correctly protected against insulation faults. More detailed information on this topic can be found in Section 7.3.3.

The AFFDs have a test button too, and its functionality can be tested easily by pressing this button.

8.4 Mechanical maintenance checklist

Cleaning and maintenance of the power units is very important for the efficient operation of the DC charger system. The most important maintenance work for DC chargers is regarding the cooling system. The dust affects the electrical circuits significantly, therefore, cleaning of dust is important. The ventilation filter cartridge of the air-cooling system should be replaced periodically using the procedure below;

- Turn- off the system power
- Clean the dust accumulated around the DC charger.
- Open the fan cartridge cover
- Take out the air filter cartridge
- Place a new cartridge. Never use old cartridges which is cleaned.
- Clean the cover with a soft cloth and vacuum cleaner, and then put it into its place.
- Turn-on the power.

If mechanical work is done in electrical installation of charging station or in EV itself, the isolated equipment may prevent person from possible electric shock shown in Fig. 8.1. Protective equipment includes non-conductive gloves, protective eyewear and a rubber blanket. Jacking, lifting, supporting of EVs is prohibited in areas where high voltage cables are routed. The battery voltage of EVs is typically 360-400Vdc. This is very dangerous voltage level and isolation conditions must be kept without ignoring any safety rules. An arc may occur in this voltage level if positive and negative electrode closes each other within thin air.

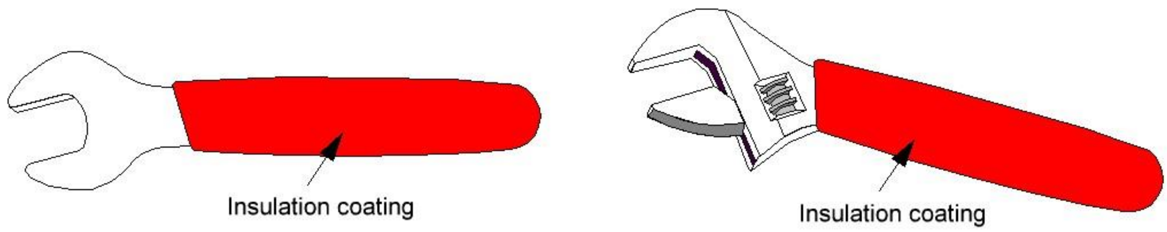

Fig. 8.1

Towing an EV is not recommended, since electric vehicles have no clutch, and the motor turns with the wheels. Thus towing may lead to voltage induction in the motor and which could harm the vehicle.

Crashed electric vehicles should only be transported by experts because the battery may start a fire. For the same reason a crash damaged EV must never be stored indoor. Batteries are potentially hazardous and should be transported only by professionals in accordance with the laws on transportation of dangerous materials.

Clean the charging station. Before starting to clean, unplug all the charging cable connected to the station. Don't use abrasive detergents or cleaners. A dry and soft cloth can be used. Do not spray water on the electronic equipment and do not clean the equipment while charging. Otherwise, it may result in death, serious injury or equipment damage.

Never try to open the battery pack, do not open or remove the orange-coloured high voltage cables. Wear rubber gloves, protective glasses. Before taken an action, refer to the user's manual.

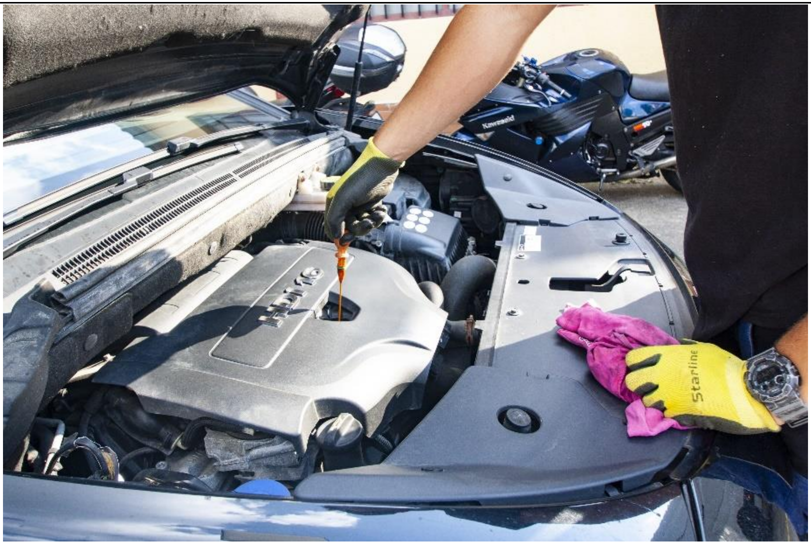

Fig. 8.2 [2]

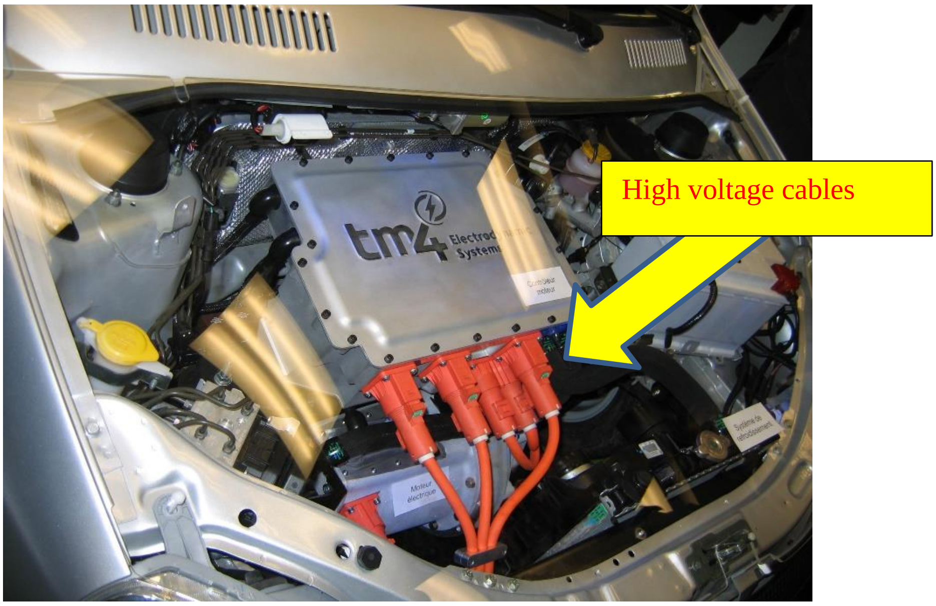

Fig. 8.3 [3]

8.5 Troubleshooting

In this section, solutions to some possible fault conditions will be detailed.

Fault	Possible Cause	Action
RCCD does not work	Damage or aging	Change the RCD
RCD cuts off the power unnecessarily	Leakage current to the Earth	Check the isolations of EVSE and EV. Check any damage in the insulating material of cable.
Charge doesn't start	Proximity pilot lock	Proximity pilot signal is lost, check cable.
	Connection lost	Communication port doesn't work, check cable.
	Power off	EVSE input power is off, open the power switch
	Charger may need membership	Charger may need membership to a community or credit card
	Time scheduling function may be activated accidentally.	Re-schedule the device.
Charge power is at lowest level, it does not increase	Control pilot	Check the continuity of the control pilot pin between EVSE and charger. The PWM signal may not be exist.
Circuit breaker opens the circuit when EV socket connected	Short circuit	EV or charger inlet may have a short circuit. Call service.
	Inrush current	MCB may trip due to inrush current. Change the MCB Type, For example, from Type-C- to Type- D,
Charger stopped	High temperature	Ventilation may required
Communication problem	Cable	Check the cable, and change if needed
	Earthing fault	Check earth connections

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PART D

MANAGAMENT

9 MANAGEMENT OF EV CHARGE STATIONS

9.1 Operation Aspect

The EV charging market is a complex system, where roles need to be distinguished to define responsibilities and services. There are numerous standards in the industry, each of them are different. The protocols and the relation between different roles in the EV industry are shown on the following figure:

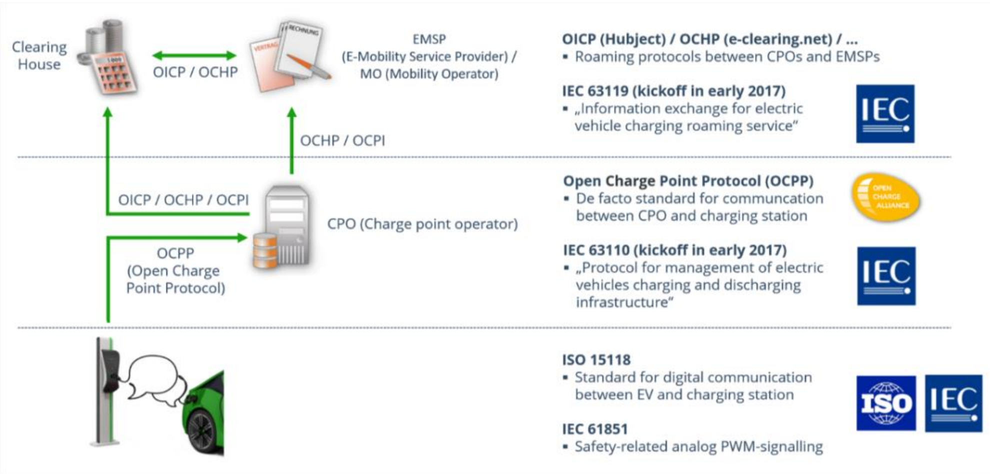

Fig. 9.1 [5]

- **Clearing House:** An institution or system that facilitates clearing for charging. There are companies specialized on this field and sometimes EMSPs are dealing with clearing.
- **Charge Point Operator, CPO:** A company that is specialized on operation and maintenance of charge points.
- **E-Mobility Service Provider, EMSP / eMSP:** A company that handles communication and billing of EV customers. Depending on the market, EMSPs are responsible of the CPO roles. However, it is important to distinguish between CPO and EMSP to allow other EMSPs to use charging points of the competitors.
- **Electrical Vehicle Supply Equipment, EVSE:** The logical unit in a Charge Point that supplies electricity via a connector. One EVSE can have one or more connectors.

Some EMSPs are E-on, T-systems and NKM Mobility in Hungary; and ZES, Esarj and Voltrun in Turkey.

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9.2 Service Level Agreements

Any member of the EV charging service chain shall be able to fulfil a given Service Level Agreement (SLA). The SLA can be defined by law and/or business contracts between customers and CPOs. SLAs guarantee the level of uptime and accessibility of chargers for customers. There are innovative solutions offered by service providers for charging point operators like preventive maintenance, remote diagnosis, and remote solutions for service cases [1].

9.3 Transaction Records

Charging Data Record (CDR) shall be stored of charging sessions considering the aspects GDPR. Storing certain data is necessary for customer support, payment, billing, business intelligence and legal data provision purposes.

CDRs send from the CPO to the eMSP after a charging session has finished. Usually, CDRs are sent ASAP the charging session has finished. There are cases when CDRs are sent periodically, once a month.

A CDR may consist of (according to OCPI 2.0) [2]:

- CDR Identification number
- Start and stop date and time of charging session
- User authorization ID
- User authorization method
- Location where the charging took place incl. which EVSE and connector
- Identification ID of the meter in the Charge Point
- Currency of the CDR
- Tariff elements
- Charging periods that make up the charging session (one session might be made up of different tariffs)
- Total cost of transaction
- Total usage of services (for example parking time or energy)
- Remark or comment

9.4 Payment

An EVSE managing system shall be able to carry out online payments. Nowadays, these are often carried out via Payment Service Providers (PSP). In case of roaming between international EMSPs, the payment service may be able to support multicurrency payments.

9.4.1 Participants of a payment system

Participants of a payment system are a processor (a payment distributor or gateway), a merchant, and a dealer.

The payment gateway's function is to authenticate payment info and transfer it securely between various groups and banks. Gateways are always provided by financial service operators or banks and are extremely available always. Dealers receive payments from financial institutions directly while PSPs are the distributors.

Some PSPs [3]:

- Amazon Payments
- Apple Pay
- Google Pay
- Masterpress
- Vodafone Wallet
- Simplepay
- PayPal

9.5 Billing Operations

The managing software of the CPO/EMSP shall be able to issue bills either to a private person or a business. The bill shall satisfice of the local requirements, it is highly important in case of roaming providers or EMSPs that are international and can issue bills for a service provided in a different country.

The EVSE managing system usually uses external 3rd party billing service providers that is connected to the CPO/EMSP-s ledger. The bills are mainly issued online and sent to the customer via email or application.

9.6 Regulations

Indicating the increasing significance of EVs, many countries start to impose regulations on EVSE operators, such as:

- Required CPO and EMSP licenses
- Minimum SLA/availability requirements
- Ad-hoc charging (to be able to start charging without permanent subscription to any EMSP service) regulations
- EVSE installation permits
- Visual requirements of charging stations (e.g. mandatory infographics or price, connection type display on EVSEs)
- Parking area requirements (e.g. visual signs, coloring)

9.7 Trends

Roaming services are the key to create a cross-country EV charging system. Similarly to the local charging infrastructure, an EU level charging system can increase EV penetration and contribute to the clean-up of the transport industry.

The ultimate goal is to allow any EV driver to charge at any charging station in the EU. There are multiple obstacles that hinder international charging of EVs:

- Functional
- Technical
- Legal
- Fiscal

As a result of R&D, developing startups and standards, EV drivers will be able to charge EVs anywhere, will be invoiced and have access to all necessary services soon.

Access to EV charging services and charger information is like location, availability and tariffs are key for an interoperable European (or any other region) EV market.

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The interoperability will improve EV industry and contribute to the clean-up of the transportation system in the following ways:

- Improved energy efficiency
- Use of renewable energy
- Decreased GHG (Green House Gas) emissions
- Improved innovation towards services

There are many organizations, platforms and groups where manufacturers, CPOs, EMSPs and other players work together to develop a common roaming system. Practically, these organizations are competing each other in some way to reach the same goal. Some examples:

- Gireve (Partners: Renault, Enedis, EDF, CNR, etc.)
- E-Clearing.net (Partners: GreenFlux, Ionity, E-on,Vattenfall, TomTom, EVBOX, etc.)
- Hubject (Partners: Innogy, Volkswagen, BMW group, Daimler, Bosch, Siemens, Enel x, EnBW, etc.)

9.8 Charging Platforms and Management Systems

EV Charging platforms are providing complete solutions for Charging Point management, end-customer services, smart energy solutions, etc. Some of the services that is available for energy companies or other players that are planning to run or are already running their own EV charging infrastructure, to become eMSPs:

- Operations and Management of charging infrastructure
  - Remote CP management
  - User management options
  - Connection to Roaming networks (to Hubject or Gireve)
  - OCPP
- Payments and billing
  - Price plans and tariffs
  - Different payment methods
  - Reporting tools and dashboards
- Smart Energy Management services

- Load management
- Optimized EV charging (Smart Charging)
- V2G

- Mobile and web apps for drivers
  - Often white-labelled apps for customers
  - Charging management
  - Paying
  - Communication
  - Marketing

Some platforms:

- Ampeco
- GreenFlux
- Fortum
- Virta

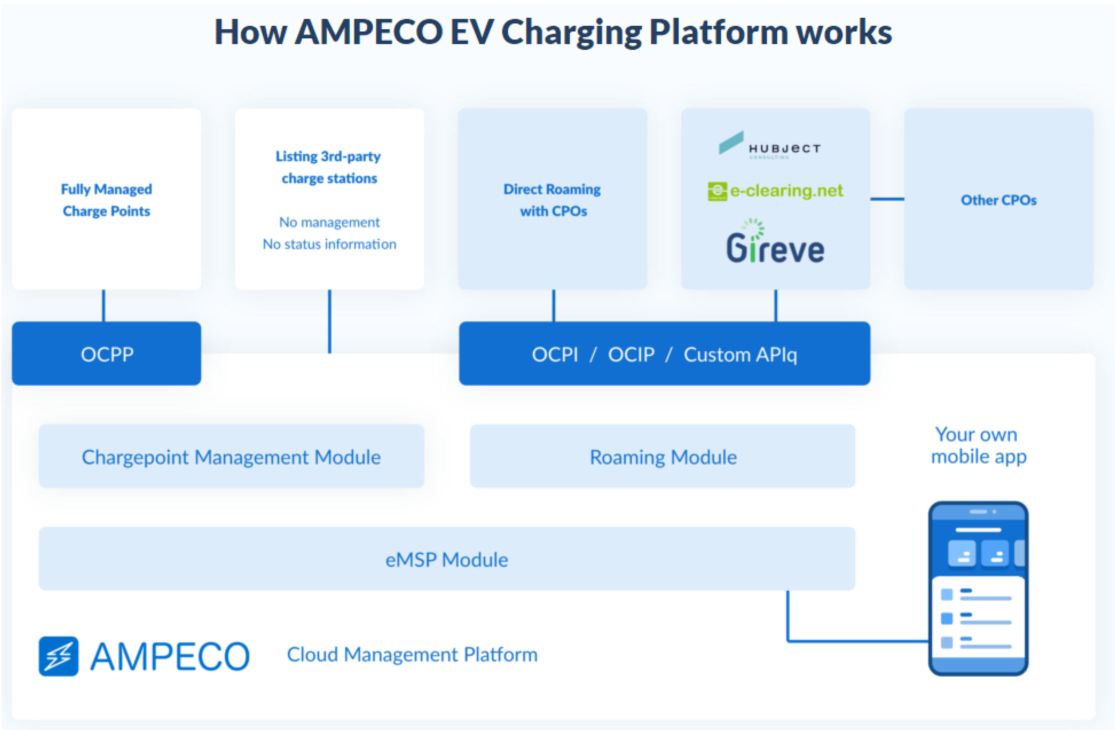

Fig. 9.2 [4]

9.9 OCPP protocol

Open Charge Point Protocol (OCPP) is a protocol for managing the communication between EV charging stations and a central management system (between CP and CPO). It is internationally applied, available for free (open-source) and vendor-independent.

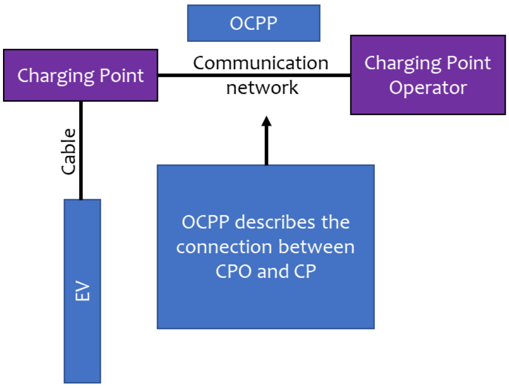

Fig. 9.3

The protocol has been developed by Open Charge Alliance (OCA), and today it is considered to be a de-facto standard (a non-official standard that is accepted and used Worldwide) by software and systems providers, charging equipment manufacturers, charging network operators and researchers. The protocol has been developed with close cooperation with industry players. The IEC and ISO 63110 standard is under development to replace this protocol in 2021. OCPP 1.5, 1.6 and 2.0 are the available today, from which 1.6 is the most widespread.

Some of the OCPI 2.0 updated functions:

- Device management
- transaction handling
- Security
- Smart charging functionalities
- Support for display and messaging
- Support Plug & Charge (ISO 15118)

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10 SMART MANAGEMENT

10.1 Energy Management

Energy Management has a great potential in case of EVs. Energy management helps to optimize the charging infrastructure by monitoring, adjusting, and managing energy consumption and by demand response.

Some of the functions that an Energy management solution can provide to the grid and to the EV industry players [1]:

- Dynamic energy supply to/from the grid
- Advanced energy management algorithms
- Real-time monitoring of power needs
- Visual topology display of energy use
- V2G and V2X
- Demand response (dynamic load balancing)
- Smart charging: support OCPP 2.0.1 with ISO15118 compliance

10.2 Smart City aspects of EVs

EVs will be the principle transportation system in the future. However, the high efficiency of these new transportation systems cannot be exploited in a traditional city, as new power distribution and traffic related problems will appear. The opportunity through to interconnect all of the smart devices (cameras, sensors, actuators, smart phones, smart cars, etc.) in cities, exchange data and communicate between the devices makes the city connected and intelligent and can be done with the help of the Internet-of-Things (IoT). This intelligence helps to manage healthcare, water, sewage and weather systems, city security and to design a more efficient energy distribution and management system.

EVs presence in cities will demand efficient and smart charge scheduling techniques (Smart charging, V2G, V2X, etc). On the other hand, smart city technologies help improve parking or traffic problems. Several studies proved that a smart city encourage the use of electric transport. Additionally, in a smart city, transportation is working optimally and consumes less energy.

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Soon, all new vehicles are equipped with wireless communication systems, and vehicles become connected. Connected vehicles are well-informed, agile, coordinated, cooperative and support road safety applications.

As a result of vehicles becomes integrated, the vehicle to building communication (V2B), the vehicle to road communication (V2R) is reality in a smart city, with the help of vehicle to internet connectivity (V2I) systems. All the information registered by city sensors can be transferred to the buildings, road management systems or to the vehicles.

The relationship between the smart city and an EV is explained on the Fig. 10.1. Information about the recharging systems, the road conditions, and the parking status is available. Each EV can be informed about the present traffic conditions. The smart city and the smart grid concept together can help to manage the V2G concept to promote faster recharge times.

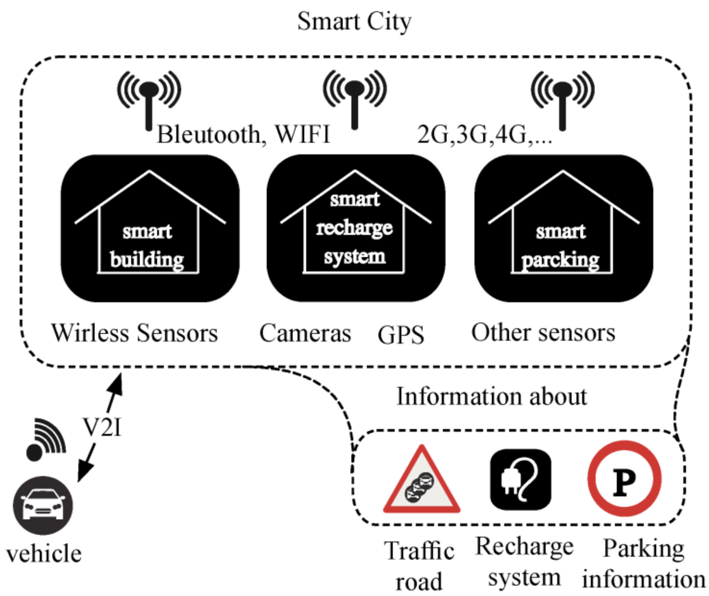

Fig. 10.1 [3].

There have been large investments into the EV sector which not only reduces transport emissions but unlock smart city opportunities and new solutions in the following areas:

- Mobility
- Energy use
- Public services
- Residential and commercial buildings
- Wider urban systems

- Citizen engagement
- Behaviour change

Accelerating EV adoption and realizing the related smart city benefits need coordinated action from organizations, technologies, consumers and products. The European Union greatly invests in the Research and Development of this field.

Some of the innovative solutions that can be a game changer in smart cities [2]:

- Intelligent management of public and private electric car fleets
- Smart management of urban and suburban logistics
- Electrification of public transport
- Fully or partially autonomous vehicles
- Innovative integrated infrastructure including Internet-of-Things (IoT)
- E-mobility solutions that serve multi-modal mobility services

10.3 Advantages for Distribution System Operators

As explained before, without the smart management of EV charging (Smart charging and V2G) Distribution System Operators (DSOs) and Transmission System Operators (TSOs) of the electricity grid would face increased energy demand focused in the afternoon peak period due to increased EV penetration.

Some of the potential results of the future load caused by EVs:

- Potential blackouts
- Transformer system overload
- Voltage and frequency drop
- Increased CO2 emission by peak power plants
- Lower renewable energy penetration etc.

Thanks to these factors, DSOs and TSOs would end up in huge investments in the grid infrastructure, in higher CO2 emissions and lower renewable penetration. Instead, great amount of money is being invested in R&D projects to develop smart cities, smart grids, smart solutions in order to integrate EVs into the electrical grid. As technologies mature and get cheaper, all the positive effect of EVs will be realized for all players of the energy industry: From generation, through transformation, to consumption.

Potential in EVs for DSOs:

- Frequency balancing
- Voltage control
- Grid balancing
- Delaying grid investments
- Peak shaving
- Demand response
- TOU tariff
- Demand Charge Management
- Renewable energy integration

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