EV charging infrastructure for Heavy Duty Vehicles - Global and Indian perspective

Seminar report

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November 2024

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Abstract

About 24% of the world's carbon dioxide emissions from fuel burning come from the transportation sector, making it a significant contributor to climate change. The transition to electric vehicles (EVs) in the heavy-duty vehicle (HDV) sector is crucial for reducing carbon emissions and advancing sustainable transport solutions. This report provides a foundational overview of electric vehicles, focusing specifically on HDVs and the infrastructure required for effective charging. Key challenges faced in deploying HDV charging infrastructure include long charging times, high energy demands and limited availability of charging stations. These issues are compounded by the distinct technical requirements and regulatory standards for HDV charging, which vary between India and international markets. This report provides the challenges of charging and highlights potential solutions, improvements in battery charging technology, and grid impact analysis. By addressing these challenges, this report aims to offer insights into the development of a reliable and scalable charging infrastructure for HDVs that can meet both present and future demands.

Contents

Nomenclature

Abbreviations

AC	Alternating current
BEV	Battery electric vehicle
CCS	Combined charging system
CHAdeMO	Charge de Move
DC	DC current
EPA	Environmental protection agency
EV	Electric vehicle
EVCS	Electric vehicle charging station
EVSE	Electric vehicle supply equipment
FAME	Faster adoption and manufacturing of hybrid and electric vehicles scheme
FCEV	Fuel cell electric vehicle
GVWR	Grosss vehicle weight ratio
HDEV	Heavy duty electric vehicle
HEV	Hybrid electric vehicle
ICCB	In-cable control box
IEC	International electrotechnical commission
ISO	International organization for standardization
LCFS	Low carbon fuel standard
LDV	Light duty vehicle
MDV	Medium duty vehicle
OEM	Original equipment manufacturers
PFC	Power factor correction
PHEV	Plug-in hybrid electric vehicle
SAE	Society of automobile engineers
TOU	Time of use

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Overview

With the goal of lowering carbon emissions and reliance on fossil fuels, electric vehicles (EVs) are an important step forward for environmentally friendly transportation. Even though they are less common than passenger cars, heavy-duty vehicles (HDVs), such as trucks and buses, contribute significantly to greenhouse gas emissions. Given that HDVs contribute a disproportionate amount of pollution, this sector must electrify in order to reach global climate goals. Thus, it is believed that electrifying HDVs is essential to lowering emissions and enhancing air quality, especially in cities close to major highways and industrial hubs.

1.2 Objective

This report's main goal is to highlihgt the infrastructure needs and standards for heavy-duty vehicle (HDV) charging, with an emphasis on both the Indian and global contexts. The purpose of this report is to give a thorough understanding of the basic ideas of EV technology as they relate to HDVs, highlight the main obstacles to the installation of effective charging infrastructure, and investigate workable alternatives. This research aims to provide suggestions to help the creation of a strong, interoperable HDV charging network by evaluating regulatory requirements and technology developments. The report's ultimate goal is to help in making a sustainable, scalable charging infrastructure for EV charging.

1.3 Issues with Heavy-Duty Vehicle Charging Infrastructure

There are significant difficulties in electrifying HDVs, especially when it comes to establishing suitable charging infrastructure. Compared to light-duty vehicles, HDVs have higher energy requirements, demanding more reliable and quick charging systems. High infrastructure installation costs, grid capacity constraints, and the requirement for fast-charging capabilities to reduce vehicle downtime are some of the difficulties. Additionally, fleet owners have operational challenges due to the logistics of charging these massive vehicles, since HDVs frequently require charging stations at depots and along roads in order to operate long-haul routes.

Chapter 2

Literature Review

2.1 Classification of electric vehicles

Electric vehicles can be categorized based on their power source and engine type: [5] [21],

- **Battery electric vehicles (BEVs):** Powered solely by electric energy stored in batteries, these vehicles do not use internal combustion engines, fuel cells, or fuel tanks. They are designed for zero-emission operation.
  Examples - Nissan Leaf, Tesla Model S.
- **Hybrid electric vehicles (HEVs):** Equipped with both a conventional internal combustion engine and an electric motor, these vehicles use a combination of fuel and electricity for propulsion. This hybrid setup optimizes fuel efficiency and performance.
  Examples - Ford Escape Hybrid, Toyota Prius
- **Fuel cell electric vehicles (FCEVs):** These vehicles generate electricity on board using hydrogen fuel cells. The chemical reaction between hydrogen and oxygen produces electricity, which powers the electric motor, emitting only water vapor as a byproduct.
  Examples - Honda Clarity, Toyota Mirai

2.2 Types of electric vehicle charging

EV chargers have undergone significant development over time, resulting in a wide range of charger types now available to cater to various EV categories. Charging options can be categorized into different types, as illustrated in Figure 2.1.

The charging infrastructure is categorized based on factors such as charging speed, charger standardization, ownership models, charging processes, and power flow direction, as depicted in Figure 2.1. This report utilizes an analytical framework to define EV charging infrastructure [21].

The different types of charging methods are shown in figure 2.2 [27].

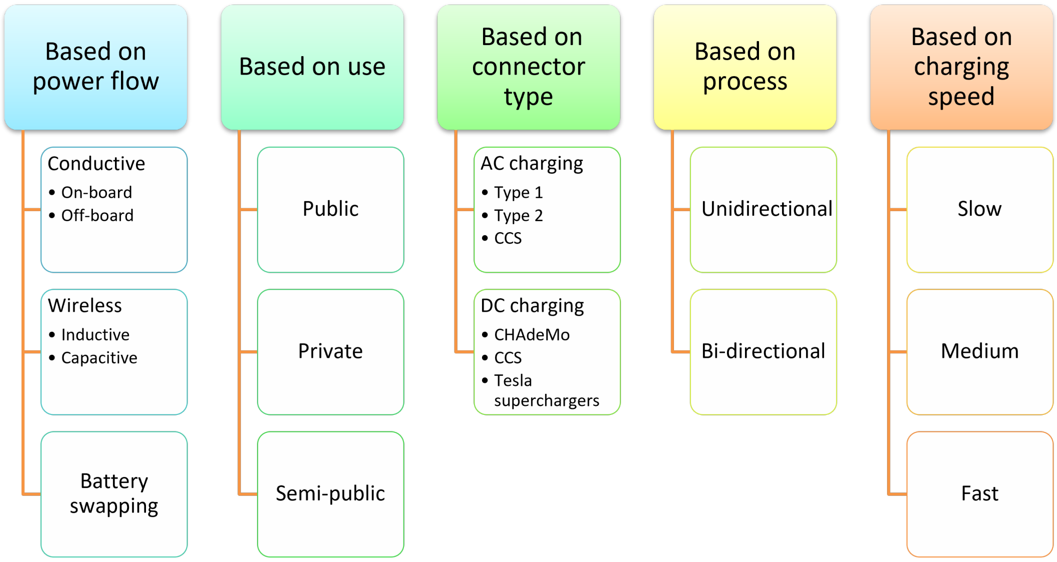

Figure 2.1: Types of electric vehicle charging

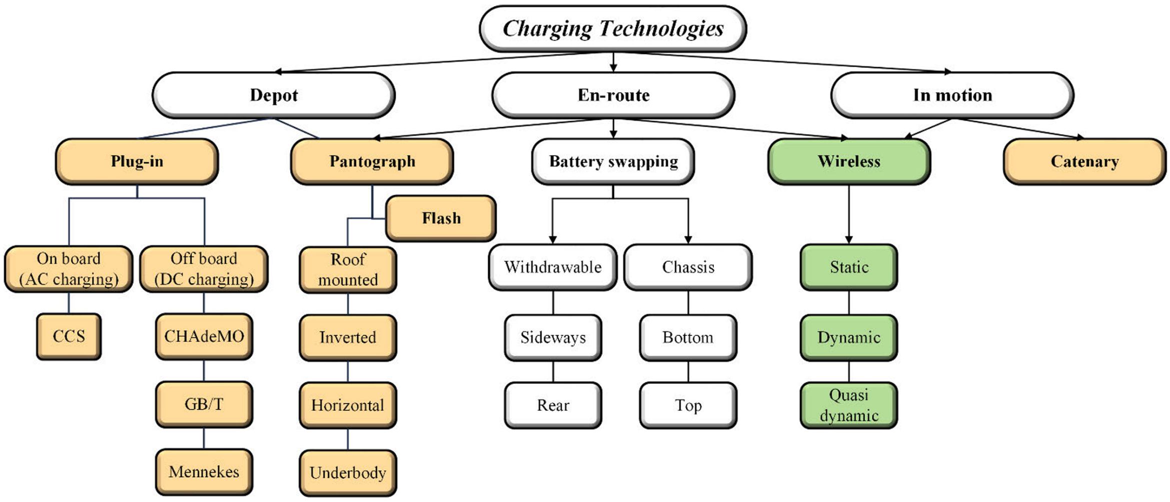

Figure 2.2: Current E-bus charging methods. The yellow boxes showing conductive charging techniques, whereas the green boxes showing inductive charging methods [27]

2.2.1 Modes of electric vehicle charging

The IEC 61851 standard has defined different modes for EV charging: [21]

- **Mode 1** - This mode operates with standard 230 V AC outlets, with a maximum charging capacity of 2.3 kW for safety reasons, as it does not include communication capabilities.
- **Mode 2** - It employs a conventional 230 V connector integrated with an In-Cable Control Box (ICCB). The ICCB determines the charging capacity, which can reach up to 7.4 kW (single-phase, 32 A) or 22 kW (three-phase, 32 A). However, it is commonly used at 2.3 kW (single-phase, 10 A).
- **Mode 3** - This mode utilizes communication between the EV and the EVCS to optimize charging capacity. Most public Mode 3 chargers support 11 kW, 22 kW, or fast charging options.
- **Mode 4** - Designed for rapid DC charging, this mode offers charging capacities starting

at 50 kW and above. (IEC 61851)

2.2.2 Levels of electric vehicle charging

Internationally, the charging of electric vehicles can be classified into various levels based on the power rating and charging technology adopted. The EV charging level standards and the associated on-board or off-board charging method have been established by SAE. The established levels are applicable in accordance with their benefits and drawbacks. [21]

- **Level 1 AC** : It can handle up to 20 A of current and has a nominal supply voltage of 120 V. With a power output of up to 2.4 kW and an on-board single-phase charger, they are mostly utilised in domestic situations. It is less expensive because it is a plug-and-play technology that doesn't need to be installed. Because of the low charging power, the charging period is rather long—roughly 8 to 12 hours.
- **Level 2 AC** : The nominal voltage and current for Level 2 AC charging are 240 V and 80 A, respectively. It has a 19.2 kW maximum power output and requires an onboard charger. If we Compare it with level 1 AC charging, it is more costly because it involves installation work. It is frequently found at workplaces, shopping centres, and public parking lots.
- **Level 3 DC** : It is also called DC fast charging. It consists of a 3-phase off-board charger which skips the need of on-board charger and sends DC power straight to the battery. It features a maximum power output of 240 kW, operates within a nominal voltage range of 200 V to 600 V, and supports a current rating of up to 400 A. Along with a suitable car, they need a DC charging port like CCS or CHAdeMO. For communication between EV and EVSE, several communication protocols are utilised, including Controller area network (CAN) and Power line carrier (PLC).

2.2.3 Connector types

Different EV manufacturers utilize various connector types for charging: [21]

- **Type 1** - This connector is primarily used for single-phase AC charging in regions such as Japan and the USA. It typically supports charging capacities up to 7.4 kW (single-phase) and is characterized by its 5-pin design.
- **Type 2** - Widely standardized across Europe, this connector is used for AC charging up to 22 kW. Also called as the Mennekes connector, it features a 7-pin design, allowing for both single-phase and three-phase charging, making it more versatile than Type 1 for higher power applications.
- **CCS 1** - This connector type combines the Type 1 AC connector with additional DC fast charging pins, allowing for both conventional AC charging (up to 22 kW) and fast DC charging (up to 150 kW or more). It is commonly used in North America.
- **CCS 2** - The CCS 2 connector is similar to CCS 1 but is designed for Type 2 AC connectors and includes additional pins for fast DC charging, supporting higher charging capacities of up to 350 kW. It is the standard for Europe and increasingly adopted globally for high-power DC fast charging.
- **CHAdeMO** - A dedicated DC fast-charging standard, CHAdeMO is used for rapid charging of electric vehicles with charging capacities ranging from 6 kW to 400 kW. Developed in Japan, it supports bidirectional charging (vehicle-to-grid or V2G) and is commonly found on older Japanese electric vehicles and some European models.

2.3 Classification of Heavy duty vehicles

Based on GVWR, the heavy duty vehicles can be classified as follows: [2]

Heavy-duty vehicles	Abbreviation	GVWR in tonnes
Light heavy-duty vehicles	HDV2b	4.2505 - 5
	HDV3	5.005 - 7
	HDV4	7.005 - 8
	HDV5	8.005 - 9.75
Medium heavy-duty vehicles	HDV6	9.7505 - 13
	HDV7*	13.005 - 16.5
Heavy heavy-duty vehicles	HDV8a	16.505 - 30
	HDV8b	> 30

Table 2.1: Summary of vehicle classifications presented in EPA guidelines

Note: *HDV7 represents heavy duty vehicles of class 7

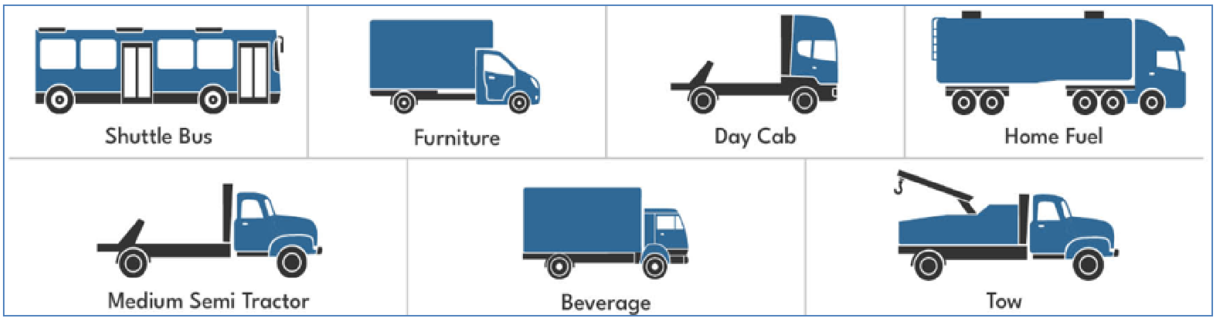

Figure 2.3: Class 7 heavy duty vehicles [30]

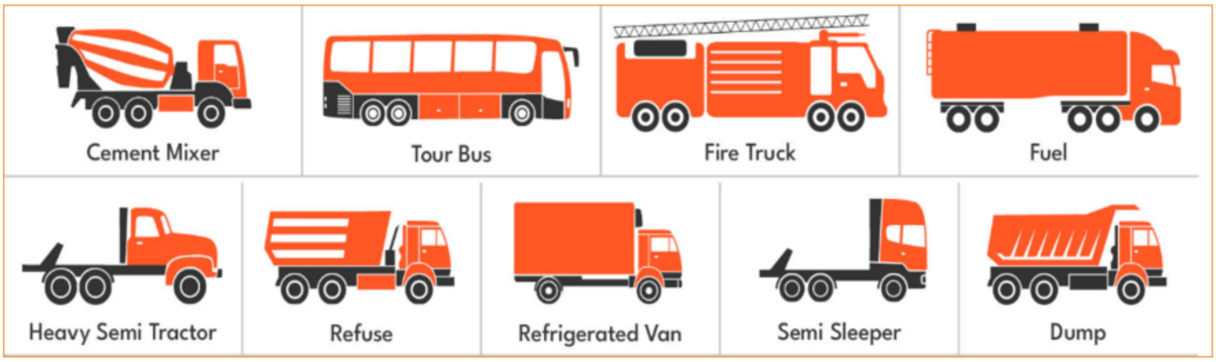

Figure 2.4: Class 8 heavy duty vehicles [30]

2.3.1 Classification of electric trucks

The heavy duty trucks can be classified as charging type, battery capacity and range etc [18], [15], [32], [23].

Globally available trucks

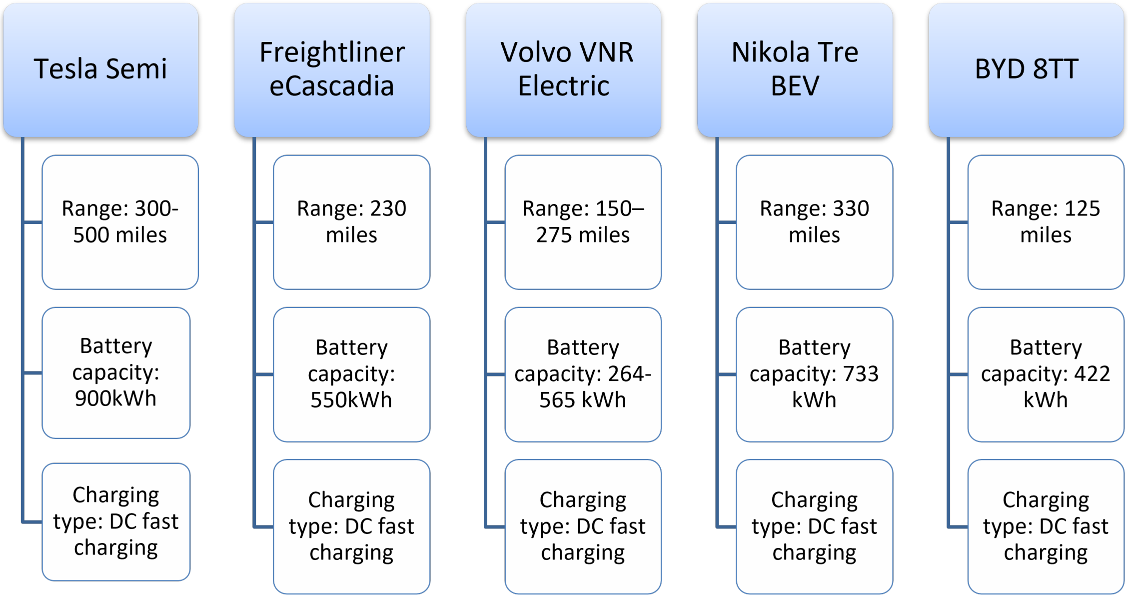

Figure 2.5: Globally available trucks with their features

Trucks available in India

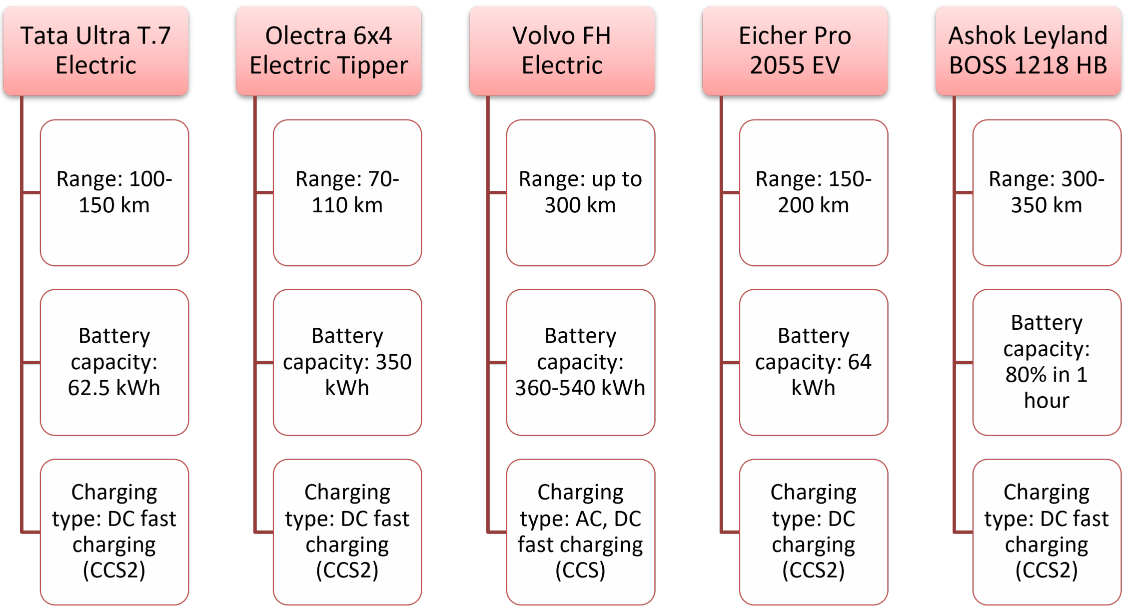

Figure 2.6: Trucks available in India with their features

2.3.2 Classification of electric buses

The heavy duty buses can be classified as charging type, battery capacity and range etc [18], [15], [32], [23].

Globally available Buses

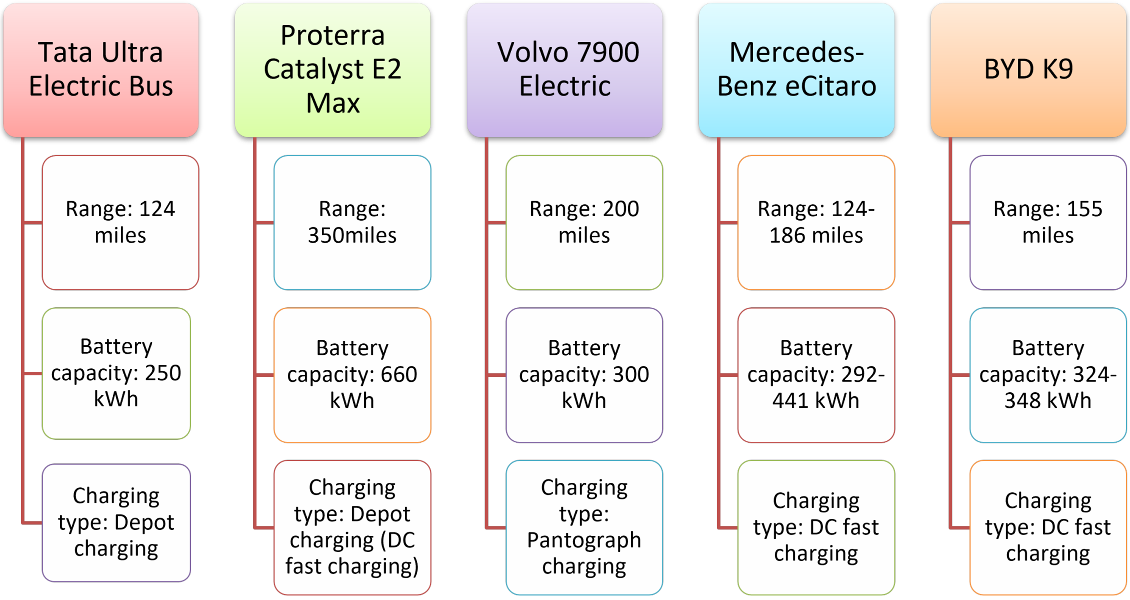

Figure 2.7: Globally available buses with their features

Buses available in India

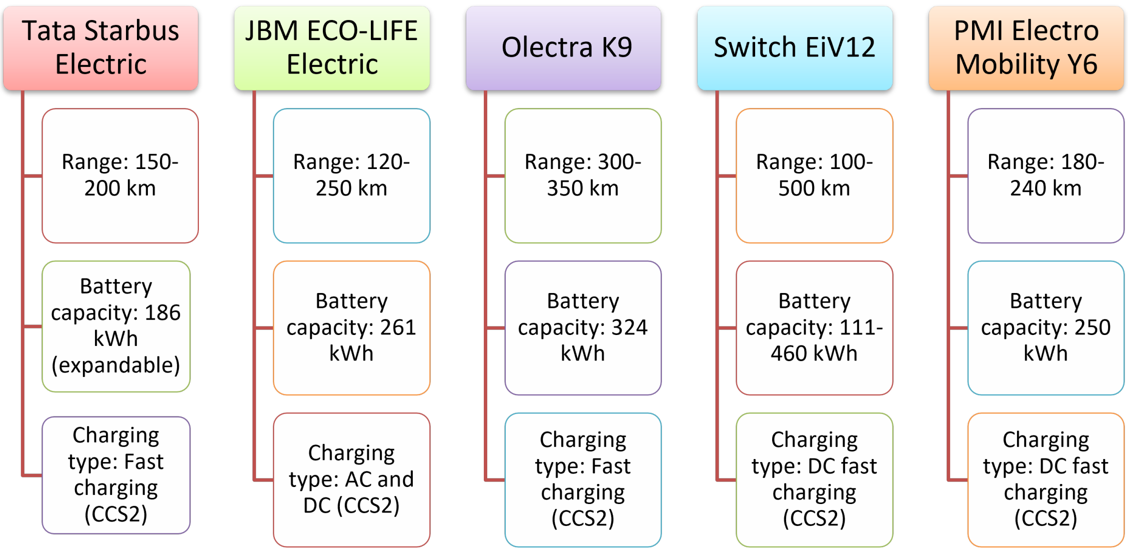

Figure 2.8: Buses available in India with their features

2.4 Charging strategies of heavy duty vehicles

Charging strategies for heavy duty electric vehicles involve a variety of approaches that aim to optimize efficiency, reduce energy costs, and minimize impacts on the power grid. [27]

1. **Plug-in charging** : The most widely used depot charging method for electric buses is plug-in charging, commonly referred to as manual cable charging. It is affordable, simple to install, compatible with a number of bus types, and provides adjustable power levels for different bus models and battery capacities [35]. But compared to fast-charging techniques, it takes longer to charge and involves operator handling, which can occasionally result in human mistake. While some buses employ CHAdeMO or particular connectors, such as BYD's Mennekes Type 2, the CCS/Combo2 standard is commonly used in Europe. Depots often use charging reels to position cables near bus ports, minimizing disruptions to bus operations caused by cables being left hanging or lying on the floor. [33].

Figure 2.9: Charging reels for flexible charging cabling in depot charging [27]

2. **Pantograph charging** : An E-bus is connected to an overhead power supply using an Automatic Connecting System (ACS) to enable pantograph charging, which provides 150–600 kW of power. Underbody, horizontal, inverted, and roof-mounted configurations are available; the roof-mounted variety being the most common due to its ease of use. Although pantograph charging takes up little space in cities, it necessitates a large infrastructure investment and possible standardisation to ensure system interoperability. ABB's TOSA invented flash charging, a quick pantograph system that allows E-buses to charge at high power in a matter of seconds during stops. This reduces downtime and permits continuous running along routes, thereby circumventing range restrictions [27], [3].

3. **Battery swapping** : It takes 2.5 to 10 minutes to swap out a drained battery for a charged one when using battery swapping for depot or on-route charging. This strategy was initially used for E-buses in China in 2008 [29]. Standardisation is difficult since different manufacturers' battery designs cause compatibility problems, even though swapping stations can sustain the grid with idle batteries. Degradation of the battery causes different capacities over time, which makes the process much more difficult. Standardising their bus fleet and batteries, however, can help public transportation agencies deal with these problems [8].

4. **Catenary charging** : Catenary charging, which is perfect for long-distance bus routes with significant demand, employs overhead wires to deliver continuous high-power charging. Although dependable, it restricts buses to certain routes with overhead wiring and necessitates a large infrastructure investment. This method, originally used for trolleybuses, allows buses to connect using a pantograph or trolley, either supplying power directly to the motor or charging the batteries [24], [25]. By enabling regular low-power recharge, the device eliminates the need for bulky onboard batteries, saving weight and space. But in cities, putting in a lot of overhead cable can be expensive and unsightly.

5. **Wireless charging** : By using conductive or inductive technologies instead of physical connectors, wireless charging for E-buses is automated and convenient. Using a magnetic coupling between coils—one in the bus and one on the road—this technique transfers energy. Modern systems can produce up to 450 kW, which is comparable to plug-in and overhead charging, and were first deployed commercially in Seoul in 2009. The only wireless charging technique that doesn't require a physical connection even permits charging while the car is moving. Interest in wireless power transfer (WPT) is growing as a result of its advancements, which allow for in-motion charging and battery size reduction.

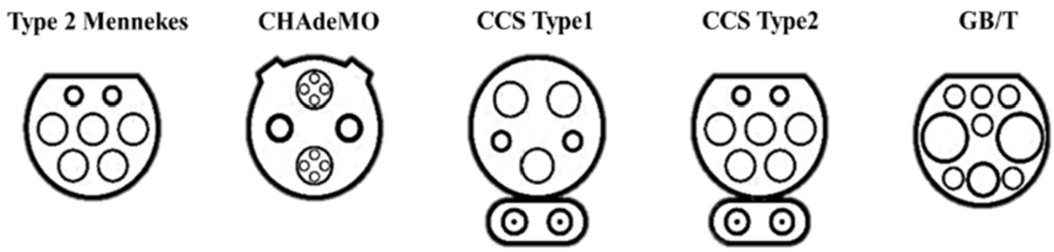

Figure 2.10: Different types of connectors of plug-in chargers used for E-buses [27]

Chapter 3

Challenges with HDEV charging infrastructure

Trucks and buses are significant contributors to air pollution and greenhouse gas emissions. While electric trucks and buses offer a promising solution, they face several challenges. This paper outlines key challenges and proposes potential solutions to guide further research [28].

3.1 Challenge 1 : Challenges in EVCS planning

In this section, our goal is to give a general overview of these difficulties in context of EVCS technology and power quality concerns.

3.1.1 Power quality and power system reliability

Electric Vehicle Charging Stations (EVCSs) demand substantial electrical power and rely on numerous power electronic converters. These requirements can result in various issues, including power loss due to mismatched demand and generation, undesirable voltage conditions (such as voltage drop, imbalance, rise, or violations), and congestion issues like transformer overloading, feeder congestion, power losses, transformer aging, and unexpected peak demands. Additionally, frequency instability, including fluctuations, rises or drops, and harmonic distortion, can occur. These challenges may adversely impact EV charging efficiency, the stability and reliability of the power system, and the optimal operation of the power distribution network. [12], [34].

Many academics have thoroughly examined these power quality concerns. For example, [37] simulates and analyses the effects of a significant number of grid-connected EVCSs on a utility system. This report examines transformer power loss, harmonics, power consumption, and voltage profile. The findings indicate that as the number of EVCSs has increased, transformers have overloaded and tripped, power demand has increased, harmonics have increased, and voltage has become unstable. The behaviour of a distribution system after EVCS integration is examined in [34].

After the introduction of EVCSs, the effects are shown by analysing variables like the line's maximum current, the network's average voltage, the coefficient of voltage imbalances, and the network's loss of active power. The system can supply EVCSs up to 35% of existing loads, according to the findings; after that, the system would collapse [17], [34].

A three-phase six-pulse rectifier is widely utilized in medium-power electric vehicle (EV) chargers. For a 4 kW EV charger operating with this rectifier topology, the harmonic content of the phase current typically includes the 5th, 7th, 11th, and 13th harmonic components alongside the fundamental frequency. The three-phase design effectively suppresses third harmonics and other multiples of three. However, the system still experiences significant total harmonic distortion (THD), calculated at approximately 35.28%. This elevated THD level arises from the inherent limitations of the rectifier's design, which results in a non-continuous current flow and amplifies harmonic distortion [22].

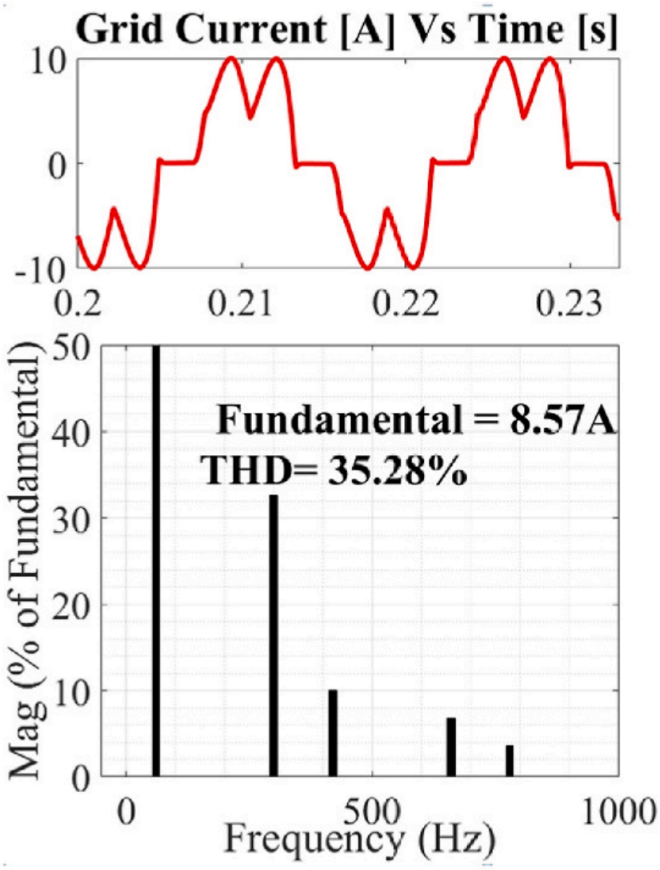

Figure 3.1: FFT spectrum of grid current for 6-pulse rectifier [22]

3.1.2 EV demand uncertainity and uncontrolled charging

It is quite difficult to predict how much electricity charging stations will require at a specific time and place. The location of charging stations, charging rates, user behaviour, charging costs, traffic volume, vehicle count, weather, and other variables all affect this uncertainty [34].

This unpredictability can result in transformer overloading, power losses, feeder congestion, increased demand for power transmission and distribution infrastructure, and unexpected peak loads. These effects can lead to abrupt shifts in the grid's energy requirements, making it difficult to maintain a consistent balance between the power generation and the power demand.

Distributed charging stations that are not under control can potentially strain the electrical grid, resulting in blackouts or system collapse. For example, an experimental setup is used in [6] to analyse the effects of integrating uncontrolled EV charging on the distribution system. According to experiment, more active and reactive power is needed. All of the buses experience a drop in voltage, with the downstream bus experiencing the most severe effects [34].

3.2 Challenge 2 : The fleet perspective : Range and charging time

Fleets anticipate that heavy-duty electric vehicles (HDEVs) should match diesel vehicles in aspects such as driving range, payload capacity, availability of trained maintenance personnel, and diversity of model options. Additionally, fleets must factor in the longer recharge times into their operational logistics. This section highlights the logistical challenges that fleet operators encounter when evaluating the transition to EVs.

3.2.1 Range

Compared to similar diesel vehicles, which can travel 2,000 miles without refueling (with two 567.75 litres tanks), electric trucks now have a range of fewer than 322 kms on a single charge. Longer ranges are now possible because to advancements in battery technology; the new Tesla Semi, for instance, is reportedly capable of travelling 804 kms between charges. The market hasn't changed enough for the majority of long-haul fleets, although fleet operators now have more electric options for trucks that go 160–322 kms [20]. Depending on variables including driving style, temperature, and hill grade, an MHDEV's real range may not match the manufacturer's stated range [28].

3.2.2 Recharging time

MHDEVs require up to nine hours to recharge, which is significantly longer than diesel truck refuelling. Fleets with depots and overnight dwell durations don't lose time, but they still need to install a charger, and they can choose between slower, less expensive chargers or more costly rapid chargers. Independent operators who own nearly 50% of MHDEVs might favour on-route billing. Additionally, public charging will be required for city buses and long-haul vehicles. Station availability and the potential cost of charging time are important considerations for on-route charging. Although the absence of public charging stations is a considerable obstacle, electrification might be greatly increased by growing the network [28].

3.3 Challenge 3 : Impact on the power grid

The integration of E-bus charging infrastructure has considerable implications for the electrical grid. The addition of numerous E-buses can lead to a significant surge in load demand, potentially straining local distribution systems and requiring upgrades to existing infrastructure. For example, fully charging a single BYD K9 E-bus overnight consumes an amount of electricity comparable to the daily energy usage of over twenty typical North American households [27]. This demand, when scaled to accommodate large E-bus fleets, may necessitate enhanced grid capacity, advanced load management systems, and robust planning to avoid operational inefficiencies and grid instability.

Uncontrolled charging of electric buses can strain the power grid, reducing its ability to handle unexpected surges in electricity demand. Rapid charging, especially in busy transit areas, may cause voltage fluctuations, affecting the stability of the power grid. The high electricity demand from rapid charging can cause increased power losses within distribution networks due to the higher current required, which increases resistive losses in the electrical components, which may cause equipment like transformers and cables to overheat, reducing their lifespan.

Additionally, rapid and two-way (bidirectional) chargers can introduce electrical disturbances, called harmonics, into the grid, which can lower the power quality and reduce the efficiency of electricity use (power factor). The non-linear characteristics of power electronics in EV chargers lead to the generation of current harmonics, which increase the RMS value of line currents. This rise in current can result in damage to various grid components, such as transformers, by causing additional heating and stress on the electrical system [13].

It has been demonstrated that the total daily energy loss in power grids incorporating rapid charging systems has increased by approximately 30% as compared to grids without any E-bus chargers integrated. This increase is attributed to the high electricity demand and the inefficiencies introduced by rapid charging technologies. [10], [19].

Chapter 4

Solutions of HDEVs charging infrastructure

Increasing the use of EVs and optimising their advantages are two major objectives for wide EV adoption.

Additionally, it is essential to develop optimal charging strategies that can effectively coordinate the charging processes of commercial electric vehicles (EVs) across different locations. These strategies are necessary to minimize grid impact, reduce energy costs, and ensure efficient utilization of charging infrastructure, taking into account factors like charging times, energy availability, and load distribution.

Some recommended solutions to accomplish these objectives are covered in this section:

4.1 Solution 1 : Smart charging strategies

In order to accomplish a variety of control objectives, smart charging strategies aim to optimize the charging of the electric vehicles at several sites. Because of the various difficult problems with commercial electric vehicle charging automobiles, intelligent charging techniques ought to be created to manage the public charging stations' charging procedure, in addition to the places where these cars are parked [1].

4.1.1 For Return-to-Base charging infrastructure

The strategic placement of public EV charging infrastructure must consider the varied transportation requirements of commercial vehicles, ensure grid stability, and promote optimal usage of charging facilities. By addressing these factors, infrastructure planning can support efficient operation and minimize disruptions. [4].

Numerous studies have investigated the best approaches to determine charging station locations for commercial electric vehicles. One approach is solving location-routing problems, where the aim is to integrate charging stations into commercial vehicle routes. This ensures uninterrupted service while minimizing combined investment and operational costs. These studies typically account for constraints like load capacities, battery sizes, and customer service time limits, tailoring solutions to logistical needs. [26].

In [26], another method involves analyzing accessibility issues for diverse commercial vehicles. Multi-day travel data from various commercial EVs is often used to cluster frequent stopping points. These clusters, constrained within specific distance thresholds, help identify potential locations for charging stations. By optimizing station placement at these candidate sites, trip failures are minimized, and infrastructure costs are reduced. Factors such as trip durations, travel distances, and vehicle dwell times are integral to these optimizations [1], [26].

4.1.2 For public charging infrastructure

The charging process for commercial electric vehicles at public charging stations must be carefully planned. These vehicles can be charged either fully or partially at various charging stations along their route, based on the constraints of their operational schedules and time-of-use (TOU) electricity tariffs. The operational schedules of commercial vehicles impose limitations on the maximum time that can be spent serving each customer along the route. This restriction affects the amount of time available for charging at each station. Additionally, the maximum charging time is influenced by the following factors [1]:

- **Queue waiting time:** Congestion at charging stations can result in longer waiting times, which reduces the available charging time.
- **Location of the charging station:** If charging stations are located far from the vehicle's daily route, detouring to reach them reduces the available time for charging.
- **Charging power rate:** The charging time is also impacted by the power rate of the station; higher power rates enable faster charging, while lower rates extend the charging time.

4.2 Solution 2 : Bus to grid (B2G) technologies

Although the Vehicle-to-Everything (V2X) concept has been widely studied and is well-established for electric vehicles such as cars, it is comparatively underexplored for electric buses (E-buses). E-buses, which have extended idle periods during the day, offer significant potential as high-capacity stationary energy storage systems. These buses could store renewable energy generated by local renewable energy systems or capture braking energy from trains or metros [11]. By leveraging the V2X technology, E-buses could serve as vital components of energy networks, facilitating energy storage and grid balancing.

These E-buses can fulfill various roles, as illustrated in Fig. 16, including supporting the grid (B2G), supplying energy directly to residential or commercial buildings (B2B), or facilitating charging for other electric vehicles with higher priority (B2V). These capabilities enable E-buses to contribute to grid stability, enhance energy distribution efficiency, and provide auxiliary services to other EVs when needed, turning them into flexible energy assets.

The integration of E-bus chargers into the electricity grid (B2G) can significantly improve grid capacity and stability. A key example is the "Bus2Grid" project launched in London in 2018, which involves 28 E-buses actively participating in interactions with the energy system. The initiative aims to develop a strategy for the large-scale deployment of B2G technology, with the goal of returning over 1 MW of power to the grid. This approach demonstrates the potential for E-buses to act as valuable energy assets, helping balance supply and demand, while supporting grid resilience [1].

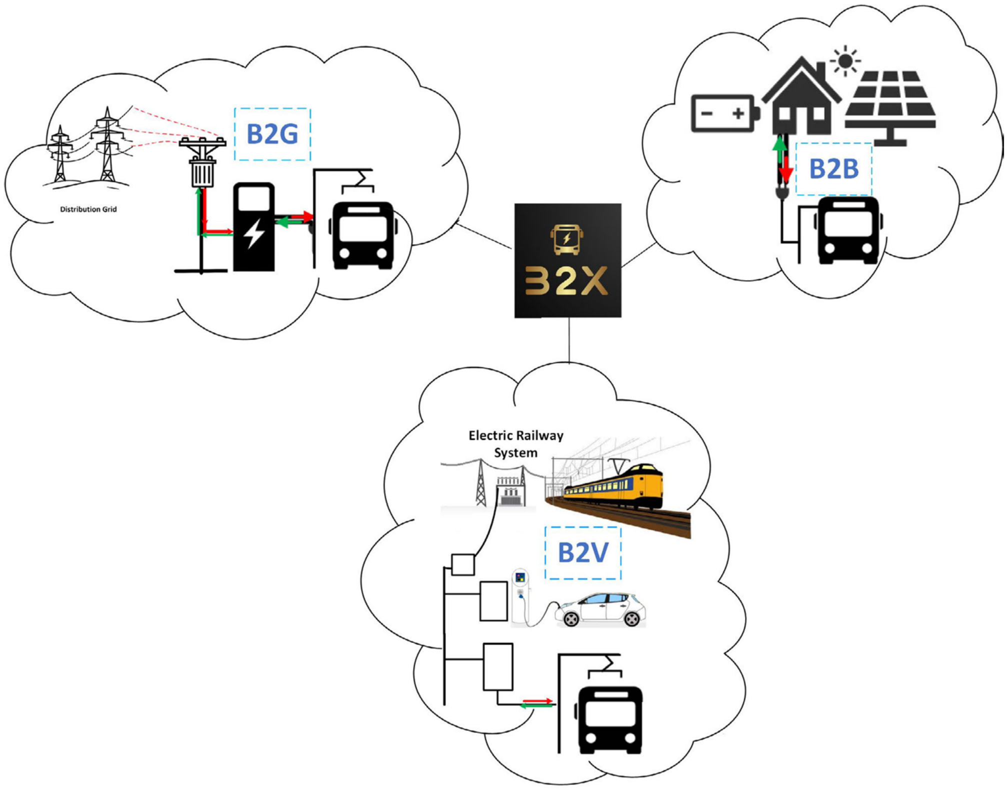

Figure 4.1: B2X technologies including bus-to-grid (B2G), bus-to-building (B2B) and bus-to-vehicle (B2V) [1]

4.3 Solution 3 : Optimal location of charging infrastructure

The placement of public charging infrastructure should be optimized to address the diverse transportation tasks of commercial vehicles, the stability constraints of the electrical grid, and the efficient utilization of charging stations [1], [7].

Several studies have explored the optimal locations of charging stations for commercial vehicles. Many of these studies focus on location-routing problems, where the goal is to identify the best locations for charging stations within the routing of commercial vehicles to ensure continuous service along their routes [16]. In these analyses, the locations of charging stations are optimized to minimize total investment and operational costs, while accounting for various constraints such as loading capacity, battery size, and customer time windows. .

Other studies have examined the localization problem of charging stations accessible to various commercial vehicles [14]. These studies involved preprocessing multi-day travel data collected from different commercial electric vehicles, followed by clustering stop points to identify potential charging station locations. These clusters were designed to stay within specific thresholds, ensuring the distance between the charging stations and points of interest did not exceed a preferred maximum. The locations of charging stations were optimized at these candidate sites to minimize trip failures and the overall infrastructure cost, factoring in trip duration, distance, and dwell time [1], [9].

4.4 Solution 4 : Grid impact mitigation strategy

This section outlines strategies to address and reduce the impacts of heavy-duty EV charging stations on the electrical grid.

4.4.1 PV-ES-Charger solution

The charger's reactive power support plays a vital role in stabilizing the system voltage during voltage drops caused by the charging load. However, when the charging load surpasses a critical threshold, reactive power alone becomes insufficient for voltage stabilization. To address this, on-site real power generation is required to offset part of the demand. A practical solution involves integrating a photovoltaic (PV) system with energy storage, which can effectively supply the required power during peak load periods.

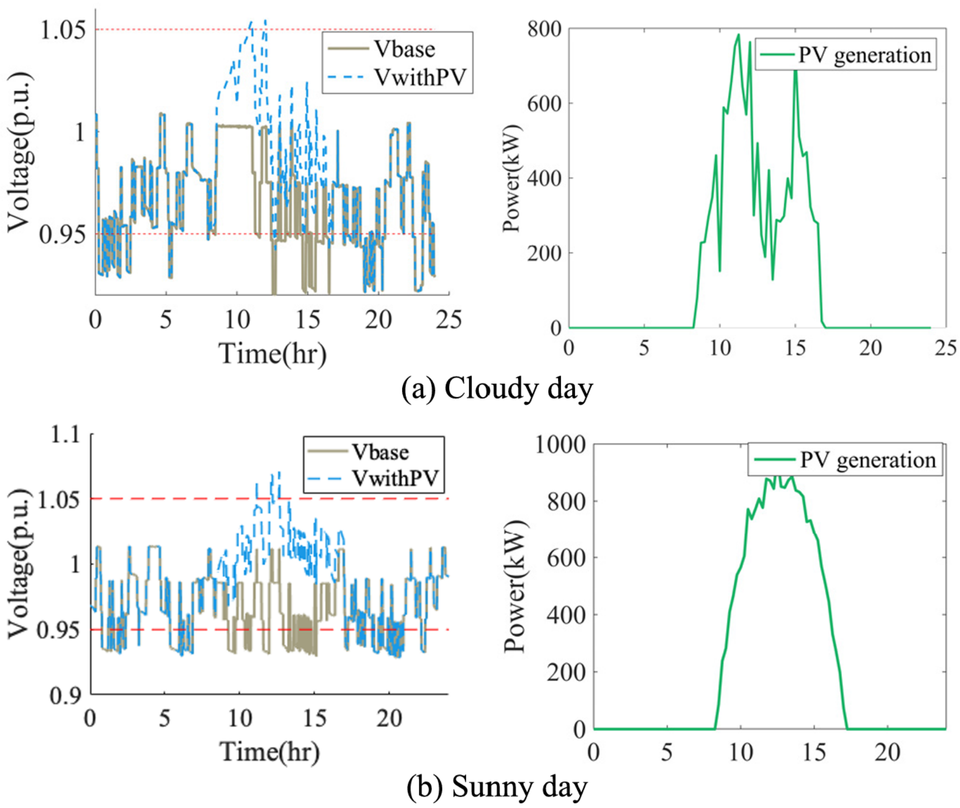

Figure 4.2: Sample cases of voltage impact mitigation using on-site PV generation [35]

- As shown in Fig. 6(a), on a cloudy day, PV power is not effectively utilized because the generation of power from the PV panels does not align with the peak charging load. When high PV power is needed to support heavy charging loads, the PV panels fail to generate sufficient power.
- In contrast, Fig. 6(b) illustrates that on a sunny day, PV power can be used effectively to reduce load on the charging station. However, excess PV power during periods of low charging load may cause an increase in voltage, surpassing the upper voltage limit (as indicated by the blue dashed line in Fig. 6(b)). The voltage profile of the connection point at a 3-port charging station is shown by V_{base} for two optimal locations in a realistic utility single feeder system.

Therefore, it is essential to properly size the three key components of the photovoltaic-energy storage-charger (PV-ES-charger) system. This ensures that the energy storage system (ES) can efficiently store surplus PV power and supply the charging load when PV generation is not available. Furthermore, the inverter should be adequately sized to provide sufficient reactive power support in situations where on-site real power generation is insufficient. Proper sizing of these components ensures efficient energy use and system reliability, especially during periods of high demand or low PV generation.

4.4.2 PV-ES-Charger sizing strategy

To balance the sizing of each component in the PV-ES-charger system, a methodology is proposed to optimize the combination of the photovoltaic (PV) system, energy storage (ES), and smart charger. The goal is to maintain the system voltage within acceptable limits while minimizing the overall capital cost of the on-site solution. This approach ensures both efficiency and cost-effectiveness by considering the power generation, storage, and charging dynamics, with a focus on maintaining grid stability and operational reliability.

By using voltage load sensitivity matrix (VLSM) [36], Voltage changes in the system can be calculated by determining how real and reactive power variations at one or more nodes affect the grid. Using the Voltage Load Flow Model (VLSM), we can estimate the voltage levels in the system during peak charging loads at the charging station, assuming the station is located at a specific node.

By comparing the system voltage during peak charging with the reference voltage, the maximum real and reactive power required to maintain the system at the reference voltage level can be determined. This approach helps in understanding and managing power requirements to ensure system stability during periods of high load [35].

Hence, the primary role of the Energy Storage (ES) system is to store excess energy generated by the photovoltaic (PV) system and discharge it when necessary to meet the charging load requirements. The size of the ES is largely influenced by the interaction between the PV generation profile and the charging load profile. While a specific vehicle's travel path might vary, the overall aggregated travel profiles for a fleet of vehicles are typically similar. As such, a set of representative charging load profiles can capture most charging scenarios at a given station. Consequently, the size of the ES at a particular station depends on the variations in the PV generation profiles and the expected charging demand.

Chapter 5

Conclusion

Heavy-duty vehicle (HDV) electrification, especially Medium and Heavy-Duty Electric Vehicles (HDVs), offers a revolutionary chance to decarbonise the transportation industry and lessen the damaging environmental effects of fleets that run on diesel. From their categories and charge types to the related issues and possible remedies, this research has examined the many sides of HDVs. Large-scale HDV adoption is hampered by a number of significant obstacles, such as expensive upfront prices, inadequate charging infrastructure, and logistical difficulties experienced by fleet operators, despite the encouraging technology developments.

As mentioned, fleet operators have good options because to the range of electric vehicles on the market, which includes anything from buses to electric trucks. However, the creation of a thorough and robust charging infrastructure is necessary for the successful deployment of these cars. To guarantee smooth integration into fleet operations, this entails growing both public and private charging networks, creating standardised connector types, and improving charging modes and levels. The adoption of HDVs can be further accelerated by on-route charging options, such as strategically positioned public charging stations and battery swapping technology, which can allay worries about range restrictions and lengthy recharging times.

In conclusion, switching to HDVs has several advantages, including as lower emissions, cleaner air, and long-term financial savings, but it also has drawbacks. Policymakers, manufacturers, fleet operators, and utilities may work together to solve these obstacles. Accelerating the shift to a sustainable, electrified heavy-duty vehicle industry will require the implementation of focused legislation, calculated investments in charging infrastructure, and assistance for small fleets. When the proper policies are in place, HDVs have the potential to significantly contribute to the development of a more sustainable and environmentally friendly transportation sector in the future.

5.1 Future Scope

The heavy-duty electric vehicle (HDV) industry is expected to see major developments in the future that might significantly improve its sustainability and viability. It is projected that advancements in charging technology, such as dynamic (on-the-go) and ultra-fast charging, will decrease downtime and improve fleet efficiency. In order to meet the demands of increasingly varied HDV fleets, improved power electronics and connectors—particularly those made for high power transfer—will also enable quicker and safer charging.

There should be significant advancements in battery technology as well. HDVs may become more feasible for long-distance travel if research is done on improving charge cycles, lowering battery weight, and boosting energy density. New battery chemistry and solid-state batteries are examples of emerging technologies that could increase battery life, decrease charging times, and enhance safety. These developments could lessen reliance on vast networks of charging infrastructure and minimize total ownership costs.

In order to further lower the carbon impact of HDV operations, renewable energy sources like solar and wind will be incorporated into the expanding HDV charging infrastructure. A degree of energy autonomy may be made possible by co-locating energy storage devices and charging stations. This is especially advantageous in distant or high-demand areas where grid dependency is less practical. In order to ensure smooth HDV operations across borders, future legislative initiatives can also promote more unified international standards and interoperability. A circular economy for HDV components might also be supported by laws that promote battery recycling, the use of renewable energy sources, and sustainable resource use.

Lastly, by improving charging schedules, routes, and maintenance plans, the application of artificial intelligence and predictive maintenance solutions is probably going to maximize fleet management. Reliability and fleet up time could be improved by using predictive analytics to identify possible charging station issues or prevent battery deterioration. It is anticipated that these policy and technology developments will work together to solve present issues and propel the HDV industry towards a more sustainable and clean transportation future [31].

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