Chapter 2

Literature Survey

2.1 Introduction

As the global transportation sector undergoes a transformative shift towards sustainable energy solutions, integrating EVs into the grid has emerged as a pivotal area of research and development. With the increasing adoption of EVs, the demand for efficient and reliable charging infrastructure has become paramount. Grid-integrated electric vehicle charging systems have garnered significant attention as they offer a promising solution to address the challenges associated with EV charging, grid stability, and renewable energy integration. This chapter overviews grid-integrated EV charging systems' fundamental principles and components, including charging infrastructure, onboard/off-board chargers, converter topology in EVs, communication protocols, and control strategies. It explores various charging methodologies, such as Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V), and examines their implications for grid operation and management. Furthermore, the chapter discusses the importance of reliability assessment in ensuring the performance and safety of grid-integrated EV charging systems, considering factors such as equipment reliability, cybersecurity, and interoperability.

2.2 EV Charging Architecture

Electric Vehicle charging infrastructure can be distinguished based on the speed of charging, standardization of chargers, ownership, charging method, the directional of power flow, and connector type, as shown in Fig.2.1 [1].

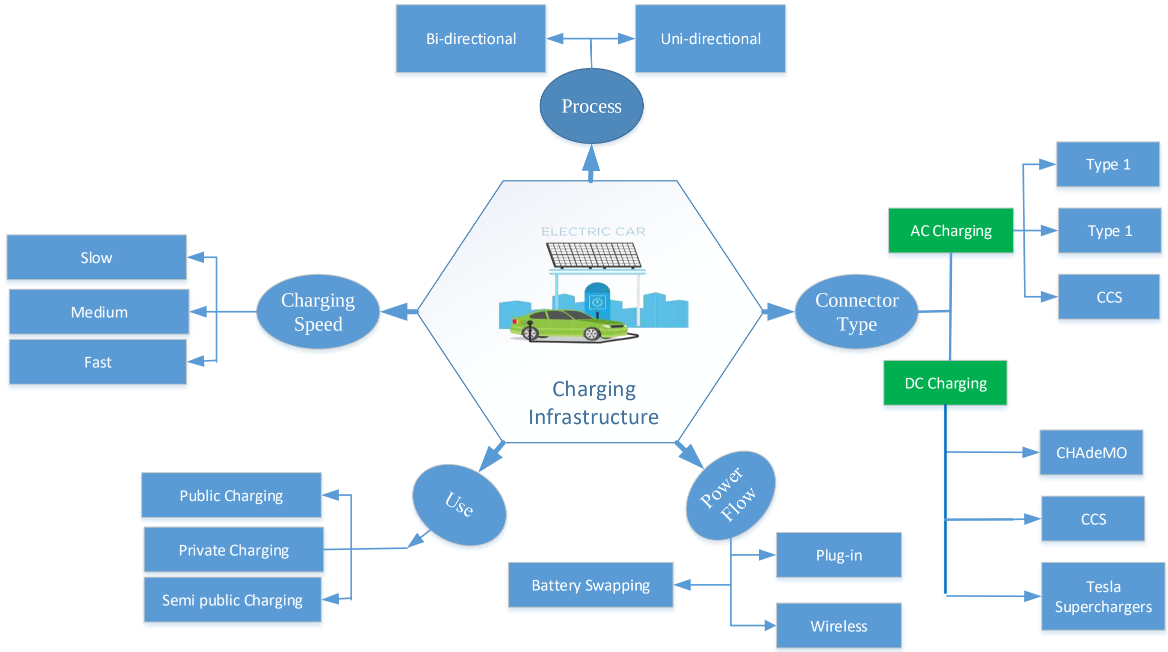


Figure 2.1: Classification of EV charging infrastructure.

2.2.1 EVs Supply Equipment (EVSE)

The EVSE recharges the battery of the EV, also known as EV charging points or EV CS [17].

ESS:

Improving battery efficiency is one of the EV sector's biggest challenges. Electrochemical batteries are the most significant energy storage technology broadly utilized for EVs. Presently, lithium-ion, lead acid, sodium nickel chloride (ZEBRA), nickel metal hydride, and zinc-oxygen (from "electric fuels") are the most common in the experimental phases. The last one uses mechanical charging instead of traditional electric charging.

Battery recycling

Various EVs utilize numerous types of batteries that are used commercially. This section covers the various chemicals used in EV batteries [18]. Since fast charging and discharging of EV batteries generate excessive heat, better safety precautions are needed.

(a) Nickel-metal hydride (NiMH) batteries

NiMH batteries are generally used by HEVs, as shown in Fig. 2.2(a), but some BEVs also use it well. In the 1980s, NiMH batteries entered the market. Their range is between 60 and 120 Wh/kg, with a 68 Wh/kg value. With these batteries, the electric vehicle should have a range of over 100,000 miles and a lifespan of 5-7 years. The battery in this particular HEV does not get power from the outside. The engine's speed, acceleration of the wheel, and regenerative braking will depend on how quickly batteries will recharge in HEVs. However, these batteries require regular maintenance and function poorly at high and low temperatures [19]. These batteries have the following advantages when used in EVs:

(i) It has 30-80 Wh/kg energy. density (far higher than that of Lead-acid)

(ii) Less dependency on fuel than conventional ICE-powered vehicles.

(iii) Low environmental pollution emissions and extreme lifespans (above 160,000 km).

(iv) High-profile manufacturers of HEVs, including Toyota and Nissan, utilize these batteries.

This battery has the following disadvantages when used in EVs:

(i)In-efficient charging is less reliable as it require only 60%

(ii) Up to 12.5 % self-discharge per day at room temperature.

(iii) Fast heat generation rates during fast charging and discharging lead to thermal runaway issues.

(b) Lead-acid batteries

Lead-acid batteries are developed in 1859. These are the oldest batteries that can be recycled and are still used in this 21^{th} century. They function like wet cell batteries and contain a moderate sulfuric acid solution. The benefit of lead-acid batteries is that they are less expensive and have been around for a while. This battery type has a limited lifespan of three years and necessitates monitoring its electrolyte levels. These batteries have Life-long free service, better temperature performance, cost efficiency, greater availability, and durability. A battery technology that is well-established and used extensively in all types of vehicles, as shown in Fig 2.2(b). These batteries have the following advantages when using in EVs:

(i) These should never be discharged to less than 50% of their capacity because doing so condenses the battery's lifecycle.

(ii) Low cost, easy production, and low per unit energy cost.

(iii) High discharge current capability and specific power.

Their drawbacks, when used in EVs, are as follows:

(i) Low specific energy and poor weight-to-energy ratio.

(ii) Slow charging is possible for lead acid batteries; a fully saturated charge takes 14-16 hrs.

(iii) It just has a short cycle life, However, frequent deep cycling reduces battery life.

(iv) The flooded battery type needs to be watered, which is not environmentally friendly.

(c) Li-ion Batteries

Li-ion batteries as shown in Fig. 2.2(c) have a very high specific energy. Li-ion cells produce lithium and discharge it from a solid lattice [20]. There is no conflict in saying that Li-ion batteries-based EVs are available in a large market volume. Nowadays, some lithium-ion batteries typically exhibit about five times the charging current compared to the stated capacity with excellent cycle endurance. This shows that quick recharging from the battery side is no longer an issue. The short life and energy retention capacity are the main reasons behind the limited use of this battery. Li-ion batteries are used in the EV sector, and studies have found they have higher specific energy (100–250 Wh/kg) and power (800–2000 W/kg) than Ni-MH batteries. The actual battery capacity of between 15 and 20 kWh is used in EVs, resulting in a high 60kW charging capacity [21]. Li-ion batteries include the following benefits:

(i) Highly efficient, high-performing, and low-maintenance required.

(ii) Light weight and has higher energy density than other rechargeable batteries.

(iii) They operate effectively at high temperatures, which may negatively affect their life cycles and energy capacities. Some of its limitations are described below.

(i) It is dangerous to explode and is more expensive than conventional batteries.

(ii) Total discharge damages to the battery.

These limitations pose a risk against the safe use of the vehicle [22].

Table 2.1: Comparative study of battery used in EVs :

Characteristics of the battery	Types of batteries used in EVs				
	Lithium-Ion	**Lead-Acid (SLA)**	**Ultracapacitor**	**Flywheel**	**Nickel-Metal Hydride**
Energy density	100-180 Wh/Kg	30-40 Wh/Kg	1734 Wh /Kg	130 Wh/Kg	60-120 Wh/Kg
Power density	1000-5000 W/Kg	180 W/Kg	20 kW/Kg	30 kW/Kg	250-1000 W/Kg
Charge/discharge Efficiency	95-99%	70-92%	85-95%	85-95%	65-80%
Discharging time	10 min -1 hour	15 min- 4 hour	1 second-1 min	10 second-10 min	5 hours
Power consumption	10 kW-10 MW	50kW-30 MW	10kW-1 MW	10kW-20 MW	10 kW-10 MW

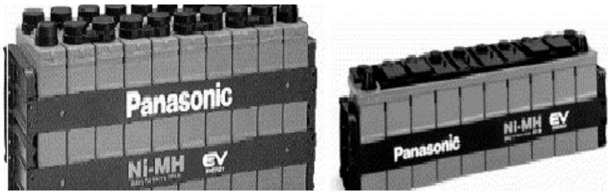
(d) ZEBRA (Na-NiCl$_2$) Batteries

The ZEBRA, also named as Na-NiCl$_2$ battery, was adopted to incorporate several concept vehicles and busses that are used for urban public transportation. This battery needs specific containers since it operates at high temperatures (270°C), so this should be warm inside when cold outside. Fig. 2.2(d) represents a picture of a ZEBRA battery as explained in [23]. These batteries are exceptional for their higher energy density (90–120 Wh/kg) and their cheaper cost compared to other technologies already in use. Other benefits include resistance to overcharge and over-discharge, longer cycle times, and constructive robustness, allowing for use in severe settings and functioning independently of temperature. The ZEBRA battery operates without any memory effect, unlike the nickel-cadmium battery; hence a full discharge is not required. Increased internal operating temperature (270°C to 350°C) is a result of the Na-NiCl2 batteries considerable reduction, and continuous use of an electric vehicle is required to prevent the battery electrolyte from freezing [24].

(e) Flywheel battery

Flywheel is stabilized by a magnet floating in a vacuum. It transfers electric energy into kinetic energy, which is subsequently transformed into electric energy using the same motor/generator.

Table. 2.1 summarised the comparative study and characteristics of various batteries used in EVs.



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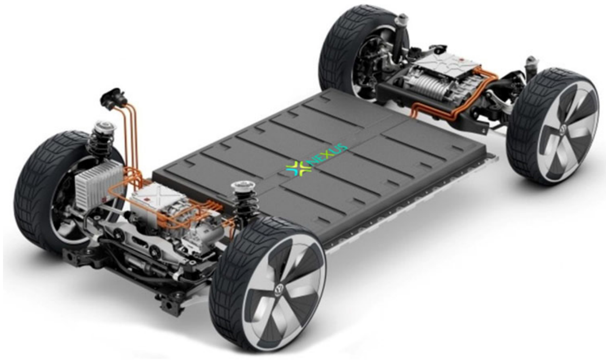

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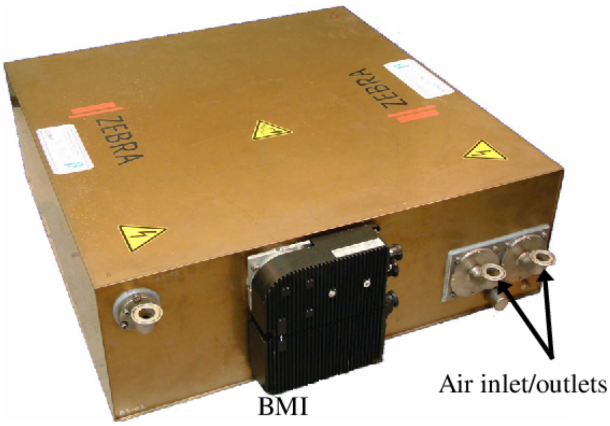


(d)

Figure 2.2: Different types of batteries: (a) Nickel-metal hydride (NiMH) Battery, (b) Lead-acid battery, (c) Li-ion battery, (d) Zeolite Battery Research Africa (ZEBRA) battery.

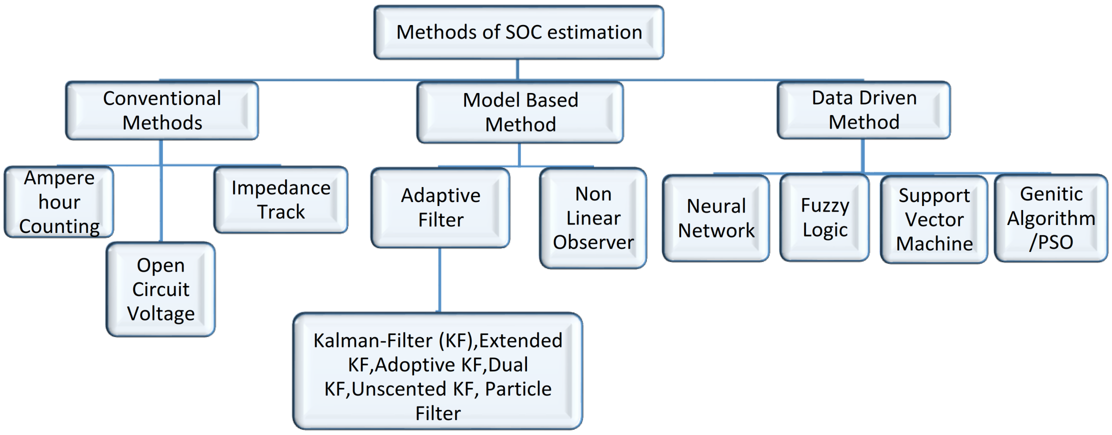


Figure 2.3: SOC Estimation Method Classification.

2.2.2 Battery Management System (BMS)

Automotive battery management system reflects critical functionality, including battery status of charge (SoC), state of health (SoH) voltage, temperature, and current monitoring, as well as cell balancing for lithium-ion (Li-ion) batteries. There are various key indicators in BMS to ensure the safe operation of designed life batteries in EVs, as follows:

(i) SoC (State of Charge)

(ii) SoH (State of Health)

(iii) SoF (State of Function)

(iv) SoT (State of Temperature)

(i) Methodologies for state indicator estimation based on Research trends of SoC

SoC estimation methods can be characterized into three parts:

(a) Model based method

(b) Data-driven method

(c) Conventional method

The conventional method includes the Open circuit voltage estimation method (OCV), impedance track method, and ampere hour method (Ah) as depicted in Fig. 2.3. These methods are easy to understand and have low computational costs for implementation [25, 26].

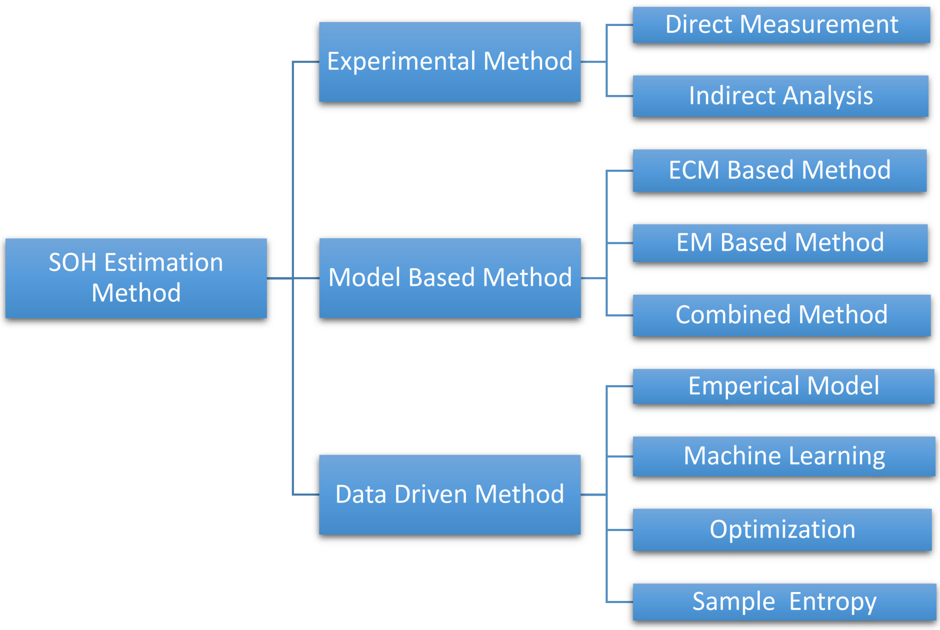


Figure 2.4: SOH Estimation Method Classification.

(ii) SoH estimation Methodology

SOH estimation techniques can typically be divided into three categories, as shown in Fig. 2.4 experimental methods, model-based methods, and data-driven methods as described in [26, 27].

(iii) State of Function (SoF)

In BMS, the state of function (SOF) refers to the ability of a battery to perform a certain function, such as delivering power, accepting charge, or handling discharge. It is an essential parameter that helps assess the real-time functionality and performance of the battery. The SOF is dynamic and depends on various factors like state of charge (SOC), temperature, battery health, and current load [27].

(iv) State of Temperature (SoT)

Temperature has a major impact on and is very sensitive to a battery's dynamic characteristics. Furthermore, since high-energy ESSs are needed, there will always be an increase in the need for high-density battery packs. High-density battery packs experience thermal management issues due to heat generation during the charging/discharging

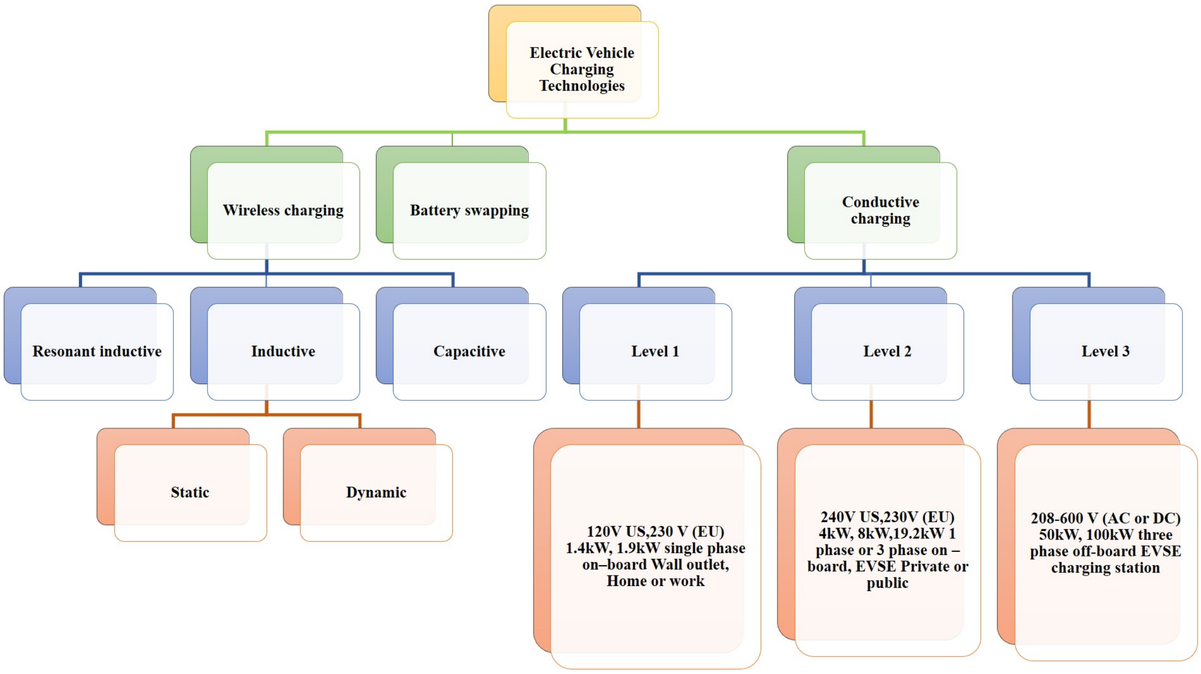


Figure 2.5: EV Charging technology classification.

operation [28, 29].

Real-time implementation

Nowadays, Many researchers have concentrated on techniques for real-time implementation of state estimation algorithms. The capabilities of BMSs are developing technologically and becoming more diversified. As a result, a trade-off between hardware performance and software complexity must be considered when estimating in real-time. Real-time estimation prevents batteries from being overcharged or discharged as described in [30, 31].

So, to prevent failures and fres for upcoming BMSs in ESSs, investigation to monitor and manage battery states is expected to be continuously conducted [32, 33].

2.2.3 EV Charging Techniques

Battery chargers

EV battery chargers with bidirectional or unidirectional power flow can be classified as off-board and on-board. Unidirectional charging reduces the hardware needed, simpli-

fies interconnection problems, and slows battery deterioration. A bidirectional charging system enables power stability with sufficient power conversion, grid-powered charging, and the grid's injection of battery energy. High power is generally limited by weight, space, and cost considerations in typical on-board chargers. This charger can operate in both discharging and charging modes, allowing the EV to provide grid support for various ancillary services. However, the repeated charging-discharging cycles required to power the grid can shorten the life of an EV battery [34]. To prevent these issues, they can be combined with the electric drive systems for on-board charging, which can be either inductive or conductive. In conductive charging methods, the connector directly interacts with the charge inlet. Magnetic energy transfer occurs in an inductive charger [35].
Three basic charging methods for EVs can be distinguished:

(i) Wireless charging (WC)

(ii) Conductive charging

(iii) Battery swapping

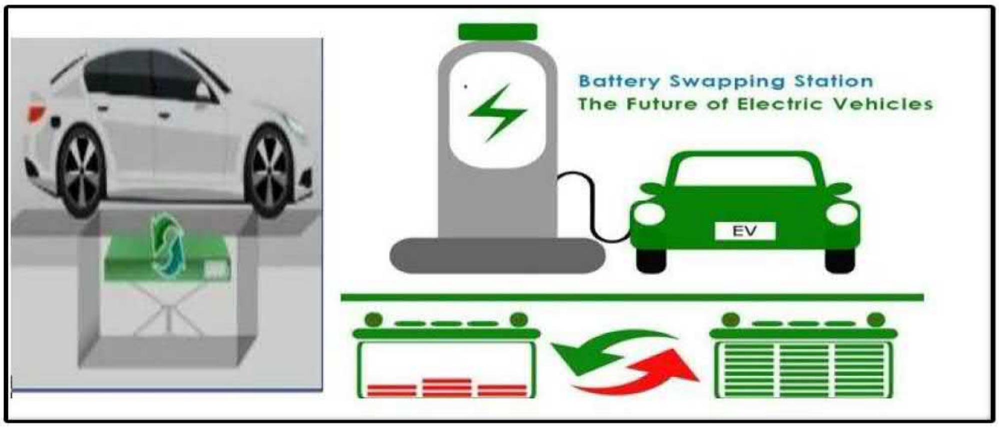
Conductive charging is the most basic and frequently used charging technology. The power supply and battery make physical contact during conductive charging but not during WC. The classification of charging techniques and different charging aspects are illustrated in Fig.2.5.

(i) Wireless power charging

Wireless power transfer (WPT) is accomplished using near-field electromagnetic coupling. WPT has two types: (a) Inductive and (b) Capacitive. Capacitive WPT couples conducting plates with an electric field, whereas inductive WPT couples conducting coils with an electromagnetic field [36].

(a) Inductive wireless power transfer (IWPT)

The IWPT technology has a transmitter side and a receiver side power electronic system. A high-frequency inverter with a current gain and compensation network compensates the transmitter side, which is magnetically connected to the receiver. A voltage gain and compensation network is coupled to the high-frequency rectifier on the receiver side. Ferrite cores are necessary for the inductive WPT to concentrate and shield magnetic flux. The system is tuned to a frequency under 100 kHz to reduce ferrite losses. IWPT's



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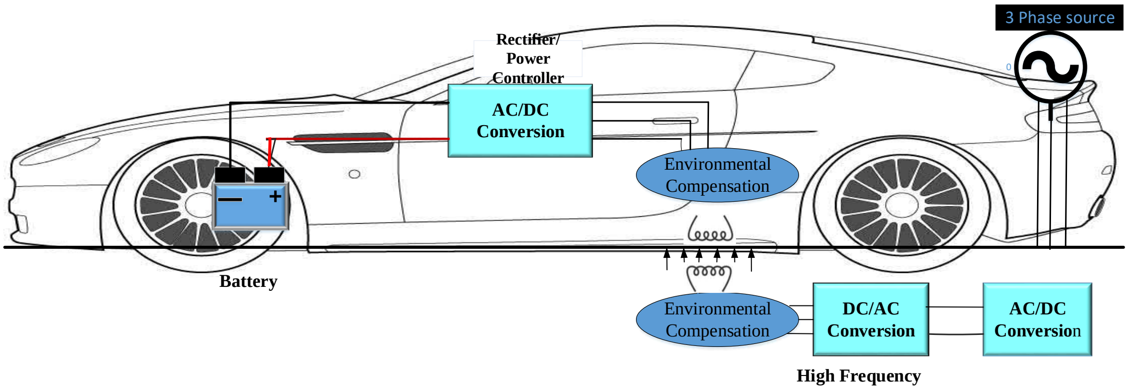


(b)

Figure 2.6: (a) Battery swapping (b) Wireless charging.

commercial feasibility is determined by its high cost and low power transfer density as a result of the large coils and bulky design. An inductive charger with a large air gap with 97% efficiency at 8.3 kW output has been developed in [37]. The vehicle is charged while it is stationary, adopting static wireless charging [38]. Static wireless charging has a higher power transfer efficiency because alignment is improved in [36]. From the year 2009, many researchers and leading companies applied this technique for EV charging [14,39]. High-frequency projects like continuous power transfer, various electromotive field characteristics, and a current-controlled inverter. Most of the issues with EVs, including range anxiety, battery capacity, and expense, are resolved with dynamic wireless charging [40].

(b) Capacitive wireless power transfer

Electromagnetic shielding is not required for capacitive wireless power transfer due to the directed nature of the electric field. It so has a significant advantage over inductive WPT. Due to the lack of ferrite, high frequency can be used, which leads to a smaller, less expensive product. The key issue with capacitive WPT is ensuring electromagnetic safety while maintaining high power transfer density and good efficiency, as described in [41].

Advantages of Wireless Charging

(i) Convenience: No need to plug in; just park and charge.

(ii) Ease of Use: Reduces wear and tear on connectors.

(iii) Aesthetic: No visible cables or plugs, cleaner look.

(iv) Safety: Eliminates tripping hazards and reduces risk of electric shock.

(v) Weather-Proof: No exposed connectors to weather conditions.

(vi) Seamless Integration: Can be embedded in roads, garages, or parking lots.

(vii) Reduced Maintenance: Fewer mechanical parts to maintain.

Disadvantages:

(i) Efficiency Losses: Lower efficiency compared to wired charging.

(ii) Slower Charging: Generally slower than wired charging methods.

(iii) High Initial Costs: Expensive to install infrastructure.

(iv) Alignment Sensitivity: Proper alignment of the vehicle is crucial.

(v) Limited Availability: Fewer wireless charging stations are available.

(vi) Technical Complexity: More complex technology and potential for higher failure rates.

(vii) Power Transfer Limits: Current technology supports lower power transfer rates.

(viii)Interference: Potential for electromagnetic interference with other devices.

(ii) Conductive (Plug-in/Wired)charging

Conductive charging between an EV and the utility grid requires direct metal-to-metal contact. This charging process is shown to be reasonably reliable and effective. Off-board and on-board are the two types of conductive chargers available in [42]. The EV is charged from EVSEs using cable charging, which can use AC or DC power. Wired

EV chargers can be either off-board or on-board, depending on whether the charger is in EVSE. The converter in the on-board charger converts AC power to DC and feeds it to the battery. The converter's size and the EV space limitations limit the power rating of the on-board charger. Therefore, they can charge the EV slowly or moderately. In contrast, the converters used in off-board chargers are a component of EVSE and provide the EV battery with DC power directly, bypassing the on-board charger and allowing users to charge. Fig. 2.8-2.9 displays the general schematic for conductive EV charging.

Advantages

(i) Widely Available: Established and common infrastructure.

(ii) Ease of Use: Simple plug-in process.

(iii) Lower Initial Costs: Cheaper infrastructure compared to battery swapping.

(iv) Compatibility: Most EVs are designed for plug-in charging.

(v) Flexibility: Can be installed at homes, workplaces, and public areas.

(vi) Energy Efficiency: Direct connection ensures efficient power transfer.

(vii) Lower Maintenance: Less complex than battery swapping systems.

Disadvantages

(i) Longer Charging Times: It takes longer than battery swapping.

(ii) Range Anxiety: Charging times can concern long trips.

(iii) Grid Strain: High demand can stress the electrical grid.

(iv) Space Requirement: Need for dedicated parking spots for chargers.

(v) Infrastructure Costs: High costs for installing fast chargers.

(vi) Wear and Tear: Frequent plugging/unplugging can wear out connectors.

(vii) Weather Sensitivity: Outdoor chargers can be affected by weather conditions.

(viii) Dependency on Grid: Limited to grid electricity availability.

(iii) Battery swapping

Changing batteries is a simple and quick process. Replacing the discharged battery, as shown in Fig.2.6(a) with a fully charged one takes a short while. There are two methods for swapping batteries.

(i) Battery swapping using a chassis, where the battery is loaded and unloaded from the vehicle's bottom.

(ii) The battery packs are changed from the side or back of the vehicle.

Most electric four-wheelers (4W) have their batteries mounted at the bottom of the chassis, so replacing their battery packs requires special tools. The majority of the two-wheeler (2W) and three-wheeler (3W) devices, whose batteries are readily available, do not have this issue [43]. Therefore, replacing the battery is technically feasible for 2W and 3W but more challenging for 4W. Tesla unveiled a battery-switching technology in 2013 that could swap out a Models' circa-1990s battery. However, Tesla found several issues, so they could not scale up the technology and only maintained one battery swapping station in California [44].

Advantages

(i) Reduced Downtime: Quick battery swaps in minutes.

(ii) Increased Convenience: No need to wait for charging.

(iii) Enhanced Battery Management: Centralized maintenance and optimization.

(iv) Cost Efficiency: Lower upfront costs for fleet operators.

(v) Energy Use Flexibility: Charge during off-peak hours, use during peak.

(vi) Urban Mobility: Efficient in space-limited urban areas.

(vii) Support for Renewable Energy: Integrates with solar or wind power

(viii) Reduced Range Anxiety: Alleviates fears of running out of charge.

Disadvantage

The drawback of this technique is that the battery is difficult to replace because the battery pack is tightly secured with many nuts and screws due to its location on the underside of the chassis. It is an expensive infrastructure setup.

2.3 Electric Vehicle Charging Standards and Power Levels

The IEA (International Energy Agency) aims for 548 million EVs by 2040 [45]. As the EV market expands, so do the numerous EVs CS, which serve as the route for EV connection with the grid. CS is classified as (i) residential CS and (ii) non-residential CS. These can be equipped with slow charging Level 1, Level 2, and fast charging Level 3 and DC fast charging technology. Slow-charging ports are currently used at home for most EV charging, although CS with all types of charging connectors is set to be installed in commercial locations in the future [46]. Several international standards include EV charging infrastructure. While IEC is widely used in Europe, SAE and IEEE are employed by manufacturers based in the United States. The CHAdeMO EV charging protocol was developed in Japan. China employs Guobiao (GB/T) standards for AC and DC charging, GB/T AC charging requirements are equivalent to IEC standards. This was developed by the Chinese National Committee of ISO and IEC. Frequently used standards related to EV charging, such as IEC and SAE standards, are included in Fig. 2.7 as described by author [47].

2.3.1 Charging power levels of EVs

EV chargers can be powered by DC or AC sources. The voltage and frequency levels of AC voltage vary depending on the power system of the relevant country. AC charging has three different voltage levels: level 1, level 2, and level 3. Level 3 charging has the most significant charging voltage. While level 3 charging facilities are being built up, installing level 2 and level 1 charging stations in a private location is possible.

(a) Level 1 charging

In level 1, slow charging is characterized as charging outlets in the US, like the NEMA 5-15R, are standard single-phase grounded outlets rated at 120 V/15 A as explained [48]. Fig.2.8 illustrates the connection using a standard J1772 connector into the EVs AC port. There is no need for additional infrastructure for residential and business areas. During off-load times, a lower charging rate is offered; at night, it is possible. The on-board chargers usually permit level 1 charging using a 120V single-phase AC supply up to a power level of 1.9 kW; the permissible charging current range is between 15 and 20 amps. An EV may be fully charged with level-1 charging in 3 to 20 hours, depending on the ESS type and its storage. Level 1 charging is ideal for overnight charging, which often occurs at homes or in parking lots due to the availability of standard power outlets and the length of the charging process [49].

(b) Level 2 charging

Level 2 charging is the main charging technology used in public and private facilities. The current level 2 chargers provide charging ranges of 208 V or 240 V (max 80 A, 19.2 kW).

EVs like Tesla have on-board chargers and need an outlet. However, their deployment at the residential and commercial levels includes special handling and installation. A 240V supply is typically available in American homes, and a level 2 charger takes overnight to charge the EV fully. Level 2 chargers are desirable to EV owners because of their short charging times and common charger-to-vehicle interfaces. Installing a level 2 charger costs USD 1000-3000 [50, 51].

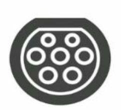
(c) Level 3 charging

The future level 3 technology has the potential to reduce EV range anxiety and ESS, which provides quick charging for companies. Fig. 2.7 illustrates the various standards, charging ports, and connectors for 1-phase/3-phase AC charging, DC fast charging, and the AC-DC Combo J1772 combination connector from SAE, which charges the EV in under one hour. These chargers are set up parallel to the gas stations on the sides of the highway. Off-board Level 3 chargers usually run on a 480V or more excellent three-phase supply. Direct DC connections can be made to the vehicle. Fig. 2.9 depicts the DC plug used for charging. The Japanese protocol CHAdeMO has received international recognition for fast charging. Level 3 chargers may cost anywhere from USD 30,000-60,000 [52, 53].

2.3.2 EV charging level comparison

The level 1 and level 2 EVSE must be on-board as per the SAE J1772 standard, while the level 3 EVSE must be off-board. A low-power charger does not negatively impact the utility system with a large load. Conversely, high-power (Level 3) chargers increase demand and impact the local distribution network, specifically during periods of peak load [54]. According to IEC 61851 and SAE J1772, there are different levels of EV charging as illustrated in Table 2.2 [55].

The various standards provide the fundamental principle, assessment, definition, safety, and protection of low-voltage electrical installation. Different sections of the standards as depicted in Fig. 2.7 provide standards for protection against electrical shocks and protection against thermal effects, overcurrent, voltage, and electromagnetic disturbances. It also provides safety standards for isolation, switching, control, and wiring systems.

	USA	JAPAN	EU	CHINA
Single phase/ three phase AC charging	 SAE J1772 Level 1, Level 2 Single phase	 SAE J1772 Level 1, Level 2 Single phase	 IEC 62196 Level 1, 2 Single/Three phase	 IEC 62196 Level 1, 2 Single/Three phase
DC fast charging/ AC-DC combo	 Level 1 +DC Level 1 +DC SAE J1772 Combo	 JEVS G105-1993 CHAdeMO DC fast charging	 IEC 62196-3 Hybrid combo	 GB/T 20234.3-2011

(a)

	USA	JAPAN	EU	CHINA
Single phase/ three phase AC charging	 SAE J1772 Level 1, Level 2 Single phase	 SAE J1772 Level 1, Level 2 Single phase	 IEC 62196 Level 1, 2 Single/Three phase	 IEC 62196 Level 1, 2 Single/Three phase
DC fast charging/ AC-DC combo	 SAE J1772 Combo; Tesla Super Charger	 JEVS G105-1993 CHAdeMO DC fast charging	 IEC 62196-3 Hybrid combo	 GB/T 20234.3-2011 DC fast Charging

(b)

Figure 2.7: Various standard (a) Charging ports, (b) Connectors.

Table 2.2: Comparative study of charging levels as per IEC 62196, IEC 61851 and SAE J1772

Type of power level	Type of charger/phase	Installed area	Power level (kW), current level (A)	Charging duration (hours)	EVs (Types)
Level 1 120 V AC (U.S.) Level 1 230 V AC (E.U.)	On board 1-Phase	Domestic	1.5 kW, 12A 1.9 kW, 20A	5-12 hours 11-36 hours	PHEVs (5-15kWh) EVs (16-50 kWh)
Level 2 240 V AC (U.S.) Level 2 400 V AC (E.U.)	On-board 1-Phase	Private and Public parking area, office, malls etc.	5 kW, 17A 8 kW, 32A 19.4 kW, 80A	2-4 hours 4-6 hours 3-4 hours	PHEVs (5-15 kWh) EVs (16-30 kWh) EVs (3-50 kWh)
Level 3 (300-600 V, Vdc) (DC fast charging)	Off-board 3-Phase	Commercial Parallel to refueling station	50 kW-350 kW, 400A	0.5-1 hours 0.4-0.6 hours	EVs (20-50kWh)
DC ultra-fast charging (Next generation)	Off-board (3-Phase) Charging at public place similar to gas stations	Charging at public place similar to gas stations	800 Vdc, 400 kW and higher , (400 A and higher)	Approximately 10 minutes	EVs (20-50 kWh)

2.3.3 Power infrastructure in EV (on-board charger/off-board charger)

A fundamental interface between the power grid and the EV, the power converter aims to enable voltage conversions and reliable charging/discharging management. Several novel power converter topologies for EV chargers have been proposed in [56, 57]. The charging topology of an EV converter can be classified into one-stage and two-stage types based on the number of conversion stages. The onboard charger usually uses a single-phase AC input due to its slow charging capability. Additionally, the conventional two-stage technique is utilized for On-board chargers, consisting of the First-Stage (AC-DC) power factor correction (PFC) converter and the second-stage (DC-DC) converter [58].

Power flow direction : Based on the direction of power flow, unidirectional and bidirectional are the two types of EV chargers, as shown in Fig. 2.8. The unidirectional EV charger topology consists of a unidirectional (DC-DC) converter and a diode rectifier. Whereas bidirectional DC-DC and AC-DC converters are used in bidirectional chargers [34].

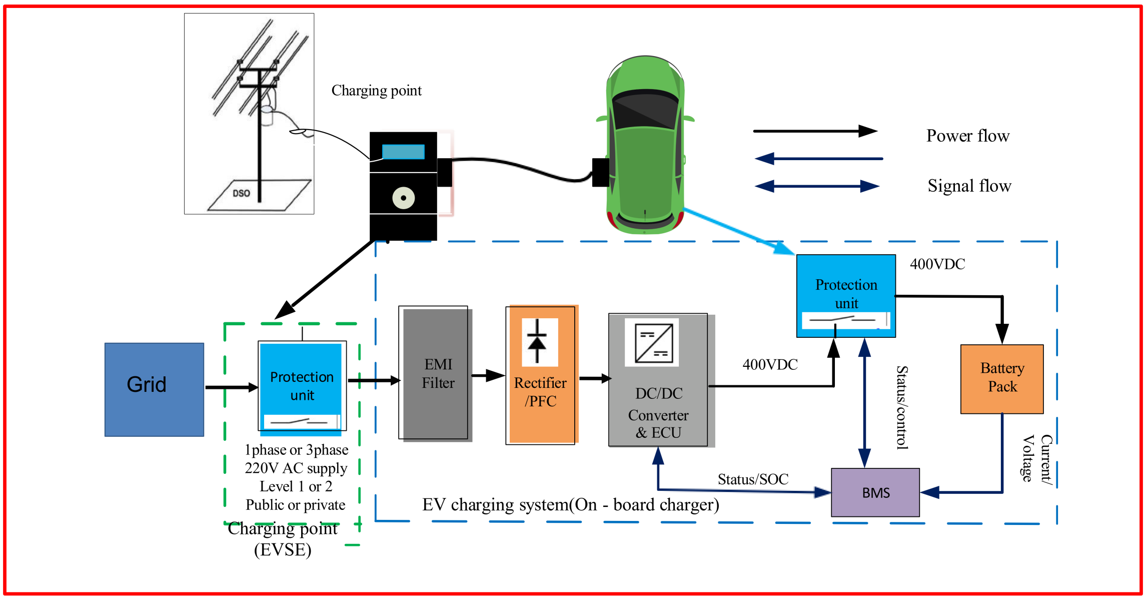


Figure 2.8: Power infrastructure in EV (On-board charger).

2.4 Converter Topologies for EVs Battery Chargers

In EV battery chargers, various converter topologies are employed to efficiently convert grid AC power to the required DC voltage for charging the vehicle's battery. Here are some common converter topologies used in EV battery chargers:

(i) AC/DC Rectifier:

- This is the first stage of the charger, converting AC grid voltage to DC.
- Topologies include diode rectifiers, bridge rectifiers, and active rectifiers.
- Diode rectifiers are simple but suffer from poor power factor and efficiency.
- Active rectifiers, using switches (such as MOSFETs) controlled by pulse-width modulation (PWM), offer improved power factor correction (PFC) and efficiency.

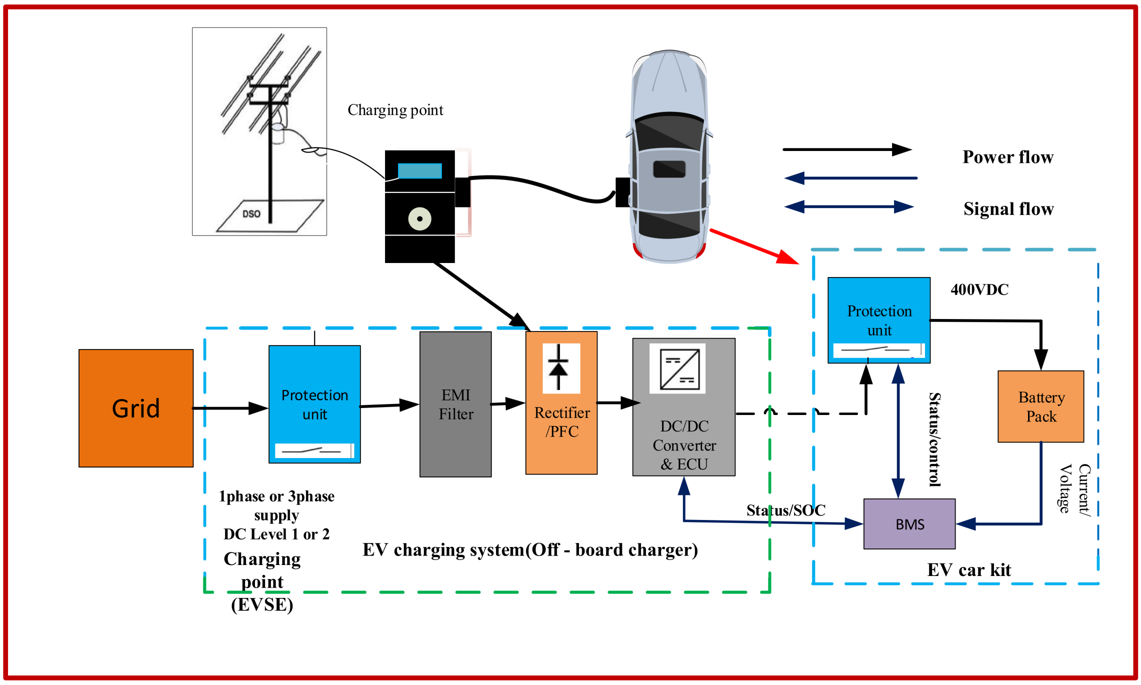


Figure 2.9: Power infrastructure in EV (Off-board charger).

- Converts mains AC to DC for electronic devices such as computers, TVs, and mobile chargers.

(ii) DC/DC Converter:

- This stage regulates the DC voltage to the required battery charging level.
- Topologies include buck, boost, buck-boost, and isolated converters.
- Buck-boost converters can handle a wide input voltage range.
- Isolated converters provide galvanic isolation between input and output, ensuring safety and potential for bidirectional power flow (for vehicle-to-grid applications).

Buck converters step down voltage, while boost converters step it up. Buck-boost converters can handle a wide input voltage range. Isolated converters provide galvanic isolation between input and output, ensuring safety and potential for bidirectional power flow (for V2G applications).

Bidirectional Converter: Some EV chargers incorporate bidirectional capabilities to allow power flow from the vehicle's battery back to the grid. Bidirectional converters

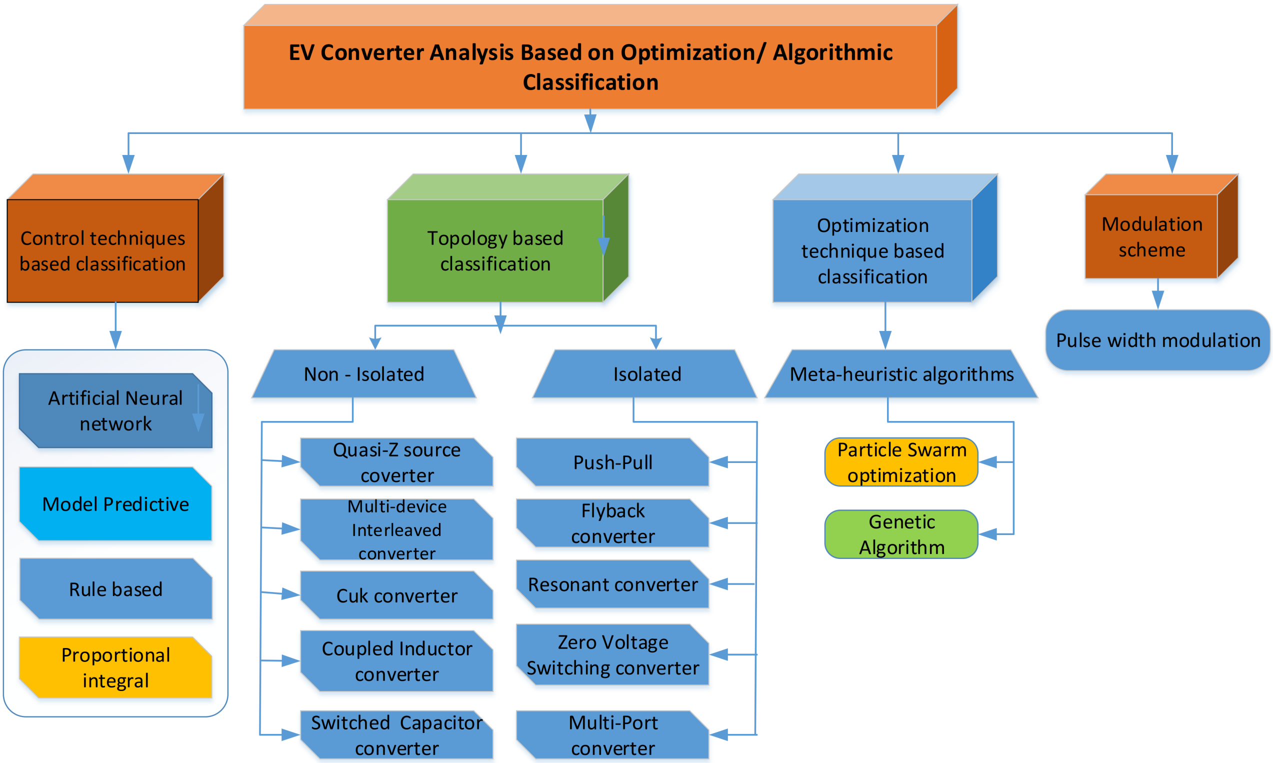


Figure 2.10: Power converter topologies for Charging EVs and different algorithms .

often combine DC/DC and DC/AC conversion stages. These converters enable functions like V2G, vehicle-to-home (V2H), or vehicle-to-vehicle (V2V) power transfer as depicted in Fig. 2.11.

Pulse Width Modulation (PWM) Control: PWM control techniques are widely used in power converters to regulate output voltage and current. PWM control is employed in AC/DC rectifiers and DC/DC converters. It allows precise control of the power delivered to the battery, optimizing charging efficiency and protecting it from overcharging or excessive current.

Soft-Switching Techniques: Soft-switching techniques, such as zero-voltage switching (ZVS) and zero-current switching (ZCS), minimize power converters' switching losses. These techniques reduce stress on power semiconductor devices, improving overall efficiency and reliability.

Resonant Converter Topologies: Resonant converter topologies, such as LLC resonant converters or phase-shifted full-bridge converters, are used in high-power EV chargers to achieve high efficiency and power density. These converters operate at high frequencies

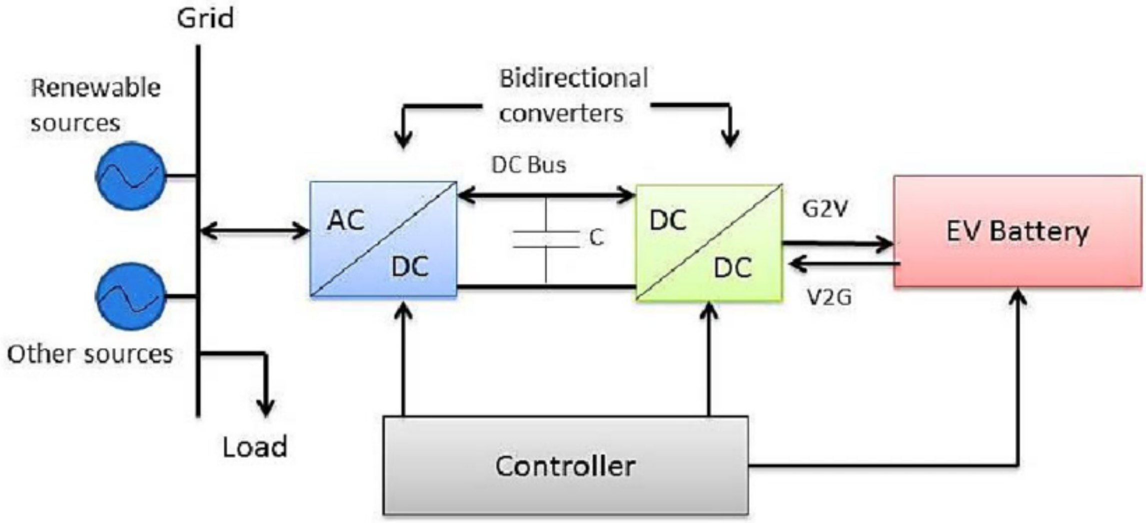


Figure 2.11: EV battery charger (Bi-directional converter).

and utilize resonant tank circuits to minimize switching losses.

EV converters can be classified into categories based on the converter topologies and control modulation techniques. Isolated and non-isolated, two types of DC-DC converter configurations are used in EV chargers [59, 60].

The concept of an integrated battery charger with front-end (AC-AC) and back-end (AC-DC) converters for charging EV batteries is also discussed. The switching technique and appropriate control algorithm depend on the hardware setups involved in battery charger architecture. Due to switching characteristics, DC-DC converters are nonlinear and display mildly damped dynamics. Therefore, an appropriate DC-DC converter control method is necessary to achieve a fixed and regulated output voltage. It is possible to control converters using conventional linear regulators, such as proportional-integral (PI) regulators. Still, their performance is constrained and inadequate under heavy loads and when system parameters change. Intelligent controllers are used to solve these issues because of their quick response time, excellent dynamic performance, and robust controllability. Due to the switching nature, DC-DC converters are nonlinear and exhibit slightly damped dynamics. Fig. 2.13 depicts the power architecture of the EV battery charger [61].

Fig. 2.10 includes information on the comprehensive classification of EV converters, including configuration, control, modulation, and optimization of EV grid integration charging system.

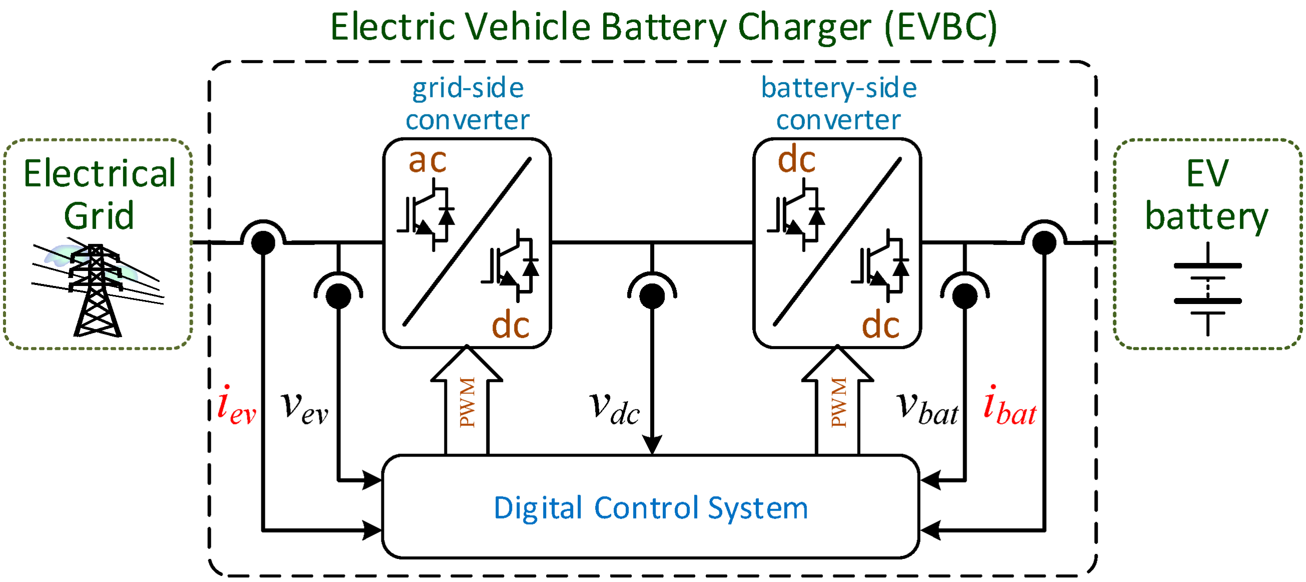


Figure 2.12: Schematic diagram of EV battery charger.

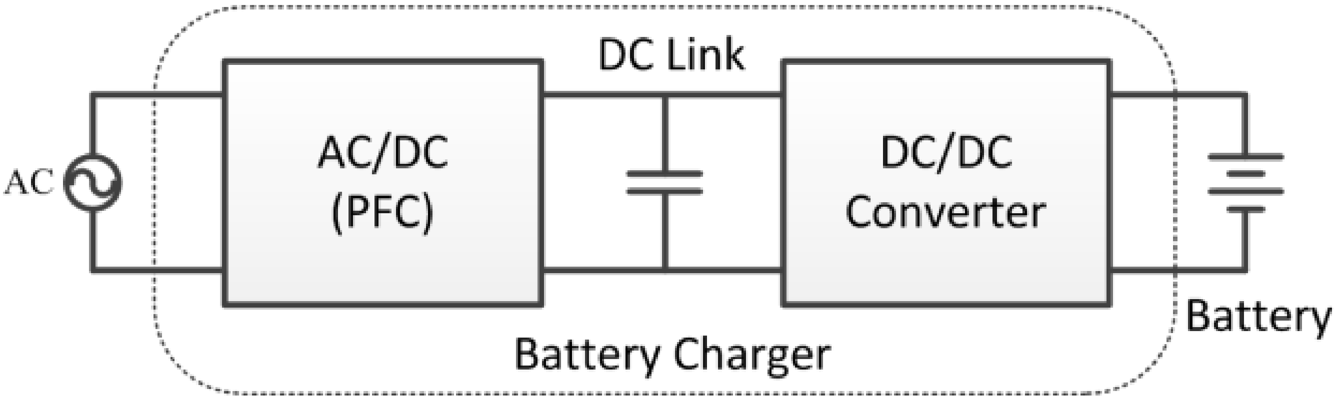


Figure 2.13: Power architecture of EV battery charger.

(a) First stage front-end converters (AC-DC)

For input supply, front-end converters are connected to the main supply, followed by an input filter. An input filter is used to eliminate current harmonics. According to the requirements of particular applications, EV charging system uses a combination of converter topologies, such as AC-DC, DC-AC, AC-AC, and DC-DC converters. The utility mains supply the AC-DC power converter's input, which transforms into an isolated DC output. Two independent converter stages were used in the development of these converters. To produce a medium-level DC voltage, rectification is the first step. A front-end converter requires the PFC technique to produce an input power factor close to unity. The EV battery receives the desired isolated DC voltage from a back-end converter.
Power Factor Correction (PFC stage) A PFC circuit is generally positioned between the rectifier and the DC-DC stage to solve the current harmonics problem and harmonics to the grid, as well as to stabilize the DC link voltage. The PFC is used to first detect the input currents and voltages before switching ON and OFF the switches to regulate the input currents to be sinusoidal and in phase with their corresponding phase voltages. The components of a typical PFC circuit are an inductor (L), an active switch (S), and a freewheeling diode [62].

(c) Second stage back-end converters (DC-DC)

The front-end (AC-DC) and back-end (DC-DC) converter topology for charging EV is the one that is most commonly used. PFC is used by the front-end topology to complete the rectification process, and the back-end (DC-DC) converter maintains the voltage level suitable for EV battery charging. Significant challenges must be overcome while designing a battery charger for EVs, like higher efficiency, isolation, cheaper costs, higher power densities, and meeting safety standards. Based on the galvanic isolation between the output circuitry and the input source, the back-end converter configurations can be isolated, or non-isolated [63]. The different converter topologies (isolated and non-isolated) have their purposes, consequences, advantages, and disadvantages. As per the recent literature, a comparative summary of back-end (DC-DC) converters is given in Table 2.3 and 2.4.

Table 2.3: Description of non-isolated (DC-DC) converter

DC-DC Converter	Purpose	Consequences	Advantages	Disadvantages	Ref.
CC (Cuk Converter)	To minimize significant energy wastage	Provides a reliable, ripple-free output.	Inductors have a lower peak-to-peak ripple current. Input and output currents that are continuous.	Stabilization is challenging. Resonance that is uncontrolled and undampened.	[64, 65]
CIBC (Coupled Inductor Bidirectional Converter)	To minimize the ripples in the output current and inductor current.	An increase in coupling coefficient results in an increase in efficiency	Inexpensive, small size and reduced ripples	There is little opportunity for improvement. Voltage ripples are not taken into consideration.	[66]
SCBC (Switched-Capacitor Bidirectional Converter)	To optimize voltage gain and efficiency	Efficiency is above 9%	Inexpensive, small in size and limited output current	Very high ripple current unable to maintain higher efficiency for a range of input to output voltage ratios	[67]
MDBIC (Multi-Device Interleaved Bidirectional Converter)	Less passive components are used. To eliminate output voltage and input current ripples.	Achieves low stress and low EMI. Compared to an interleaved boost converter (IBC), reduces current and voltage ripple. Reduces the size of both the inductor and capacitor compared to IBC.	High performance. For high efficiency, ideal. Easy control strategy. Heat sink and components size reductions.	Complex circuit because there are so many components. Duty cycle is quite sensitive towards switching sequence.	[68]
QZBC (Quasi-Z-Source Bidirectional Converter)	To get a broad range of voltage gain	The maximum efficiency is 96.44%, and the minimum efficiency is 88.17%.	Reduced switch stress Moderate component ratings. Buck/boost features and functionalities	The input current is intermittent. the high voltage stress on the capacitor.	[69]

2.5 Electric Vehicle Grid-Integration (EVGI)

By reducing reliance on fossil fuels and greenhouse gas (GHG) emissions, EVs will be essential to developing a sustainable transportation system. However, because of the rise in load demand, impacts on power quality, and power losses, high levels of EV integration into the distribution grid have created several issues for the power grid operation, safety,

Table 2.4: Description of Isolated converter

DC-DC Converter	Purpose	Consequences	Advantages	Disadvantages	Ref.
PPC (Push–Pull Converter)	To adjust the DC power supply's voltage	severely limits initial power.	Better use of transformers and transistors.	The usage of two switches is infrequent in flux walking phenomena.	[70]
FC (Flyback Converter)	In order to deal with a large voltage input variation	Achieves lower leakage inductance that is within reasonable parameters	The output is isolated from primary. The ability to control the various output voltages	It has ripple current, more losses. Increased input and output capacitance. Right half pole is present in the compensating loop.	[71]
ZVSC (Zero-Voltage Switching Converter)	To deliver reliable power under a variety of load fluctuations. To conduct -out the soft-switching in an effective way. The output diode bridge voltage must be clamped.	Under all load conditions, achieves zero voltage switching. Ensures a reliable and steady process when there is no load due to the symmetric auxiliary circuits.	Minimal switching loss. External clamping circuit is not essential.	It requires a large capacitor. A lack of fault tolerance. Higher current ratings.	[72]
RC (Resonant Converter)	To reduce the quantity of passive filters and magnetic components.	High step-up/down capability is achieved. Succeeds with great efficiency.	Low price, high conversion rate, and high efficiency	Costly controller. Integrated transformer as being complex.	[73]
MPIC (Multi-Device Interleaved Bidirectional Converter)	To regulate duty cycle in order to optimise system performance. To minimize the system's overall losses. To evaluate dynamic analysis and associated control strategies	Achieves a broad voltage gain range. A quick dynamic responsiveness is attained. Power flow is independently controlled. High efficiency is attained by phase-shift and duty cycle control.	Gain at high voltage. Galvanic separation	There are so many components. Under equilibrium mode and transient conditions, complex analysis. High sensitivity is associated with duty cycle fluctuations as the load varies.	[74]

and network planning [75]. The impacts of EVGI can be categorized into two aspects as shown in Fig. 2.14 as explained below, i.e., Positive and negative effects also summarized

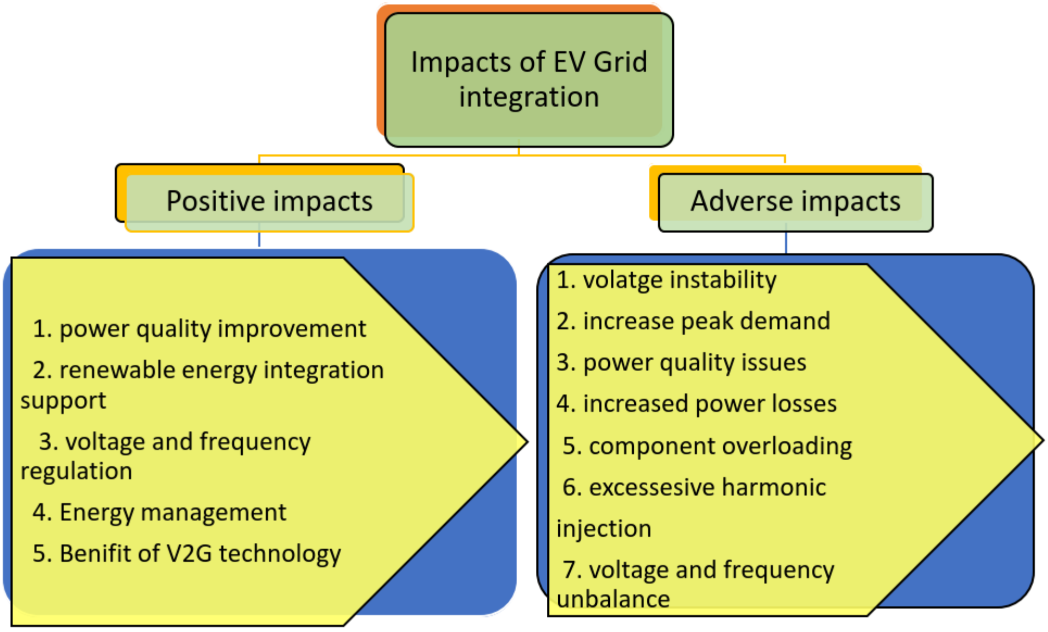


Figure 2.14: Impacts of grid integration.

in Table 2.5 and 2.6.

2.5.1 Negative impacts

Electric utilities face enormous difficulty due to adopting EVs. An excessive integration of EVs into the distribution system may affect the load profile, components performance, frequency, voltage imbalance, excessive harmonic injection, power losses, and grid stability [76].

2.5.2 Positive impacts

There are various positive impacts of EV integration in the grid because the battery storage of EVs can be used for ancillary services, mitigating the intermittent nature of RESs, peak saving, etc. [77].

2.5.3 Utilization of EVs to improve reliability or better renewable energy grid integration system

EV is charged from the grid in G2V, whereas the vehicle discharges electricity to the grid, i.e., V2G. It is possible to regulate the bidirectional flow of electrical energy between

Table 2.5: Positive impacts of grid integration :

Advantages	Description /Methods
Power quality improvement [77–79]	(i) Controlled EVGI can reduce voltage surges brought on by unchecked distributed energy resources penetration. (ii) It is possible to eliminate voltage flickers.
Renewable energy integration support [80, 81]	(i) By using EVs as energy storage, the renewable energy sources can have less unpredictability in renewable energy(RES) may be minimized. (ii) EVs can save money by reducing greenhouse gases by acting as a barrier to renewable energy.
Voltage and frequency regulation [82]	(i) Grid frequency deviation correction for frequency regulation. (ii) EVs can save money by reducing greenhouse gases by acting as a barrier to renewable energy. (iii) Controlling voltage by generating or absorbing reactive power. (iv) Power flow balance achieved by saving surplus power. (v) Accelerating power absorption electric networks in remote locations are becoming more reliable.
Power Management Techniques [83, 84]	(i) Enhanced power management is possible by using scheduled charging/discharging. (ii) Scheduling allows for the fulfilment of peak load demand. peak hours for discharge.

Table 2.6: Negative impacts of EV grid integration

Power loss [85]	(i) Large-scale real power demand from EV grid penetration results in power loss. (ii) The increase in power loss during off hours can reach 40% if 60% of the vehicles are associated with the utility system are electric vehicles. (iii) Coordinated charging can potentially increase load factor and reduce power losses. (iv) The grid's power loss can be decreased with the right location and capacity.
Component overloading [85]	(i) Electric vehicle grid integration in an extra-large no involves added load demand which must be generated and transmitted. (ii) The extra loads are too much for components of the existing power system, which can cause overloading and impair transformer lifespan.
Harmonic injection [86]	(i) High penetration of power electronics converter emitting harmonics can cause harmonic pollution in the grid. (ii) Some studies find that the THD level brought on by EV charging is less than1%, while it may rise as more chargers are connected.
Stability [87]	(i) The power system becomes unstable because EV loads are nonlinear and consume a lot of power rapidly. (ii) Due to increased demand growth of EVs in the grid, the overall power system becomes more susceptible to disturbances and takes longer to system stabilize. (iii) EVGI can improve power grid stability when properly managed.

the cars and the electric grid in the standard system. Demand response services with electric vehicles and the grid presented by V2G are intelligent network operations. In this context, V2G presents the transmission of electricity and relative data with network and transportation systems, trying to implement the mutually advantageous interactions necessary to create a smart city as shown in Fig. 2.15 [88].

(i) Vehicle-to- Grid (V2G), Vehicle-to-Home (V2H), Sun-to-Vehicle (S2V) The V2H and V2G are included in smart cities' electric power distribution systems to evaluate reliability. V2G will provide frequency regulation and spinning reserve as described in detail by the author [89, 90]. Similarly, with fuel-based vehicles, EVs now use worldwide demand charging stations. Sun-to-vehicle (S2V) or EV-PV charging recharges solar energy to use a charging station powered by photovoltaic cells [91]. The amount of energy made accessible by EVs depends on the extent of outages, the amount of time needed for charging, and spatial patterns. Electric "V2H" is a source of energy to meet home needs. When power loss along the lines is a factor, EVs are helpful. Then, an optimization issue is identified. This optimization issue aims to achieve the least quantity of ENS residue at each node. So, a non-linear optimization strategy is used to achieve low loss and increased reliability.

(ii) V2X technology This technology introduced the concept of utilizing the energy stored in EV batteries for additional uses (V2G). To control the bidirectional power flow between EVs and the grid, V2G intends to deploy intelligent EV charging. The EV can be charged during off-peak hours, and the utility can use the electricity stored in the EV to supply the peak load. V2X expands the concept to cover a variety of EV power use cases and destinations, including V2H, V2B, V2F, and V2L and vehicle to infrastructure(V2I). One of the most recent communications and automobile technology developments is V2I as shown in Fig. 2.15. When using V2I, vehicles connect to the road system to share information. The various vehicle speeds tend to produce a dynamic performance with this technology. Road safety and workload growth are two significant issues that V2I technology helps to address, all while having a less negative environmental impact, as the author has discussed in detail in [92].

2.6 Reliability Assessment Techniques in EVs

Reliability assessment uses investigative approaches based on traditional methods and computational simulations. Several novel techniques have been recently suggested for reliability analysis. To gain deeper insight into the reliability of the BEV power train,

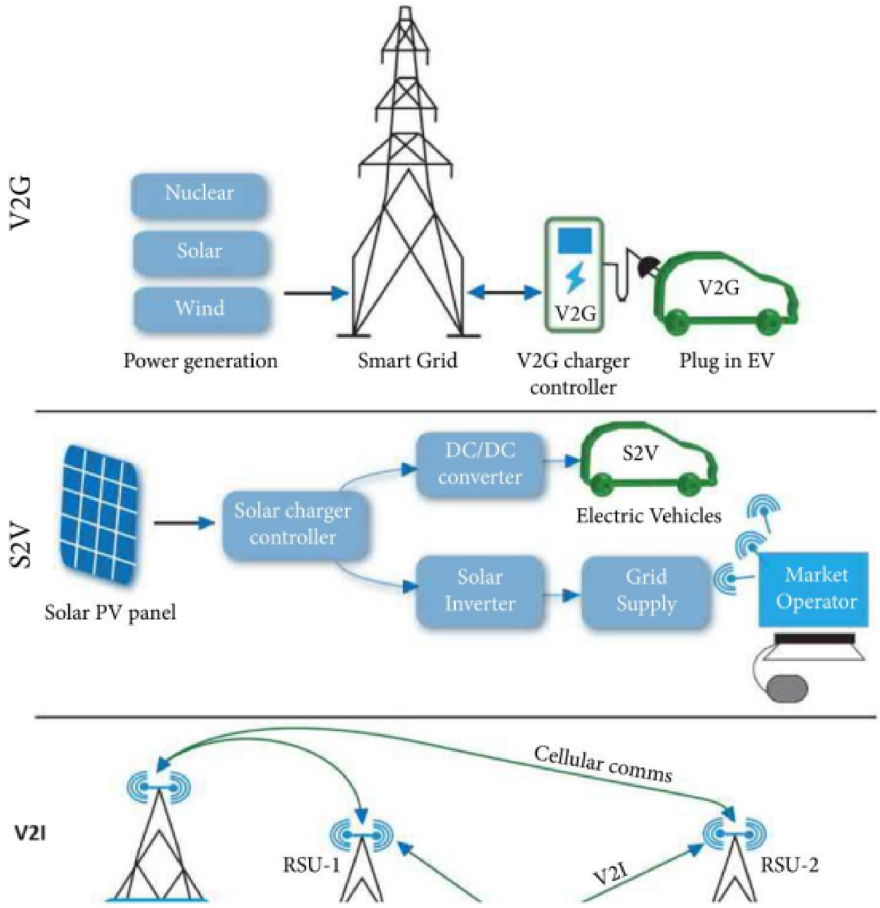


Figure 2.15: A schematic diagram of a V2G, S2V, and V2I structure.

a review of the reliability metrics was carried out for both the complete system and its separate elements. These techniques ensure that EVs meet safety, durability, and performance standards. Here are some common reliability assessment techniques used in the EV industry. Fig. 2.16 presents the categorization of reliability evaluation methods.

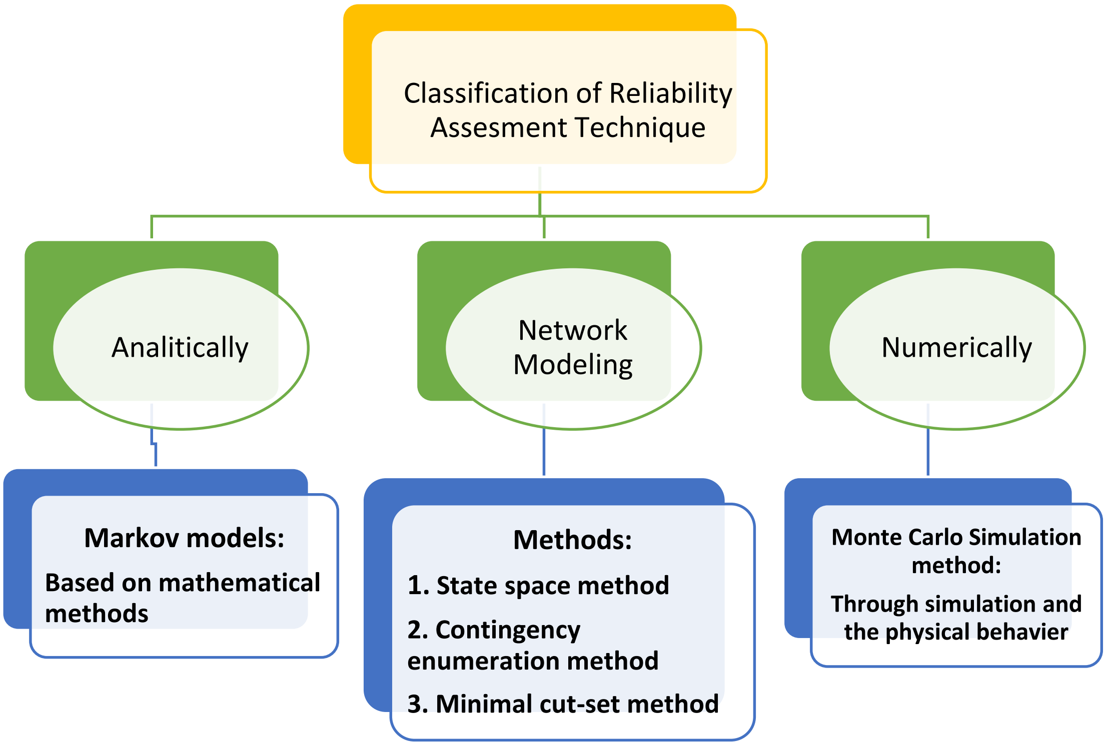


Figure 2.16: Classification of Reliability Assessment technique

2.6.1 Markov model

Markov models are frequently used to analyze the reliability of engineering and systems that are resilient to faults. The Markov model outperforms alternative approaches in assessing the reliability of a complex system where components are meticulously modeled. This modeling technique is particularly effective for components that can be accurately characterized using mathematical methods. The Markov model can be depicted as discrete and includes temporal and spatial aspects. In evaluating reliability for electrical systems, using stationary Markov models is fundamental. These models exhibit discreteness in spatial representation while maintaining continuous temporal representation. Fig. 2.17 presents an overview of the design process for the analysis of Markov models.

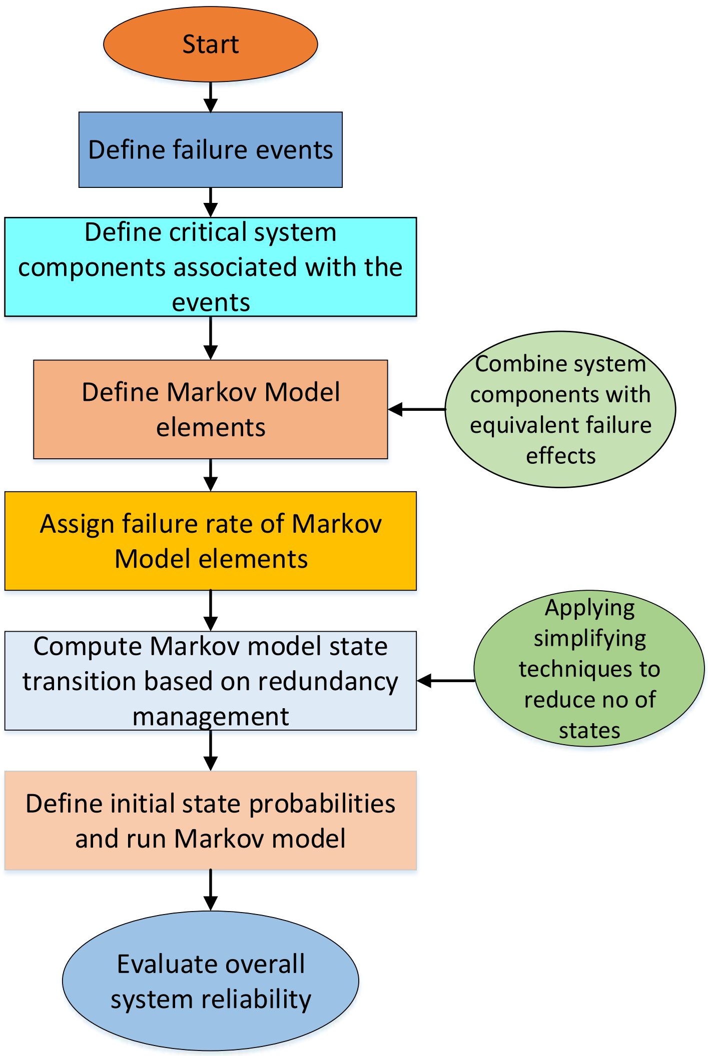


Figure 2.17: Markov model design process

2.6.2 Monte Carlo Simulation (MCS)

The utilization of MCS provides the option to incorporate more advanced component models, encompassing the effects of aging of the components. The application of the MCS method to manage the charging of EVs within the operation of the electric power system (EPS) has a notable impact on the planning of the electric market. The EV charging load mainly drives the influence. This effect emerges because of the irregular distribution of electric vehicles both in space and in time.

The MCS is the premier method for predicting the duration and power of EV charging. It is rooted in the traditional probability distribution of vehicular data. In forecasting the EV charging load using the MCS method, a Probability Distribution Function (PDF) is crafted considering starting charging moments and conditions, factoring in aspects like the count of EVs, battery size, and other pertinent factors. Following this, MCS utilizes mathematical simulations to sum up the charging demands of each separate EV to compute the overall charging demand. Numerous statistical tests are conducted using the MCS methodology to tackle both computational and tangible issues [93].

This specific technique simulates EV driving and charging actions to determine charging time and power based on the PDF of EV attributes. The starting moment for charging is typically represented as illustrated in equation 2.1.

$$f_x(y) = \begin{cases} \frac{1}{\sigma_x\sqrt{2\pi}}\left[\exp(-\frac{(y-\mu_x)^2}{2\sigma_x^2})\right], & \mu_x - 12 < y \leq 24 \\ \frac{1}{\sigma_x\sqrt{2\pi}}\left[exp(-\frac{(y+24-\mu_x)^2}{2\sigma_x^2})\right], & 0 < y \leq \mu_x - 12 \end{cases} \tag{2.1}$$

Furthermore, the Probability Distribution Function (PDF) for the daily mileage is established as depicted in equation 2.2.

$$f_z(y) = \frac{1}{y\sigma_z\sqrt{2\pi}}\left[exp(-\frac{(\ln y - \mu_z)^2)}{2\sigma_z^2})\right] \tag{2.2}$$

in which the pertinent shape parameters for the PDFs are denoted as σ_x, μ_x, σ_z, and μ_z, enhancing reliability. When applying the MCS technique to address challenges, the outcomes frequently manifest as mathematical forecasts for a designated random factor. This factor is produced via a conceptual test using exact technical information. The issue is fundamentally tackled by using the average value of this particular factor. The significant need for random numbers in MCS cannot be overstated. Figure 2.18 illustrates the design process of the MCS.

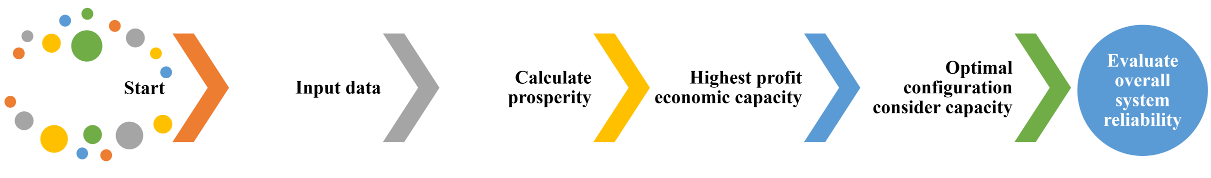


Figure 2.18: Monte Carlo Simulation design process

2.6.3 Contingency Enumeration Method

Another analysis method is the contingency enumeration technique, which gauges reliability by scrutinizing a set number of contingencies. This method is particularly useful for assessing the trustworthiness of electrical systems. The contingency enumeration procedure can be broken down into four consecutive phases. Figure 2.19 illustrates the contingency enumeration method. The initial phase outlines the analysis framework, encompassing

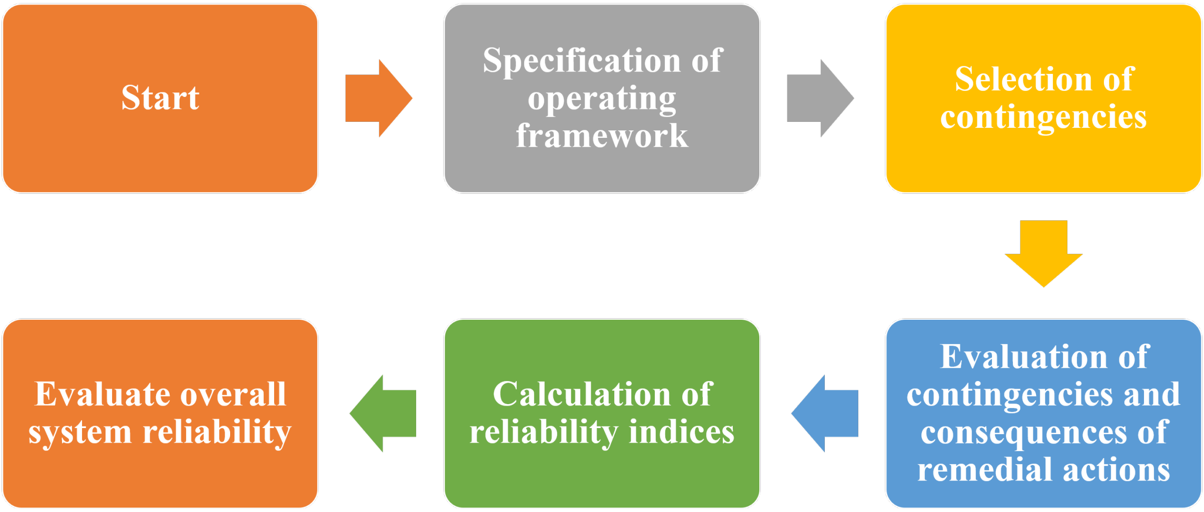


Figure 2.19: Contingency enumeration method process

system boundaries and the chosen load flow technique. Moving on to the subsequent phase, the focus shifts to handling contingencies involving various outage combinations. Here, it is essential to account for all conceivable contingencies, even in cases where this leads to prolonged computational efforts. These calculations are crucial in identifying potential electrical system issues arising from these contingencies. Ultimately, the reliability metrics are computed, and the cumulative annualized indices are derived by aggregating results across all relevant operational scenarios and potentialities.

2.6.4 State Space Method

The state space approach generally hinges on the ideas of "upstate" and "downstate." Fundamentally, this approach is anchored in three core parameters, as depicted in Figure 2.20.

In Figure 2.21, m represents the standard operational time of the system, while r signifies the duration of failure, and T stands for the average time between instances of failure.

The diagram in Figure 2.21 illustrates the state space of an individual component within a larger system. As in this context, t, λ represents the rate of failures, while μ pertains to the rate of repairs [94].

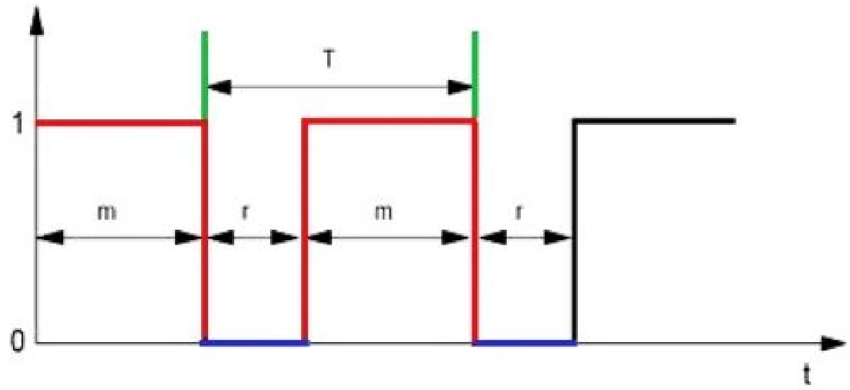


Figure 2.20: State space method process

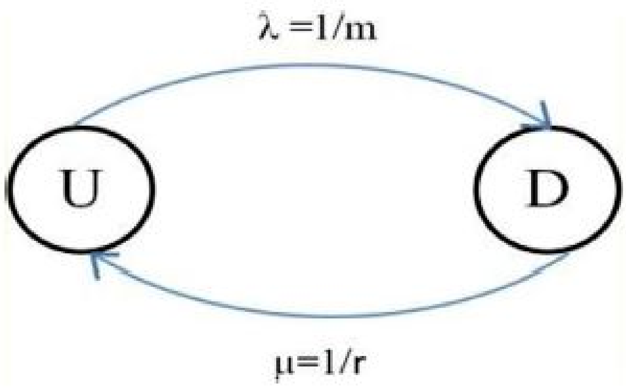


Figure 2.21: Diagram depicting the state space method for an individual element within a system

Impact on Reliability

The supply chain's dependability and customer satisfaction are strongly correlated in a distribution network. The SAIFI, SAIDI, and CAIDI customer-oriented reliability indices are those for which statistical data on failure rate, repair rate, average outage time, and the number of consumers at the connected load is essential. ENS and AENS are energy-focused reliability indices. The primary reliability indices evaluated are listed and classified as depicted in Fig. 2.22, as briefly described by the author in [95].

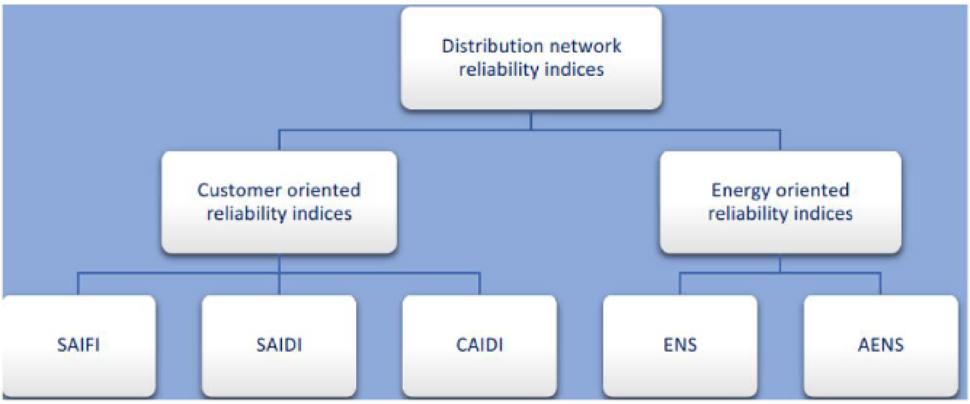


Figure 2.22: Classification of different reliability indices.

The crucial factors to be considered in the reliability assessment of EVs are outlined as follows:

- Understanding the functioning of power components within EVs.
- Pinpointing component malfunctions in EVs.
- Analyzing the sequence of failures.
- Proposing a framework to depict these malfunctions.
- Choosing an approach to gauge the reliability of EVs.
- Evaluating reliability from the manufacturing angle is complex, given the myriad of procedures in battery cell production.
- One approach to mitigate the aforementioned issues is to restrict the State of Charge (SoC) within a specific range. Operating the battery beyond this range can harm battery lifespan, reliability, and safety.

2.6.5 Fundamental Considerations in Assessing the Reliability of EVs

Car manufacturers have undergone substantial policy and strategy adjustments with the increasing global demand for EVs. Within this context, a critical emphasis lies on assessing reliability, which can be divided into two principal domains:

1. The evaluation of reliability in contemporary electrical grids incorporating EVs.
2. The analysis of reliability concerning the internal systems of EVs.

When assessing the reliability of EVs, various viewpoints need to be considered, such as:

- Understanding reliability from the perspective of the customer
- Interpreting reliability from the standpoint of the manufacturer
- Grasping reliability from the viewpoint of the seller

The evaluation of reliability from the aforementioned perspectives holds substantial importance in the strategic planning and overall operational lifespan of various components within EVs, encompassing aspects like power electronic converters, battery packs, and electric motors. Within the operational phase of EVs, three distinct areas (production, sales, and customers) carry relevance from a reliability standpoint. Fig. 2.23 visually represents these three zones, demonstrating the implementation of each element in assessing EV reliability. The utmost significance of the reliability concept for the components of EVs.

Due to the presence of multiple sub-systems within EVs, conducting reliability and safety analyses becomes notably challenging. Moreover, the intricate interdependence among components adds uncertainty, prompting the utilization of a logical framework to explore the uncertain relationships of failures in EV components. To evaluate the reliability of EVs, it is essential to consider the failures that arise in crucial electrical components. Fig. 2.24 depicts the categorization of primary failures in the electrical components of EVs. The crucial factors to be considered in the reliability assessment of EVs are outlined as follows:

- Understanding the functioning of power components within EVs.
- Pinpointing component malfunctions in EVs.
- Analyzing the sequence of failures.
- Proposing a framework to depict these malfunctions.

- Choosing an approach to gauge the reliability of EVs.

- Evaluating reliability from the manufacturing angle is complex, given the myriad of procedures in battery cell production.

  To investigate the reliability of the battery pack, it is imperative to address four significant concerns.

- **Chemical issues:** During the battery manufacturing process, it is essential to account for the electrochemical factors contributing to battery failures.

- **Thermal issues:** An additional crucial aspect in evaluating the reliability of the battery pack pertains to maintaining safe conditions through thermal management. The thermal analysis for battery pack heating is subdivided into two key components: battery cell thermal analysis and comprehensive battery pack thermal analysis. Various cooling systems have been employed to regulate the temperature of the cells.

- **Mechanical issues:** The primary mechanical-related failure that can influence the reliability of EV batteries is the result of mechanical stresses experienced during different modes of operation and collisions. These failures encompass stress-based and strain-based mechanisms. Notably, advancements are being made in testing and modeling the mechanical characteristics of the battery pack, along with its individual components, such as cathodes, anodes, and separators.

- **Electrical issues:** Several critical electrical parameters within the battery are pivotal in addressing reliability concerns.

  (i) Over-voltage: The condition where the battery charging voltage surpasses the established standard, leading to issues like battery plating and overheating, is called over-voltage.

  (ii) Under-voltage: Another problem that results in battery pack failure is under-voltage during the charging process.

- **Power electronic converter/Battery charger** Central roles of the battery charger encompass channeling energy from the electric grid to the battery, refining the charg-

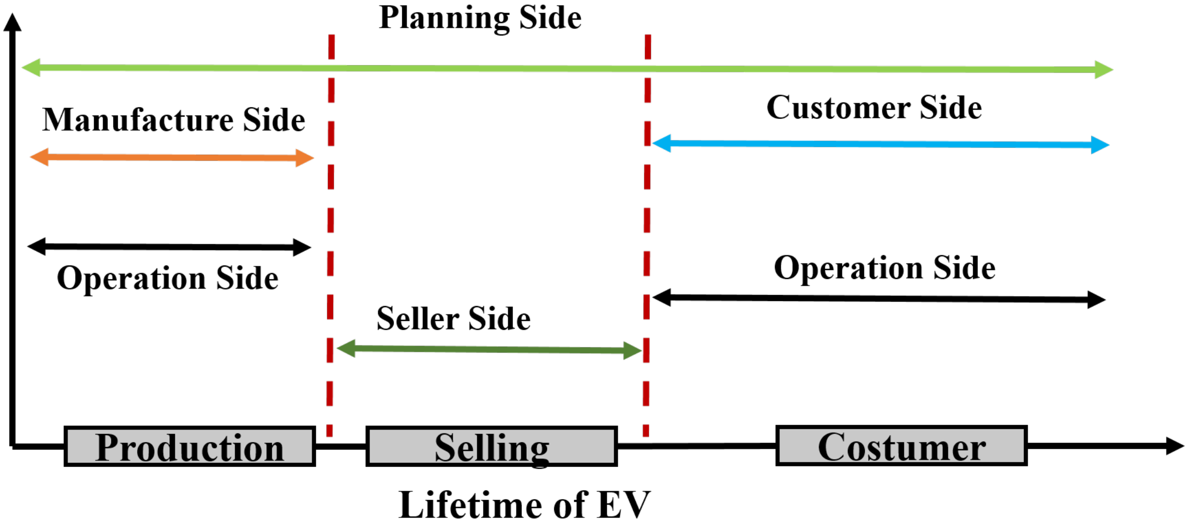


Figure 2.23: The utmost significance of the reliability concept for the components of EVs

ing sequence, and halting the charge when the battery reaches full capacity. Any functional interruptions directly influence the dependability of the battery charger.

One approach to mitigate the aforementioned issues is restricting the SoC within a specific range. Operating the battery beyond this range can harm battery lifespan, reliability, and safety.

2.6.6 Reliability Evaluation using a V2G Approach and High EV Penetration

Reliability assessments can indeed be conducted using analytical or chronological probabilistic models, depending on the specific context and the nature of the system or process being analyzed. These models help evaluate the likelihood of a system or component functioning correctly over a given period or under certain conditions.

1. Analytical Probabilistic Models

- **Probability Density Functions (PDFs):** Analytical models often use probability density functions to describe the distribution of failure or reliability over time. For example, the exponential distribution might be used to model the failure rate of a component.

- **Weibull Distribution:** The Weibull distribution is frequently used in reliability

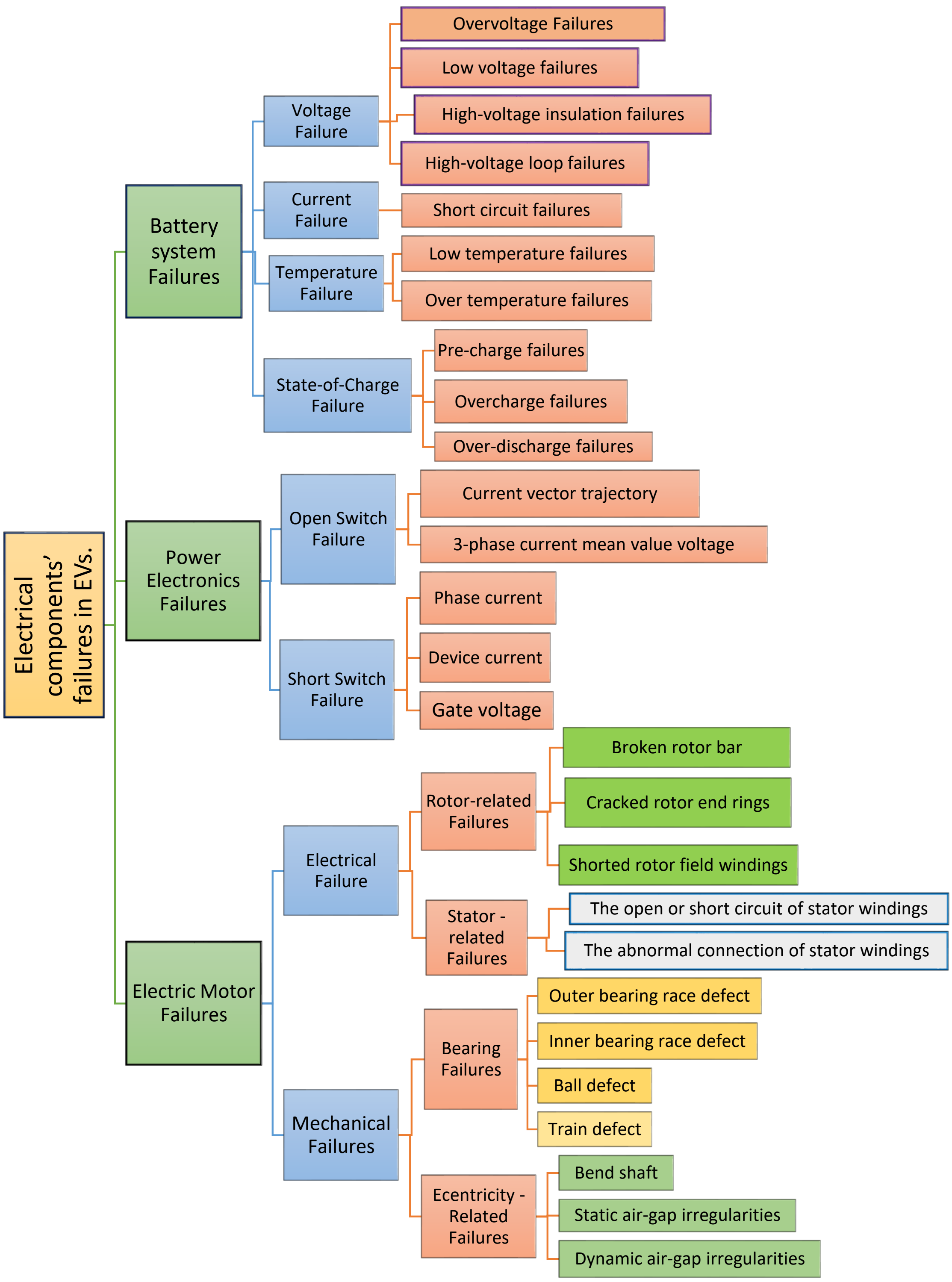


Figure 2.24: Categorization of Primary Electrical Component Failures in EVs

engineering to model the failure rates of components, with its shape parameter allowing for modeling various failure patterns.

- **Monte Carlo Simulation** Analytical models can also incorporate Monte Carlo simulations to account for complex, interconnected systems or situations where exact mathematical models are not available. This involves generating random inputs and analyzing the output distribution to assess reliability.

2. Chronological Probabilistic Models

- **Markov Models:** These models are used when analyzing systems with discrete states and transitions. Markov models consider the probability of transitioning from one state to another over time, allowing for the assessment of system reliability and availability.

- **Fault Tree Analysis (FTA)** FTA is a top-down deductive approach used to identify and evaluate the probability of failure events in a system. It uses a graphical tree structure to represent how different events or failures can lead to system failure.

- **Event Tree Analysis (ETA)** ETA is complementary to FTA and is used to assess the consequences of various events or failures, considering different possible outcomes and their probabilities.

- **Reliability Block Diagrams (RBD)** RBDs are graphical representations that break down a system into individual components and their interconnections, allowing for system reliability analysis by combining component reliability data.

To address the requirement for chronological modeling of EV consumption, the study will employ a method known as "chronology." This method involves generating virtual scenarios for both electricity generation and demand, which will then be utilized to compute reliability indices. Traditional generating units are characterized by two conditions: By applying the exponential CDF to create a virtual scenario for the time-to-failure (TTF) and time-to-repair (TTR), the mean-time-to-failure (MTTF) and mean-time-to-repair (MTTR) are stated, respectively, in years [96].

There may be problems with the generation units that cause load interruptions. The annual system and interruption indices can be used to separate the various reliability indices [97].

There are many available annual system indices:

(i) Loss of load expectation (LOLE) in hrs./yr

(ii) Loss of Energy Expectation (LOEE) in megawatt hrs/yr,

(iii) Loss of load frequency (LOLF) in interruptions/yr [98].

Numerous Interruption indices are available

(i) Energy Not Served per Interruption (ENSPI) in megawatt hrs/interruption

(ii) System Average Interruption Frequency Index (SAIFI) in interruption/customer(int./cu.)

(iii) System Average Interruption Duration Index (SAIDI) in h/cu.

Various reliability indices for NI interruptions over N years can be determined in the following Eqs. (2.3)-(2.8).

$$\text{LOLE} = \sum_{i=1}^{NI} \frac{h_i}{N}, \tag{2.3}$$

$$\text{LOEE} = \sum_{i=1}^{NI} \frac{ENS_i}{N}, \tag{2.4}$$

$$\text{LOLF} = \frac{NI}{N}, \tag{2.5}$$

$$\text{ENSPI} = \sum_{i=1}^{NI} \frac{ENS_i}{N} = \frac{\text{LOEE}}{\text{LOLF}} \tag{2.6}$$

$$\text{SAIFI} = \frac{\text{The number of customers interputions}}{\text{Total customers served}} \tag{2.7}$$

$$\text{SAIDI} = \frac{\text{Total durations of customers interuptions}}{\text{Total customers served}} \tag{2.8}$$

2.6.7 Reliability Parameters

EVs possess the dual capability of serving as an energy provider and an electricity user, attributed to their engagement in V2G operations [99]. The extensive interplay between their V2G and G2V functionalities and their time-space characteristics necessitates recognizing this unique aspect and formulating fresh criteria for EV reliability. In alignment with this goal, the reliability metrics for EVs predominantly bifurcate into two categories, illustrated in Fig. 2.25. A more detailed categorization and explanation can be derived from recent research findings [100].

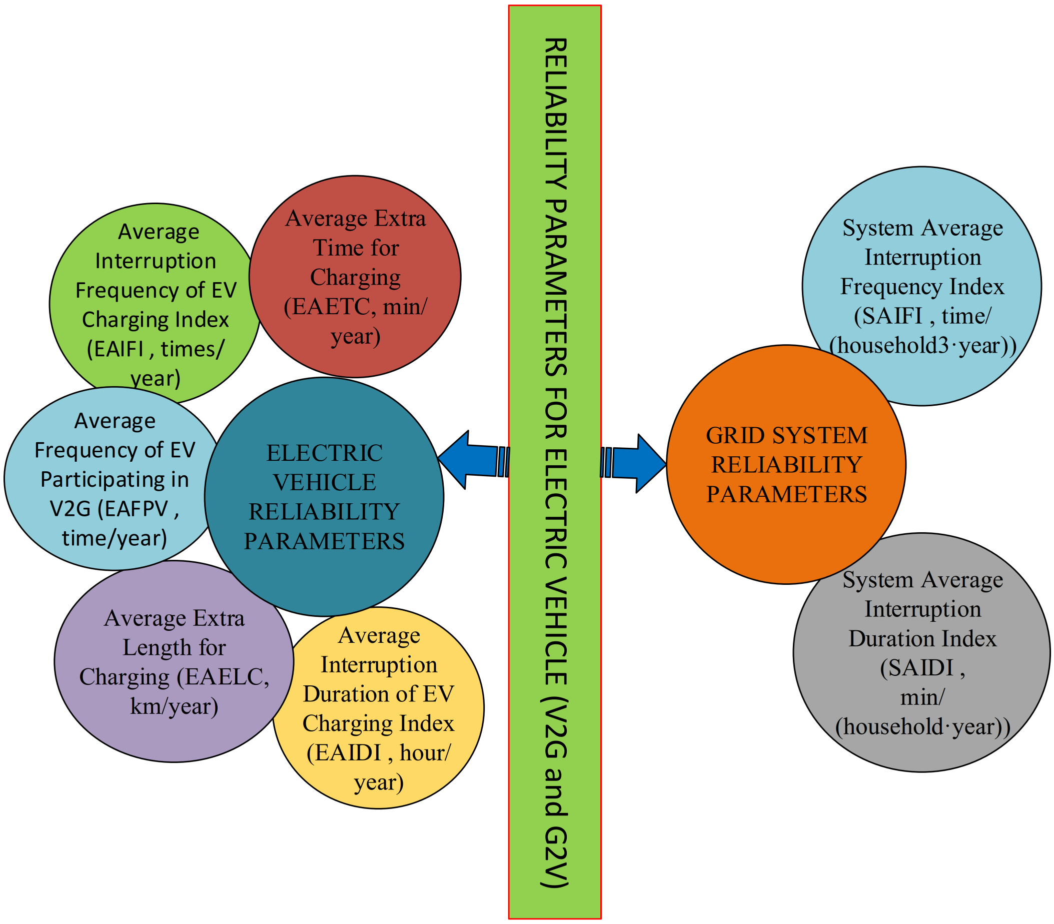


Figure 2.25: Reliability Parameters for EVs

Reliability Parameters of EVs

1. **Average Interruption Frequency of EV Charging Index ($E_{\mathbf{AIFI}}$, t/yr):**

$$E_{\text{AIFI}} = \frac{\sum_{i=1}^{N} \lambda_i}{N.Y} \tag{2.9}$$

The symbol λ_i denotes the count of charge interruptions over the period of EV simulation. Here, N signifies the total number of electric vehicles, while Y indicates the simulation duration in years.

2. **Average Interruption Duration of EV Charging Index ($E_{\mathbf{AIDI}}$, hr/yr)**

$$E_{\text{AIDI}} = \frac{\sum_{i=1}^{N} t_i}{N.Y} \tag{2.10}$$

In this context, t_i stands for the cumulative charging disruption time during the simulation period for the i^{th} EV.

3. **Average Extra Length for Charging ($E_{\mathbf{AELC}}$, km/year)**

$$E_{\text{AELC}} = \frac{\sum_{i=1}^{N} \Delta l_i}{N.Y} \tag{2.11}$$

In this scenario, l_i denotes the distance covered by the i^{th} EV due to a power outage when $SOC_i < S_i$, as it searches for an alternative charging station throughout the simulation duration.

4. **Average Extra Time for Charging ($E_{\mathbf{AETC}}$, min/yr):**

$$E_{\text{AETC}} = \sum_{i=1}^{N} \frac{t_i^E}{N.Y} \tag{2.12}$$

Here, (t_i^E) represents the time taken by the i^{th} EV due to a power failure when $SOC_i < S_i$ as it seeks a new charging station over the course of the simulation interval.

5. **Average Frequency of EV Participating in V2G ($E_{\mathbf{AFPV}}$), t/yr)**

$$E_{\text{AFPV}} = \frac{\sum_{i=1}^{N} c_i}{N.Y} \tag{2.13}$$

Here, c_i indicates the cumulative count of instances the i^{th} EV engaged in V2G activities during the simulation duration.

Grid System Reliability Parameters

Although EVs are transportable and interrupt load for the distribution system, the impact of power loss on them is relatively minimal. In order to remove an electric car, the existing distribution network described below is referred to by system reliability indices.

1. **System Average Interruption Frequency ($S_{\mathbf{AIFI}}$)(t/(household·yr)**

$$S_{\text{AIFI}} = \frac{\sum_{i=1}^{M} f_i}{M.Y} \tag{2.14}$$

In this context, M refers to the total number of households, and fi_i denotes the count of power interruptions experienced by the i^{th} user throughout the simulation period.

2. **System Average Interruption Duration Index ($S_{\mathbf{AIDI}}$) min/(household·year)**

$$S_{\text{AIDI}} = \frac{\sum_{i=1}^{N} t_i^s}{M.Y} \tag{2.15}$$

Here, t_s^i signifies the total duration of the power outage experienced by the user.

3. **System Expected Energy Not Supplied($S_{\mathbf{EENS}}$)MWh/(household·year)**

$$S_{\text{EENS}} = \frac{\int_{i=0}^{Y} P_c(t)dt}{Y} \tag{2.16}$$

Here, $P_c(t)$ indicates the system's load decrease at time t and is set to zero when the network operates normally.

4. **Average Extra Length for Charging ($E_{\mathbf{AELC}}$, km/yr)**

$$E_{\text{AELC}} = \frac{\sum_{i=1}^{N} \Delta l_i}{N.Y} \tag{2.17}$$

The methodology and Reliability parameters outlined above necessitate a profound understanding of the mechanical, electrothermal, and lifespan characteristics of the vehicle's drive-train and its sub-components [101].

2.7 Future Advancement in Grid Integrated EV Technology

Considering all of the aforementioned major facts, it is recommended that the following factors be considered in order to successfully adopt the integrated EV infrastructure in the future.

2.7.1 Improvements in Charging techniques

In the present situation, there are numerous economic, environmental, and smart grid benefits, but the customer's concerns about price, range anxiety, reliability, and charging time are still evident. One method for resolving some of these issues is by using battery storage advanced technologies [102].

(i) one of the most important aspects of battery vehicles is also essential for developing electric vehicles, as it is critical to make charging simpler and more efficient so that EVs can travel longer.

(ii) There are now three different types of standard connectors for carrying out fast charges; as the author has already discussed in Fig. 2.7, conventional connectors for doing quick charges are as follows: The CCS was added to J1772, and CHAdeMO was added to IEC-62196, the GB/T as described in Fig. 2.7(b), and it might need to take the one Tesla uses in its supercharger into consideration [103].

2.7.2 Global communication and artificial intelligence (AI) in EVs

According to global communication and AI with applications like autonomous vehicles, real-time traffic monitoring, and intelligent navigation systems, AI is a significant factor in the EV sector. It can be used for various safety applications, such as tracking driving behavior, equipment predictive maintenance, and transportation security, as indicated in the following point.

(i) Artificial algorithms that are used to optimize the charges can revolutionize the charging process by reducing expenses or making better use of the electrical infrastructure.

(ii) The research assumes that there are still a lot of open issues and future suggestions for further research in this field, such as the utilization of communications between vehicles and their power infrastructure and pulling artificial intelligence-based technologies (such as optimization strategies or deep learning techniques) [104].

(iii) Due to wireless communication networks, it will be feasible to interface cars with a communication system that allows communications capabilities between vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). A wide range of new opportunities will be opened up by the use of AI-based algorithms, which will give vehicles some intelligence and ultimately significantly enhance transportation [105].

(iv) We can find many AI-based proposals for many EV topics, including energy-efficient routing, better and more intelligent charging, and battery temperature management [106].

(v) Artificial neural networks (ANNs) should be considered in relation to battery temperature management to enhance the system and use less available energy. The use of artificial intelligence and communications will stimulate the emergence of innovative solutions [107].

2.7.3 Solar to Vehicle Charging techniques

Solar-to-vehicle charging techniques involve using solar energy to charge EVs, as shown in Fig.2.26. This can be achieved through various methods and technologies.
(i) Direct Solar Charging (Solar Panels on Vehicles): Solar panels are installed directly on the vehicle's surface, providing continuous charging while in sunlight. Limited by available surface area and slower charging rates.
(ii) Solar Charging Stations
(a) *Standalone Solar Charging Stations:* Dedicated stations with solar panels on canopies or structures can support multiple vehicles and require space and infrastructure.
(b) *Integrated with Parking Lots* Solar panels over parking lots provide shade and generate electricity. Dual-purpose infrastructure, scalable, but with high initial costs.
(iii) Home Solar Charging
(a) *Rooftop Solar Panels* Installed on home rooftops, connected to the home's electrical system, allowing for dual use (home and vehicle power) and dependent on location and roof suitability.
(b) *Solar Carports:* Structures with integrated solar panels providing shelter and power. Requires additional cost and space.
(c)*Portable Solar Chargers* Mobile units with fordable or portable solar panels offer charging flexibility anywhere. Limited power generation and slower charging rates.
(iv) Grid-Connected Solar Systems
(a) *Grid-Tied Solar Systems* Solar panels feed power into the grid, with vehicles charged using grid electricity. No need for large battery storage, but dependent on grid availability.

(b) *Vehicle-to-Grid (V2G) Integration* Vehicles feed power back to the grid during peak demand, acting as energy storage. Balances grid load but requires compatible infrastructure.

(iv) Battery Storage Integration

Solar panels charge a stationary battery, which then charges the vehicle. Provides power during non-sunny periods, with additional storage costs.

Each technique offers unique benefits and challenges, from direct charging with vehicle-mounted panels to advanced grid-connected systems and battery storage. Efficient implementation requires careful consideration of cost, scalability, and integration with existing energy infrastructure.

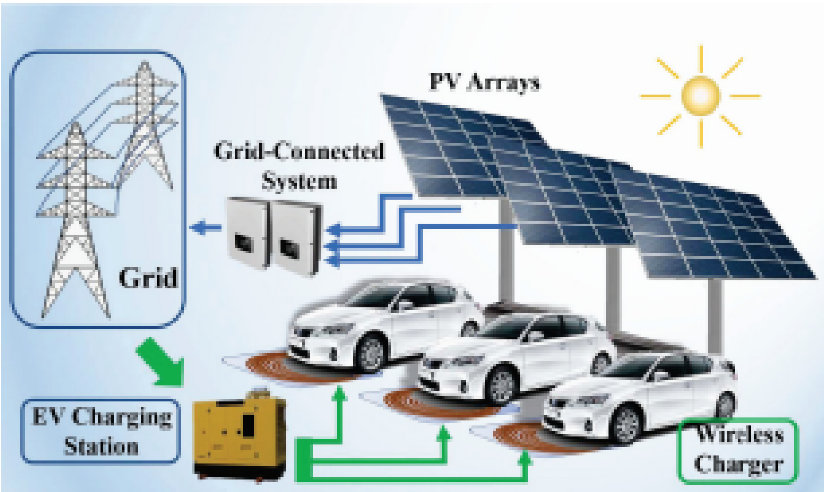


Figure 2.26: Centralized Solar EV Charging Station.

2.7.4 Smart charging techniques

This is the technique of externally controlling EV charging for predetermined objectives and constraints.

EV smart charging features must be more extensive in the environment, comprising various charging powers, CS, battery swapping stations, retail and wholesale trading, and ancillary parts of the system, to more correctly and honestly mimic the practical implementation as shown in Fig. 2.27. Continuous research should be done to determine the best trade-off between computational load and performance [15]. EV technologies must overcome a lot of obstacles, including delayed

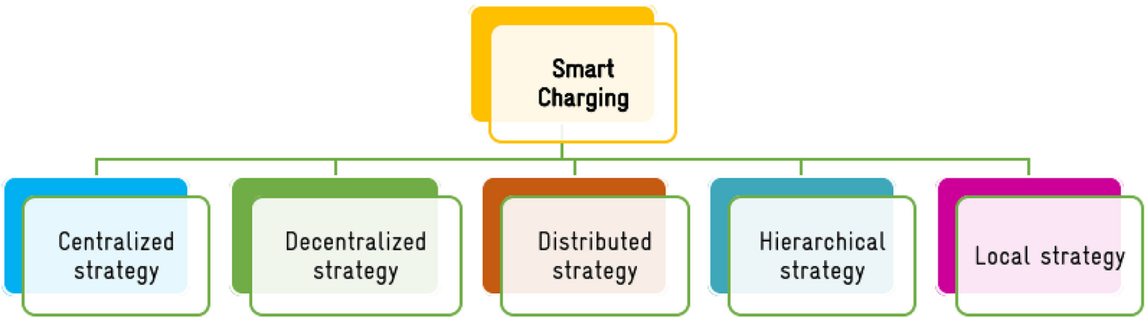


Figure 2.27: smart charging algorithm.

charging, isolation, power loss caused by converter structure, the reliability of power electronic components, and the temperature of EV batteries. So, the reliability of electronic components associated with EV converter technology ensures the reliable performance of the entire system as discussed in [16]. The purpose of the present work has been summarised in Table 2.7.

Table 2.7: Summary Table

Comparative analysis based on literature								
Ref.	Types of EVs	Advanced Charging topologies/ methodologies	EV battery characteristics/ BMS/ESS/BSS challenges	Converter topologies/ isolated/ non-isolated	Power levels/ on-board/off-board charger	EVs Grid-integration and its impacts	EV Charging application/V2G and G2V/challenges	Reliability Indices
[108]	×	✓	✓	✓	✓	×	×	×
[3]	×	×	✓	×	✓	×	×	×
[109]	✓	×	✓	×	✓	×	✓	×
[110]	×	✓	✓	✓	×	×	×	×
[111]	×	✓	✓	✓	✓	✓	✓	×
[112]	✓	✓	×	×	×	✓	✓	×
[113]	✓	✓	✓	✓	×	×	✓	×
In present work	✓	✓	✓	✓	✓	✓	✓	✓

2.8 Summary

This chapter demonstrates comprehensive information on EVs and their types and a comparative study of recent research on converter topologies of contemporary converters. These converters have problems such as high fluctuation current, low voltage, low impedance, stress, current, and sensitive duty cycle. This comprehensive review includes a comparative study of charging infrastructure, connection standards, interfaced power architectures, DC/DC converter topology (isolated/non-isolated), and the performance of EV grid integration. A concentration on recent research on the penetration of EVs, reliability indices, reliability parameters in EVs, reliability assessment techniques, and reliability challenges in G2V and V2G technology. Finally, The assessment concludes with demonstrations of the impacts of grid integration (both positive and negative), significant problems, reliability issues, synchronization reliability during motoring and braking, and suggestions for improvement of possible future use in the advancement of EV charging stations. The direction of the next research studies in next chapters are methodologies and issues related to achieve a faster response from grid-integrated EVs during motoring and braking, as well as during charging and discharging (V2G and G2V) modes in the future, synchronization is essential.