Advancements and Challenges in Electric Vehicle Battery Charging: A Comprehensive Review

Trupti Dhanadhya 1[1], *Swaraj Kadam* [2], *Shashikant Prasad* [3], *Harshal Vaidya* [4]
[1]Electrical Engineering Department, Dr. D Y Patil Institute of Technology Pimpri, Pune 18
[2]Electrical Engineering Department, Dr. D Y Patil Institute of Technology Pimpri, Pune 18
[3]Electrical Engineering Department, Dr. D Y Patil Institute of Technology Pimpri, Pune 18
[4] Department of Engineering Sciences, Marathwada Mitra Mandal's Institute of Technology, Lohgaon, Pune-47

Abstract. Electric vehicles (EVs) stand out as more efficient in conserving energy, reducing emissions, and safeguarding the environment compared to their fuel-powered counterparts. Consequently, as they find broader applications in the transportation industry, their significance continues to grow. The impending reality of widespread EV adoption is evident as their usage increases daily. In the shift towards the electronic revolution within the automotive sector, the manner in which EVs are charged becomes a pivotal concern. This comprehensive review examines recent advancements and persistent challenges in EV battery charging technologies. The paper analyzes various charging methodologies, including conductive, inductive, and battery swapping systems, evaluating their technical characteristics, implementation challenges, and impact on charging infrastructure. Key developments in fast-charging protocols, wireless power transfer efficiency, and smart grid integration are discussed. Critical challenges addressed include charging time optimization, infrastructure scalability, standardization issues, and grid stability concerns. The review also explores emerging technologies such as dynamic wireless charging and along with their potential impact on future EV adoption. Finally, the paper identifies research gaps and suggests future directions for improving EV charging technologies. This systematic review provides valuable insights for researchers, industry practitioners, and policymakers working towards advancing sustainable transportation solutions.

Keywords— Electrical Vehicle, Battery, Charging Methods

1 Introduction

Electric vehicle charging is about how we power up electric cars. There are different ways to charge them, like slow charging at home (Level 1), faster charging at home or public stations (Level 2), and really fast charging for quick top-ups on the road (fast charging or DC charging).

1) Level 1 Chargers:
These chargers are use for 120-volt AC household. As these chargers are slower but convenient for overnight charging at home.

2) Level 2 Chargers: This charger operates on a 240-volt AC power source, these provide faster charging than Level 1 and are commonly found in homes, workplaces, and public

3) Fast Chargers (Dc Chargers):
These high-speed chargers use direct current (DC) and are faster than Level 1 and Level 2 chargers. They're mostly installed at public charging stations.

Universal Chargers: Universal Chargers are the unique type and are designed to be compatible with multiple EV. They support various charging standards and connector types, offering a standardized solution for EV charging. When we charge the vehicle, we use methods to make sure the batteries stay safe and last longer. It's like giving the right amount of power at the right time. There's also something called a universal charger that can work with lots of different electric cars, making it easier for everyone to charge their vehicles. Universal Charger has many advantages like they eliminate the need for multiple charging stations. They simplify the installation and maintenance of charging infrastructure. It is easy for the EV owner to charger the vehicle without worrying about the compatibility issues. As the EV market is evolving with new technologies and charging standards, universal chargers can be updated to support these changes, ensuring continued compatibility with newer EV models. The use of universal chargers in EV infrastructure contributes to a more accessible, user-friendly, and standardized charging network, encouraging the widespread adoption of electric vehicles [1].

2 Basic parameters of Battery Performance

2.1.1 Energy Density

The measurement of the amount of energy a battery can store in proportion to its weight or size is called energy density. Batteries having high energy density are desirable for EVs as they can provide longer driving ranges without adding excessive weight to the vehicle.

2.1.2 Power Density

It refers to the amount of power that can be delivered per unit of weight. High power density batteries are crucial for EVs because they can deliver more power to the electric motor. This, in turn, allows the EV to accelerate faster and perform better.

2.1.3 Charging Time

The charge time represents the duration required to replenish a battery from empty to full capacity. Prolonged charge times can be inconvenient for drivers, making this a crucial aspect to consider in the design and manufacture of EVs.

2.1.4 Cycle Life

Cycle life is a crucial factor to consider when evaluating batteries for EVs, as it determines the number of charge and discharge cycles a battery can undergo before requiring replacement. High cycle life batteries are highly desirable for EVs, as they can last longer and significantly reduce the cost of ownership.

2.1.5 Temperature range

The safe operational temperature range is a crucial factor for batteries employed in EVs. Adverse temperatures have the potential to harm the battery and diminish its efficiency. Therefore, Batteries used in EVs are designed to operate in a wide range of temperatures, from below freezing to extremely hot conditions.

2.1.6 Cost

The affordability of electric vehicles is directly linked to the cost of batteries. When batteries are more affordable, it makes EVs accessible to a broader range of consumers

2.1.7 Battery's Voltage

A battery's voltage determines the quantity of electrical energy it can supply. Higher voltage batteries are typically more efficient because they require less current to provide the same amount of power.

2.1.8 Maximum Continuous Discharge Current

It is the highest current at which the battery can consistently discharge. The battery manufacturer typically sets this limit to avoid excessive discharge rates that could harm the battery or diminish its capacity

3 Common Charging Methods

3.1.1 Constant Voltage

Once the battery voltage reaches a specified level, the charger switches to a constant voltage mode. At this stage, the charger maintains a steady voltage while the current decreases gradually. This phase allows the battery to reach full capacity without overcharging

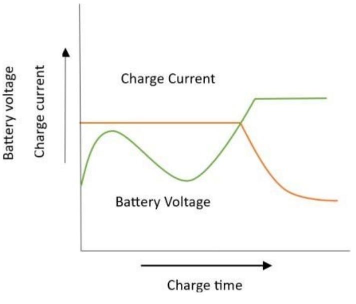

Fig. 1. Constant Voltage Charging

3.1.2 Constant Current

In this initial phase, the charger supplies a constant current to the battery. During this stage, the battery voltage gradually increases while the state of charge (SoC) rises steadily. This phase provides a rapid charge to the battery

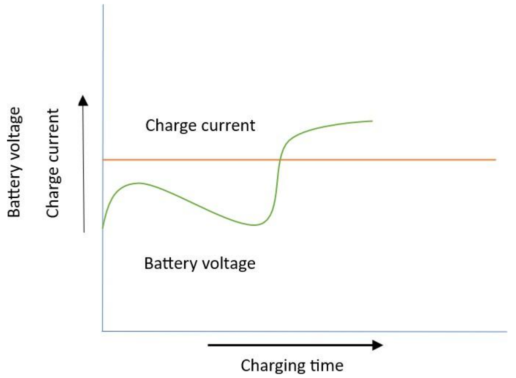

Fig. 2. Constant Current Charging

3.1.3 Constant Current and Constant voltage charging

This charging method combines the CC and CV stages. Initially, the charger provides a constant current until the battery voltage reaches a set threshold. Then, the charger maintains a constant voltage, allowing the battery to complete its charging cycle while limiting overcharging.

This charging technique ensures a safe and controlled charging process for lithium-ion batteries, optimizing their lifespan and performance. It's a widely used method in electric vehicles.

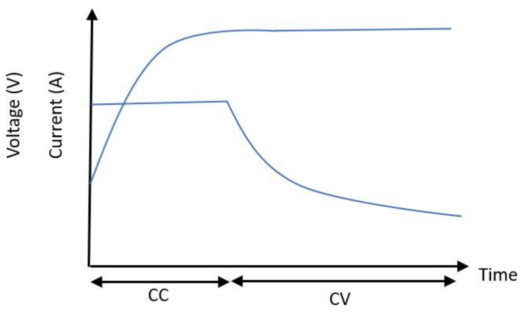

Fig. 3. Constant Voltage and Constant Voltage

4 Types of chargers with the help of architectures

4.1.1 On-Board Charger

The onboard chargers play a crucial role in managing the flow of current from the grid to the traction battery, allowing electric vehicles to charge from any source without relying solely on charging stations. Moreover, OBCs also help to regulate current and voltage at which the battery is charged. The architecture of an on-board charger is shown in fig 4[2]. The capacity of a standard single-phase on-board charger ranges from 7.2 kW to 11 kW, while a three-phase on board charger has a capacity of 22 kW. The standard DC charging stations have a much higher capacity than single-phase onboard chargers, with a range of 50 kW to 300 kW.

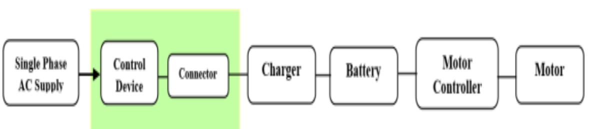

Fig. 4. On board charger

4.1.2 Off-Board Chargers

An off-board chargers are designed to convert AC power from the grid into a controllable DC power supply to charge the vehicle power battery. The architecture of an off-board charger is shown in fig 5[2]. Off-board chargers are known for their ability to deliver "fast charging" to the vehicle battery due to their high-power output. These chargers are fixed outside the electric vehicle, which means they are not limited by the space and weight constraints of the vehicle and has larger volume and power. The basi c features of off-board chargers typically include higher kW transfer and more sophisticated BMS systems compared to onboard chargers.

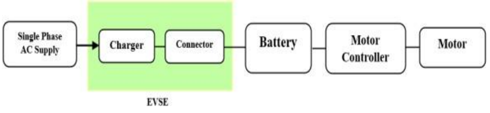

Fig. 5: Off board charger

5 Types of different Charging Technologies

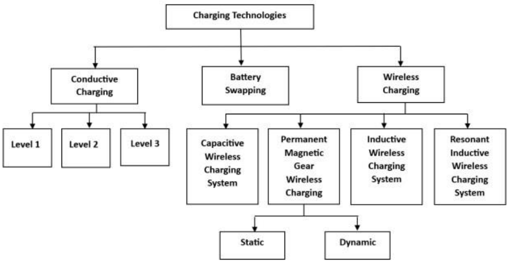

Fig. 6. Types of different Charging Technologies

5.1.1 Conductive Charging

This is the most common charging method it has in two categories given below:
a) Conductive AC charging b) Conductive DC charging

a) Conductive AC charging : The most commonly used method is to charge your device using an AC wall box or, in the absence of a second choice, a domestic plug point. In electric vehicle there is a convertor the convertor converts the power from AC to DC and supply back to the vehicle battery. In the conductive charging means directly contact with the charging station to the vehicle. In the conductive charging the ac conductive charging is most used. One most of electric vehicle charge, and practically all of the chargers run on AC electricity. Fig 7 shows AC Charging System Power Flow [3]. The EV's most we use on board charger is provided by an AC charger, which also changes the electricity from AC to DC so that the battery may be charged [4].

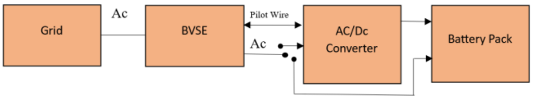

Fig 7: AC Charging System Power Flow

5.1.2 Conductive DC charging:

Dc power is suitable for high power EV charging, and the power output of fast charges is limited only by the ability of the batteries to accept the charging power. After that, the power is transformed before going into the car. Electricity is c onverted and then fed directly into the car battery, avoiding the converter in the vehicle. The Dc conductive charging is fast recharge than the ac charging and in the dc charging we use the off board charger. Off-board chargers provide you more options when it comes to how much electricity you can deliver outside of your vehicle. The off board charger is not connected in the vehicle. This is a fast- charging method of EV [4]. Fig 8 shows DC Charging System Power Flow [3].

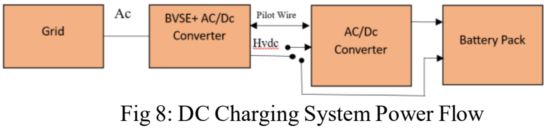

Fig 8: DC Charging System Power Flow

Advantages:

1. The device's architecture allows for both high and low charging rates, and its weight and size are not restricted.
2. Less time is needed for high-power DC charging.

Disadvantages:

1. As compared to AC charging, the charger installation costs are higher.
2. Negative effect on the electricity system: increased grid power demand, particularly during peak hours.

Because the BMS and the off-board chargers are physically apart, dependable communication is essential to guaranteeing proper charging conditions.

When it comes to conductive charging electric vehicles, the charging stations can be either domestic or non-residential, offer fast or slow charging, and allow for either a one-way or two-way power flow from the vehicle to the grid. Three different types of AC or DC conductive charging can be distinguished: Level 1, Level 2, and Level 3.

i) Level 1- 120 Volt Charging: This is the most basic type of charging, requiring a 120V AC connection to a typical home or business electrical outlet that can provide 15-20 amps of current at a power drain of about 1.4 kW[5].

Advantages:

1. Installation costs are lower.
2. Minimal effect on peak demand fees levied by electric utilities, which are frequently assessed on business accounts.

Disadvantage:

1. Slow charging adds three or five miles to the range each charging hour.

ii) Level 2 - 208/240 Volt Charging: This kind of charging drastically cuts down on charging time and requires a 208/240 ac power connection. The majority of electric cars (EVs) use the J1772-standard connector, which has a maximum current capacity of 80 amps (19.2 kW). However, most vehicles now on the road only require 30 amps for 3.3 to 6.6 kW of charging [5].

Advantages:

1. Compared to Level 1, the charge time is much faster. EVs can travel 10 to 20 miles on a single charge in an hour.
2. For brief charging activities lasting less than an hour, more energy-efficient than Level 1.
3. A range of producers offers unique items for various markets and needs.

Disadvantages:

1. Depending on the equipment and installation difficulties, installation expenses might vary greatly and are more than for Level 1.
2. A possible increase in the impact on electric utilities.

iii) Level 3: DC Fast Charging: This is level 3, where high power is directly delivered to an EV battery system by equipment, allowing for quick charging. For many electrical vehicles, an 80% charge can be obtained in 30 minutes or less.

Advantages:

1. There is a significant reduction in charging time; an 80% charge usually takes 30 minutes.

Disadvantages:

1. In comparison to level 1 and level 2 charging, equipment and installation costs are greater.
2. The possibility of higher peak power demand fees from the electric company

5.1.3 Battery Swapping

Electric vehicle battery switching involves replacing an electric vehicle depleted battery with a fully charged one. By doing this, the time spent waiting for the vehicle battery to charge is eliminated. Battery swapping stations, as opposed to charging stations, offer an ease of mind because each battery transfer just takes a few minutes and requires much less space needed for installation Additionally, replacing a battery reduces the cost of purchasing a vehicle and saves time.

An automated system will then position the car, swap out the old battery, and install a brand-new, fully charged battery. At order to be used later, the exhausted batteries are recharged at the station. The method is based on the idea that the owner of an EV is the car, not the battery. Ensuring that only authorized vehicles and charging stations can charge batteries necessitates the development of a reliable method for estimating the condition of the batteries to evaluate usage patterns [6].

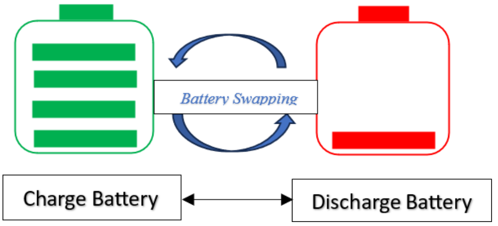

Fig 9. Battery Swapping

Advantages:
1. Absence of range anxiety
2. Fast and simple refilling, similar to a car's combustion engine tank
3. EV batteries may be charged for longer periods of time than quick DC charging

Disadvantages:
1. The necessity for many automakers to use a common battery interface.
2. Acceptance by the customer of replacing the car battery and not having a battery of their own

A. Wireless Charging Systems

Based on operating techniques wireless charging of electric vehicle can be classified into four types:
a) Capacitive Wireless Charging System
b) Permanent Magnetic Gear Wireless Charging System
c) Inductive Wireless Charging System
d) Resonant Inductive Wireless Charging System

a) Capacitive Wireless Charging System:

This power transfer technique uses advanced geometric and mechanical structures of the coupling capacitor and makes it very useful for low power applications such as portable electronic devices and cellular phone chargers. The transfer of energy between transmitter and receiver is accomplished by means of displacement current caused by the variation of electric

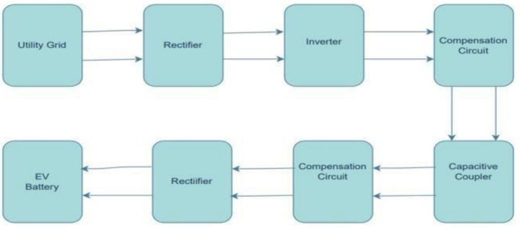

Fig 10. Block Diagram of capacitive wireless power transfer

This sort of wireless charging is based on the workings of an electric motor. Both the transmitter and the receiver are made up of an armature winding with synchronized permanent magnets at the core. Mechanical torque is generated when AC voltage is delivered to the transmitter winding via permanent magnets. Changes in the transmitter's permanent magnetic field drive synchronized mechanical torque in the receiver's permanent magnet, which produces AC current in the receiving winding the receiver becomes a power generator when the mechanical torque in its permanent magnet is transferred to alternating current in its winding. The coupling of rotating permanent magnets is known as magnetic gear. The AC current from the magnetic gear is rectified and filtered on the receiver side before being used to charge the electric vehicles battery [7].

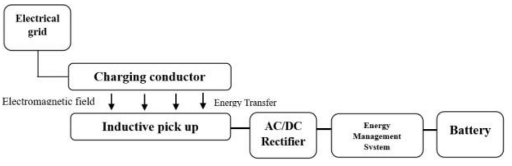

Fig 11. Block Diagram of Permanent Magnetic Gear Wireless Charging System

The advantages of this strategy include:

1. Convenience 2. Suitable for self-driving cars.

The disadvantages are:

1. High investment. 2. Limited space and weight of charging pads.

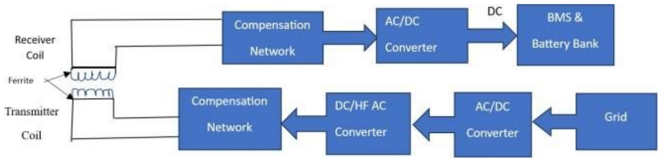

Fig 12: Block diagram of static wireless electric charging system

c) Dynamic charging: The alternative approach to charge an automobile wirelessly is known as dynamic charging. The coils attached to the electric lines that supplied the power are buried in the road. The coils emit an electromagnetic field that is detected by vehicles moving over them and turned into electricity to power the vehicles [8].

Advantages:
1. Short stand-in charging time
2. Low battery depth of discharge
3. Smaller battery size.

The challenges are:
1. High investment costs
2. Foreign objects, changes in coil structure, and coil misalignment on the road
3. Applicability to many automobile kinds and universal coil type selection.

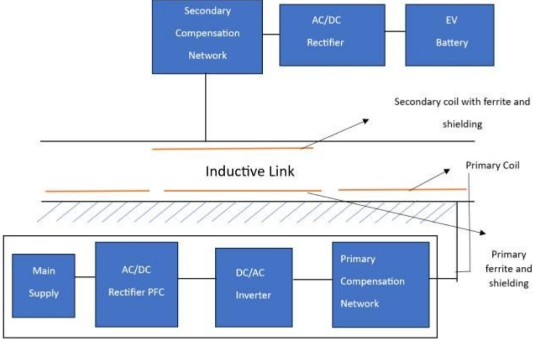

Fig 13: Block diagram of dynamic wireless electric charging system

d) Resonant Inductive Wireless charging: Basically, resonators having high Quality factor transmit energy at much higher rate, so by operating at resonance, even with weaker magnetic fields we can transmit the same amount of power as in IWC. The power can be transferred to long distances without wires. Max transfer of power over the air happens when the transmitter and receiver coils are tuned i.e., both coils resonant frequencies should be matched. So to get good resonant frequencies, additional compensation networks in the series and parallel combinations are added to the transmitter and receiver coils. This additional compensation networks along with improvement in resonant frequency also reduces the additional losses. Operating frequency of RIWC is between 10 to 150 KHz

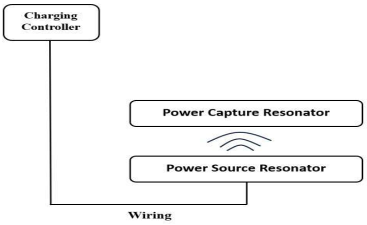

Fig 14. Resonant Inductive Wireless charging

Advantages:
1. Wireless electricity is ideal for most workplaces and home spaces.
2. Power can be given in any direction (omnidirectional).

3. The magnetic fields utilized in wireless power transfer are safe for living things.
4. Aesthetic appeal by decluttering the office or home space.
5. No need for meter rooms or electrical closets.
6. Reduce e-waste by removing the need for power cords.

Wireless charging ensures a secure connection. This prevents corrosion because the electronics are completely enclosed, away from water and oxygen in the atmosphere

Disadvantages:

1. Power transfer only takes place if the flux satisfies certain conditions.
2. Power transfer becomes in efficient as the distance between the transmitter and receiver increases.
3. There is a loss of power transmission if there is a strong ferromagnetic substance present between the transmitter and receiver.
4. There is need for standardization and adaptation to avoid overheating that occurs because of different voltages.
5. It requires completely new hardware which could become very expensive.
6. Less efficiency compared to traditional charging.
7. Possibility of energy theft increases.

6 Conclusion

Table 1. Comparative Overview of Different Electric Vehicle (EV) Charging Techniques

Charging Technique	Key Findings	Considerations
Level 1 Charger [6]	Basic charging option	Slow charging
Level 2 Charger [6]	Balance between Efficiency and cost- effectiveness	Moderate charging speed
Level 3 Charger [6]	- Efficient (DC fast charging)	Rapid solution
Battery Swapping [7]	Rapid solution	Infrastructure requirements
Wireless Charging [8]	Convenience	Concerns about efficiency, standardization, and cost

In conclusion, the research paper provides a thorough examination of diverse electric vehicle (EV) charging techniques, encompassing Level 1, Level 2, and Level 3 chargers, battery swapping, and wireless charging systems, including capacitive, permanent magnetic gear, inductive (static and dynamic), and resonant inductive wireless charging. Key findings emphasize the efficiency of Level 3 (DC fast charging) and the rapid solution offered by battery swapping, while considerations for cost, flexibility, and standardization play a crucial role and face challenges in standardization and economic viability. Level 2 chargers and Level 3 emerge as favorable choices for their balance between efficiency and cost-effectiveness. Wireless charging, particularly inductive static charging, is highlighted for its convenience, but concerns about efficiency, standardization, and cost are persist. The overarching recommendation underscores the importance of ongoing advancements and standardization to facilitate the seamless integration of electric vehicles into the mainstream automotive market.

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