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In Cooperation with

NITI Aayog

# Recommendations for Deployment of Smart Charging for Electric Vehicles in India

## Simulation-based study to evaluate the effects of E-mobility smart charging strategies

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# Forward

This publication has been prepared under the GIZ project, NDC -TIA (Nationally Determined Contributions - Transport Initiative for Asia). Under the India component of the NDC – TIA project, the study "Simulation-based study to evaluate the effects of Emobility smart charging strategies" was carried out by the consortium led by Fraunhofer-Institute for Energy Economics and Energy System Technology IEE, Kassel in collaboration with Indian Institute of Technology, Bombay (IITB), Universidad Pontificia Comillas (IIT Comillas), Technical University of Denmark (DTU). The publication has been prepared by the consortium and Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) India.

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The study was initiated given the high relevance in addressing the imminent energy demand from electric vehicles. We hope the outcome and recommendations from this detailed study will encourage and benefit industry and policy makers in India in making informed decisions.

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# Abbreviations

| Abbreviation | Description |
|---|---|
| 1Φ | 1 phase |
| 2W | two-wheelers |
| 3W | three-wheelers |
| 3Φ | 3 phases |
| 4W | four-wheelers |
| AC | Alternate Current |
| AFID | Alternative Fuels Infrastructure Directive |
| AI | Artificial Intelligence |
| BIS | Bureau Of Indian Standards |
| BPT | Bidirectional Power Transfer |
| CCS | Combined Charging System |
| CEA | Central Electricity Authority |
| CERC | Central Electricity Regulatory Commission |
| CIM | Common Information Model |
| CMS | Charging Management System |
| CP | Contact Pilot |
| CPO | Charge Point Operator |
| CPP | Critical Peak Price |
| CPUs | Central Processing Unit |
| CS | Charging Station |
| CSMS | Charging Station Management System |
| CTI | Coordination Time Intervals |
| CSO | Charging Station Operator |
| DC | Direct Current |
| DER | Distributed Energy Resources |
| DG | Distributed Generation |
| DISCOMs | Distribution Companies |
| DR | Demand Response |
| DSO | Distribution System Operator |
| eMIP | E-Mobility Inter-Operation Protocol |
| EMOCH | E-Mobility Clearing House |
| EMS | Energy Management System |
| EMSP | E-Mobility Service Provider |
| EP | Electricity Provider |
| ESI | Energy Services Interface |
| EV | Electric Vehicle |
| EVCS | Electrical Vehicle Charging Stations |
| EVSE | Electric Vehicle Supply Equipment |
| G2V | Grid To Vehicle |
| HEMS | Home Energy Management System |
| HPGP | Homepluggreen PHY |
| ICE | Internal Combustion Engine |
| ICT | Information And Communication Technology |

# Abbreviations

| Abbreviation | Description |
|---|---|
| IEC | International Electrotechnical Commission |
| IEE | Institute For Energy Economics And Energy System Technology |
| ISO | International Organization For Standardization |
| LG | Line To Ground |
| LLL | Line-Line-Line |
| MILP | Mixed-Integer Linear Programming |
| ML | Machine Learning |
| MoP | Ministry Of Power (India) |
| OCHP | Open Clearing House Protocol |
| OCPI | Open Charge Point Interface |
| OCPP | Open Charge Point Protocol |
| OEM | Original Equipment Manufacturer |
| OICP | Open Inter-Charge Protocol |
| OSCP | Open Smart Charging Protocol |
| OTI | Overcurrent Time Inverse |
| PCS | Public Charging Station |
| PLC | Power-Line Communication |
| PMAO | Public Metered AC Outlet |
| PnC | Plug & Charge |
| PP | Proximity Pilot |
| PSI | Population Stability Index |
| PTR | Peak Time Rebate |
| PV | Photovoltaic |
| PWM | Pulse Width Modulation |
| R&D | Research And Development |
| RA | Relay Agent |
| RIW-FR | Random In Window With Fixed Charging Rate |
| RIW-VR | Random In Window With Variable Charging Rate |
| RTP | Real-Time Price |
| SECC | Supply Equipment Communication Controller |
| SERCs | State Electricity Regulatory Commission |
| SGAM | Smart Grid Architecture Mode |
| SLDCs | State Load Dispatch Center |
| TCC | Time Coordination Curve |
| ToU | Time Of Use |
| TSO | Transmission System Operator |
| V1G | Unidirectional Vehicle-To-Grid |
| V2B | Vehicle-To-Building |
| V2G | Vehicle-To-Grid |
| V2H | Vehicle-To-Home |
| VT | Voltage Tranformers |
| WP | Work Package |

# 01 Introduction

## 1.1 About the Study

Under the NDC-TIA India Component, the project "Simulation-based study to evaluate the effects of E-mobility smart charging strategies" is focused on relevant smart coordinated charging strategies that will need to be adopted in different scenarios and conditions in India. This project is carried out by consortium led by Fraunhofer Institute for Energy Economics and Energy System Technology IEE, Kassel (IEE) in collaboration with Indian Institute of Technology, Bombay (IITB), Technical University Denmark (DTU), and Universidad Pontificia Comillas (IIT Comillas).

This specific study focuses on EV smart charging strategies and approaches, related policy and regulatory measures, technical aspects, grid integration of EVs, and the way forward for smooth EV adaption in the Indian EV ecosystem. The study will use real life data to develop models of distribution feeders in India, implement charging and coordination algorithms using a robust open-source simulation environment. The results of the analyses will act as a strong base in identifying gaps and refining scope of work for adoption of smart charging approaches at each necessary level/node of the EV ecosystem. The study based on a combination of desk research, simulation, regular workshops with the selected DISCOM(s), consultations with stakeholders, will be used to identify and recommend various smart charging interventions and guidelines that can be adopted for the use by regulators, policy makers, DISCOMs, and other stakeholders, and later adopted state-wide.

## 1.2 Aim of the Study

The study, "Simulation-based study to evaluate the effects of E-mobility smart charging strategies", aims to conduct a high-quality simulation supported study on smart charging strategies (unidirectional power flow) with high impact/ quality reports that can be used by the Government of India including State Governments, distribution system operators/ companies (DISCOMS), transmission system operators (POSOCO, SLDCs), planning and regulatory agencies (Central Electricity Authority (CEA), Central Electricity Regulatory Commission (CERC), State Electricity Regulatory Commission (SERCs) and other stakeholders (EV industry etc.) to frame, adapt, and/or revise policies, regulations for smart charging strategies for EVs and their integration with distribution grid. Secondly, it focuses on improvement of the overall environment (technical, policy, regulatory) related to EV charging infrastructure, smart charging strategies, and consumer response.

## 1.3 About this Report

This report is the second and final report in the series of the overall study – "Simulation-based study to evaluate the effects of E-mobility smart charging strategies" providing recommendations and way forward for adoption of smart EV charging in India. The recommendations are derived from a detailed simulation analysis carried out on an Indian distribution system and international experiences.

The report is structured into chapters detailing the selection of smart charging strategy, simulation of the strategies, the technical-economic analysis and the recommendations for deployment of smart charging in India.

# 02 Strategy Selection

## 2.1 Introduction

EV smart charging is necessary to manage the charging demand with the available grid infrastructure and generation capabilities. It plays a vital role in achieving different objectives, such as cost minimization, loss minimization, congestion management, grid support and grid stability, depending on the type, preferences, and required infrastructural and computational capabilities of consumers.

The charging strategy is selected based on the computational and communicational infrastructure. Computational infrastructure is related to arithmetic or logical processing units, i.e., CPUs and central processors. In contrast, communicational infrastructure comprises the devices or networks used to communicate various needed information or data. For additional low-cost and computational infrastructure, the local charging strategy is a better option. For medium-cost and computational infrastructure, decentralized, distributed, and hierarchical strategies are used since it distributes the computational burden among all the participating entities rather than concentrating on a single unit. Smart charging strategies can be classified on the basis of topology/architecture, location, ownership, methodology/approach, objective, and price structure. The detailed information on the various EV smart charging strategies have been explained in report 1 of this study. [1]

This chapter deals with the subsequent selection of smart charging strategies considered for the simulation studies. For the selection of strategy, a decision matrix has been developed. The matrix contains list of most relevant parameters for enabling smart charging. Each parameter has been assigned a priority factor depending on the level of importance and relevancy of the parameter. [2]

## 2.2 Development of the decision matrix

Each strategy has been rated on a scale from 1-10 for each decision parameter depending on how well it applies to the strategy. Each decision parameter has a priority factor assigned to it depending on the level of importance and relevance. The points (1-10) allocated in a category are multiplied by the priority factors (Table 1) to weigh the parameters according to importance.

1. A Critical Review: Smart Charging Strategies and Technologies for Electric Vehicles, Single-resource - Digital Library on Green Mobility - DLGM (greenmobility-library.org)
2. The priority factor has been considered in consultations with the expert team (research group and the distribution company from which the data has been taken). The weightage is considered taking the current smart charging ecosystem in India.

Table 1. Decision Matrix for Smart charging strategy

| Decision parameters | Priority factor |
|---|---|
| Practicability (technical feasibility ) | 5 |
| Grid-friendliness | 4 |
| Security | 4 |
| User acceptance | 4 |
| Efficiency | 4 |
| Amount of necessary measurements | 2 |
| Necessary additional ICT infrastructure | 1 |

### Practicability (technical feasibility)

The most important factor when evaluating control strategies for electric vehicle charging is their practicability. Sophisticated control strategies found in literature may not be helpful in real-life power system if they cannot be implemented without any major difficulties. A high rating is given to strategies that seem practicable and appropriate for their real-life implementation.

### Grid-friendliness

Grid-friendliness refers to the capabilities of control strategies to avoid critical grid situations (avoiding congestions) and increasing the reliability of the power system. Strategies with grid-friendly properties are given a higher rating.

### Amount of necessary measurements

The functionality of a lot of control strategies is based on measurements in the distribution grid such as bus voltages and line and transformer loadings. In many distribution grids, there is currently insufficient available measuring infrastructure, which hinders the implementation of control strategies. Therefore, control strategies that need a lower number of measurements are currently preferred as their implementation can be realized more easily and sooner. For this reason, strategies that do not need many (additional) measurements are rated higher.

### Necessary additional ICT infrastructure

In addition to measurements, additional ICT infrastructure may be necessary to realize some of the control strategies e.g. to transmit specifications or control signals from the DSO/DISCOM to the charging stations. In many distribution grids, there is currently not a lot of related ICT infrastructure available, and the implementation of some strategies might therefore be difficult without such additional infrastructure. For this reason, strategies that do not require a lot of additional ICT infrastructure are given a higher rating here as their implementation could be taken care of more easily.

### Security

As stated above, communication is involved in some strategies to transmit specification signals limiting the charging power, for example. In some cases, as with centralized approaches, faults in this communication might be more problematic than in others. These and other related aspects of control strategies are summarized under security. Strategies that are not as prone to problems caused by security issues receive a higher rating.

### Efficiency

An efficient strategy is one that achieves a favourable result (e.g. avoiding grid congestions) with little effort and in a relatively simple manner, e.g. with a power limit that is easily determined and implemented. A higher rating is given to efficient strategies.

### User acceptance

As control strategies can have a significant impact on charging processes and therefore directly influence the user, user acceptance is an important factor to consider when choosing and implementing control strategies. User acceptance can be influenced by ensuring vehicles are available when needed, reimbursing customers and by making the strategies easy to understand. Strategies with an expected high user acceptance gain a higher rating.

Other parameters nor considered in this study: One relevant factor for evaluating and selecting control strategies for the simulations that is not explicitly listed in the above parameters is the cost of control strategies. Major cost factors related to control strategies are hardware costs, costs of measuring and ICT infrastructure as well as the influence on the cost of grid extension measures. Except for the last one, these costs are implicitly considered in the other decision parameters and therefore not listed separately. To determine the influence on the cost of grid extension measures additional simulations are necessary. Therefore, this parameter has not been considered during the preparation stage of the planned simulation studies in this project.

The strategies are rated on a scale from 1-10 for each of these parameters depending on how well a parameter can be fulfilled or how well it is applicable. As some parameters are more relevant than others, i.e. practicability being the most important one, priority factors are introduced to weigh the decision parameters according to importance. This is done by multiplying the score of a decision parameter (1-10) by its priority factor (1-5). A higher priority factor refers to a more relevant criterion.

## 2.3 Smart Charging strategy

### 2.3.1 Centralized Control Based Strategy

In this strategy, the aggregator decides the pattern for EV charging within its contract by considering the system operator's constraints and the charging energy requested by the EV owner. For simplification the aggregator and the system operator are the same in this control approach. The information signal for the energy request flows from the EV owner to the aggregator. The aggregator's role in the strategy is to maintain the system while fulfilling the energy demand of the EVs. All the charging decisions are taken by the aggregator. To quickly address the energy requirement of the EVs, the strategy requires high-bandwidth communication in real-life environments.

**Strategies**

*Centralized EV Charging Coordination*

*Centralized Congestion Management*

**Decision matrix for the centralized control-based strategies**

In the centralized control-based approach, due to the high-bandwidth communication an ICT infrastructure is necessary, which leads to non-standard EV charging interfaces. However due to the information flow to a central unit, this control approach leads to increased hosting capacity, enables congestion management, and reduces the curtailment of renewable energy resources. As it affects the complete charging system if a fault occurs on the central unit this control approach shows low reliability and robustness. Challenges in regulations regarding smart charging might occur and therefore lead to unconventional challenges.

Table 2. Decision matrix for centralized control-based strategies

| Decision parameter | Centralized EV Charging Coordination | Centralized Congestion Management |
|---|---|---|
| Amount of necessary measurements | 4 | 4 |
| Grid-friendliness | 7 | 7 |
| Practicability (technical feasibility) | 5 | 5 |
| Necessary additional ICT infrastructure | 5 | 5 |
| Efficiency | 6 | 6 |
| User acceptance | 6 | 6 |
| Security | 4 | 4 |
| **Sum** | **130** | **130** |

While there is quite a lot of additional ICT infrastructure necessary to realize them (lower rating), centralized approaches are promising with regard to their grid-friendliness as one entity has an overview of the entire grid and can find the most fitting solution for the control of electric vehicles, which is why the grid-friendliness of these approaches is rated quite highly. However, in order to achieve such an overview, the number of necessary measurements is rather high resulting in the lower rating in that category. The efficiency and user acceptance of these approaches is quite good if users can easily understand what is happening and are fairly reimbursed where applicable. The centralized approaches seem rather promising and will therefore also be considered in the simulations in an appropriate manner.

### 2.3.2 Decentralized Control Based Strategy

In decentralized control architecture, less computational power is needed because of the shift in the decision-making entity from one entity to more entities. However, unlike the centralized control architecture, the decentralized charging approach does not guarantee the global optimum solution for the system.

**Strategies**

*Charging Coordination via Non-Cooperative Games*

*Decentralized Charging Coordination with Battery Degradation Cost*

*Decentralized Charging and Discharging Coordination*

**Decision matrix for the decentralized control based strategies**

In decentralized control approaches, unconventional challenges might occur as there is no central unit to control the behaviour of all EV charging stations. Therefore, there is also no guarantee for a global optimum. The controlled charging system might continue working even if a fault occurs at the central level, so the overall reliability and robustness is higher compared to the centralized approach. However, it does not allow direct control of charging power, which influences the system stability.

Table 3. Decision matrix for decentralized control-based strategies

| Decision parameter | Charging Coordination via Non-Cooperative Games | Charging Coordination with Battery Degradation Cost | Charging and Discharging Coordination |
|---|---|---|---|
| Amount of necessary measurements | 4 | 5 | 5 |
| Grid-friendliness | 5 | 3 | 3 |
| Practicability (technical feasibility) | 2 | 6 | 6 |
| Necessary additional ICT infrastructure | 5 | 6 | 6 |
| Efficiency | 4 | 5 | 5 |
| User acceptance | 3 | 5 | 5 |
| Security | 4 | 5 | 5 |
| **Sum** | **87** | **118** | **118** |

The decentralized approaches are rather diverse and therefore also earn different overall ratings. While the charging coordination via non-cooperative games is currently not practical, resulting in the low overall score (also due to other reasons such as questionable user acceptance and a high number of necessary measurements). It will therefore not be considered in the simulations. The other two approaches "Charging Coordination with Battery Degradation Cost" and "Charging and Discharging Coordination" gain a higher rating as they appear to be more practical and do not require as much additional ICT infrastructure. Especially "Charging and Discharging Coordination" seems feasible in the simulations. However, as their grid-friendliness is not rated as highly as other approaches, simulation other strategies is preferred. If insufficient strategies are found for the simulation, "Charging and Discharging Coordination" will be considered in the simulations.

### 2.3.3 Distributed Control Based Strategy

The distributed control is the advanced version of decentralized control as the EV owners are more involved in the decision making processes. Additionally, the aggregators communicate among themselves, to find the optimal operating point considering the maintenance of system stability. This control benefits the system reliability as it might continue controlled charging operations if any fault occurs in the central unit.

**Strategies**

*Distributed Power Profile Tracking for Heterogeneous Charging of Electric Vehicles*

*Decision matrix for the distributed control based strategy*

As a communication between the aggregators needs to be established there is a need for further ICT infrastructure. The approach does not allow to maintain system constraint limits directly at central level.

Table 4. Decision matrix for distributed control based strategy

| Decision parameter | Distributed Power Profile Tracking for Heterogeneous Charging of Electric Vehicles |
|---|---|
| Amount of necessary measurements | 3 |
| Grid-friendliness | 7 |
| Practicability (technical feasibility) | 4 |
| Necessary additional ICT infrastructure | 1 |
| Efficiency | 4 |
| User acceptance | 4 |
| Security | 6 |
| **Sum** | **111** |

While a good grid-friendliness could be achieved with this distributed strategy, it is currently not practicable as a high number of measurements and lots of additional ICT infrastructure is needed to realize it in the power system. Therefore, it will not be considered in the simulations either.

### 2.3.4 Hierarchical Control Based Strategy

The hierarchical control is divided into a number of layers as per the nature of problem space and types of participants. The architecture is divided into a central aggregator, subordinate layers of sub-aggregators, followed by EV owner layer. The control can again be sub-divided into several control strategies based on the decision-making authority, information signal flow, and required computation. It combines the benefit of centralized and decentralized strategies of directly controlling the charging and transferring the computational requirement for decision-making to the subordinate layer. Each layer of the architecture takes its own decision for achieving the desired objective without disturbing the other entities' objective.

**Strategies**

*Hierarchical Centralized Control*

*Hierarchical Hybrid Control Strategy*

*Hierarchical Decentralized Control*

**Decision matrix for the hierarchical control based strategy.**

Depending on the hierarchical control strategy several use cases can be addressed. The same use cases as in centralized and decentralized control approaches can be investigated. So, an optimal solution while considering network constraints can be found but if a fault occurs at any layer the subordinate layers will break down in centralized hierarchical strategies. However, decentralized hierarchical strategies do not guarantee the optimal solution as the charging decision is taken by the EV owner. As a hybrid approach combines the benefits of these two approaches, this approach covers most of the use cases. The central aggregator takes the charging decision considering network constraints. Sub aggregator has the information of the energy that it can deliver. At this stage, the sub aggregator cannot dispatch the power according to the availability because of decentralized decisions taken by the EVs. So, the sub aggregator's role is to limit the requested charging energy within the allotted value and failure of this will lead to the sub aggregator getting penalized. To maintain the allowable energy limits the sub aggregator varies the electricity prices in order to influence the charging behaviour of the customers.

Table 5. Decision matrix for hierarchical control based strategy

| Decision parameter | Hierarchical Centralized Control | Hierarchical Hybrid Control Strategy | Hierarchical Decentralized Control |
|---|---|---|---|
| Amount of necessary measurements | 3 | 3 | 4 |
| Grid-friendliness | 6 | 5 | 5 |
| Practicability (technical feasibility) | 6 | 5 | 4 |
| Necessary additional ICT infrastructure | 5 | 4 | 4 |
| Efficiency | 7 | 5 | 3 |
| User acceptance | 4 | 4 | 3 |
| Security | 4 | 3 | 3 |
| **Sum** | **125** | **103** | **88** |

As with the decentralized control approaches, there are several hierarchical ones. Due to the relatively high amount of necessary additional ICT infrastructure, the hierarchical hybrid control strategy and the hierarchical decentralized one will not be considered in the simulation as their practicability is also relatively low along with the user acceptance. The hierarchical centralized control approach appears to be more efficient, practicable and grid-friendly, which is why it might be considered for the simulations. However, it needs to be evaluated if it would have any other effect on the electrical grids than the aforementioned centralized control approaches.

### 2.3.5 Local Control Based Strategy

In this strategy, only the EV owner is involved in maintaining local parameters and EV charging decision. Local control only considers the local parameters, local constraints, and pricing signal for taking charging decision. This control only deals with the limited local constraints and linear single objective function, so the computation power required is significantly less than other smart charging control strategies. The decision signal is found at the local control, so communication (except the price information) is not required in this type of control. Different advanced local controllers are proposed in the literature that effectively handles multiple objectives at the local level.

**Strategies**

*Random in window with fixed charging rate (RIW-FR)*

*Random in window with variable charging rate (RIW-VR)*

**Decision matrix for local control based strategy**

This control approach is very simple to implement and has low computational efforts required compared to other smart charging strategies. It is the best choice for home charging in a time-use tariff structure. Due to the consideration of peak times increased hosting capacity and congestion management are possible with this smart charging approach. However, this control approach is unable to consider and maintain all network constraints. There is also no guarantee for a global optimal solution.

Table 6. Decision matrix for local control based strategy.

| Decision parameter | Random in window with fixed charging rate (RIW-FR) | Random in window with variable charging rate (RIW-VR) |
|---|---|---|
| Amount of necessary measurements | 7 | 6 |
| Grid-friendliness | 5 | 7 |
| Practicability (technical feasibility) | 9 | 8 |
| Necessary additional ICT infrastructure | 8 | 6 |
| Efficiency | 5 | 7 |
| User acceptance | 7 | 5 |
| Security | 8 | 7 |
| **Sum** | **167** | **162** |

These local control approaches both earn high ratings, mostly due to their practicability, low number of necessary measurements and low additional ICT infrastructure. Therefore, they are also highly relevant for the simulation and will be considered.

### 2.3.6 Objective-Based Strategies

The objective based strategies are applied to achieve predefined objectives based on the stakeholder's perspective. From the system operator's perspective, the basic objective is to maintain system stability by maintaining the network parameters within the given limits. The centralized control strategy is considered the preferred choice to achieve system stability. The main objective of smart charging based on the EV owner's perspective is to minimize the charging cost. The aggregator is appointed to coordinate between the system operator and EV, whose main role is to schedule the EV charging such that the objectives of both stakeholders are achieved. In addition to the prime role of coordinating and maintaining both objectives, the aggregator has one more personal objective: to earn profit from the scheduled charging. The decentralized charging control architecture best suits earning profit by an aggregator. A decentralized control strategy is considered to elaborate more on the mechanism of earning the profit by an aggregator. In this strategy, the aggregator has a role in maintaining the system constraint. The EV demand needs to be reduced to maintain system constraints within limits, But the aggregator does not directly control the EV charging in the decentralized architecture. For maintaining the constraint parameters, the aggregator increases the price of electricity for EV owners. The price difference between the electricity cost from DSO and electricity cost from aggregator generates profit for an aggregator.

**Strategies**

*EV Charging Coordination Under Feeder Capacity Constraints*

*Coordinated EV Charging and Distributed Generation Control in the Distribution Network*

**Decision matrix for objective based strategies strategies**

Some objectives of smart charging are load flattening and increase in renewable energy utilization. Various objectives of smart charging strategies based on different stakeholder's perspective are given below.

**System operator's desired objectives**

- Maintain feeder line constrain within limit.
- Valley filling
- Maximum utilization of renewable generation
- Frequency regulation
- Power regulation
- Reducing the system's constraint
- Min energy loss and transformer operating cost
- Maintain voltage within limit (power factor correction)
- Minimize system cost
- Load flattering and minimize peak load or load variance

**EV owner's desired objective**

- Charging cost minimization
- User's satisfaction maximization (min difference between the price offered by the grid and expected price of the owner)
- Reduce queue and waiting time
- Profit maximization
- Maximize charging rate
- Min charging time, travelling time
- Plan charging stop on the highway with limited infrastructure

**Aggregator's desired objectives**

- To maximize green energy consumption
- Electricity cost minimization
- Maximize profit
- Maximize solar utilization

Table 7. Decision matrix for objective based strategies strategies

| Decision parameter | EV Charging Coordination Under Feeder Capacity Constraints | Coordinated EV Charging and Distributed Generation Control in the Distribution Network |
|---|---|---|
| Amount of necessary measurements | 3 | 5 |
| Grid-friendliness | 8 | 6 |
| Practicability (technical feasibility) | 6 | 5 |
| Necessary additional ICT infrastructure | 3 | 6 |
| Efficiency | 3 | 8 |
| User acceptance | 5 | 9 |
| Security | 3 | 6 |
| **Sum** | **115** | **157** |

While the grid-friendliness speaks for the first of these strategies "EV Charging Coordination Under Feeder Capacity Constraints", a lot of additional ICT infrastructure is necessary for example. The approach "Coordinated EV Charging and Distributed Generation Control in the Distribution Network" is very efficient and will most likely have a high user acceptance as it will lead to an efficient grid operation, eventually resulting in lower customer prices.

### 2.3.7 Smart charging strategies based on optimization algorithms.

From the computational perspective, smart charging is an optimal solution of EV schedule considering various constraining parameters, which can be found out using several different established methods. Optimization methods, data-driven method, AI and ML-based methods, fuzzy method, model predictive control method are some of the approaches for finding optimal EV schedules while maintaining network constraints. Mostly linear optimisation algorithms are used to perform the most important parameter of cost minimization considering basic network constraints such as operators maximum allowed power.

**Strategies**

e.g. *Mixed-integer linear programming (MILP)*

**Decision matrix for strategies based on optimization algorithms.**

Similar to objective based strategies. the optimization algorithms are based on various objectives. Depending on the algorithm different objectives can be addressed. However, there is high need for ICT infrastructure and there is no convenient real life implementation yet.

Table 8. Decision matrix for strategies based on optimization algorithms

| Decision parameter | Smart Charging Strategies Based on Optimization Algorithms |
|---|---|
| Amount of necessary measurements | 3 |
| Grid-friendliness | 5 |
| Practicability (technical feasibility) | 2 |
| Necessary additional ICT infrastructure | 3 |
| Efficiency | 3 |
| User acceptance | 4 |
| Security | 4 |
| **Sum** | **83** |

While this approach is highly interesting in theory, it really lacks in terms of practicability and would require lots of measurements and additional ICT infrastructure resulting in the low rating. It will therefore not be considered in the simulations.

### 2.3.8 Artificial Intelligence/Machine Learning-Based Charging Approach

Data-driven AI and ML-based solutions are another approach for scheduling and coordinating EV charging. In this approach, models are built and learn, understand the behaviour and characteristic of participating entities with many scenarios with different participating entities. This training is performed using standard training sets or different scenarios generated in simulations. Based on the available training sets, AI/ML-based strategy is categorised into supervised learning and unsupervised learning. There is limited labelled standard training data is available. The available training data is also sensitive to geographical location, so the available training data is also not used to train the data for the model at any other geographically different place. Due to the scarcity of available training data unsupervised learning algorithm is the popular choice. In an unsupervised algorithm, unlabelled training data is used, and the results differentiate the EV charging behaviours from given input parameters. K-means clustering, Gaussian mixture model, Kernel density estimator are some of the methods used in literature for unsupervised learning. Linear regression model, decision tree, random forest, space vector machine are some supervised methods. When the input information is provided to the model, it predicts the change in the smart charging profile and provides the optimal charging power dispatch to EVs requesting it.

ML predictive models also depend on the quality of the data set used for training. The standard training data is taken from available EV charging projects for residential and non-residential charging. Based on the response variable to be predicted, the problem is called a regression problem with a continuous predicted response variable. If the response variable is categorical, then the problem is classified as a categorical problem. Deep learning and reinforcement learning are more advanced ML algorithms that learns from mistakes and errors.

**Decision matrix for Artificial Intelligence / Machine Learning-Based Charging Approach**

As this approach for smart charging is very new and innovative it is out of scope in this project as there is no real life implementation or any use case yet. But the approach might be implemented in the future.

Table 9. Decision matrix for Artificial Intelligence / Machine Learning-Based Charging Approach

| Use Case | Artificial Intelligence / Machine Learning-Based Charging Approach |
|---|---|
| Amount of necessary measurements | 3 |
| Grid-friendliness | 5 |
| Practicability (technical feasibility) | 2 |
| Necessary additional ICT infrastructure | 3 |
| Efficiency | 3 |
| User acceptance | 4 |
| Security | 4 |
| **Sum** | **83** |

Due the low practicability of such approaches at the moment, this will not be considered in the simulations.

### 2.3.9 Price Based Coordination Methods

Electricity price is categorized into fixed price and dynamic price based on time of use and energy demand. However, the fixed price is generally not effective for pricing. Hence, dynamic prices are adapted for pricing the EV based on coordination methods. The pricing schemes for dynamic electricity prices are divided as Real-time price (RTP), Time of use (TOU), Critical peak price (CPP), and Peak time rebate (PTR). Each of these pricing strategies is applied to influence the charging behaviour of customers indirectly.

**Strategies**

*Real-Time Pricing*

*Time of Use Tariff*

*Critical Peak Price*

*Peak Time Rebate*

*Dynamic Price-Based Coordination Methods*

**Decision matrix for price based coordination strategies**

Price based coordination methods might influence the charging behaviour, but there is as potential for monopoly and exploitation of the tariff mechanisms. In order to set the information, flow an ICT infrastructure is necessary. The different charging stations need to receive different pricing signals. These pricing signals can lead to an increased hosting capacity but don't necessarily lead to a global optimum. Different prices for renewable energy resources have a positive impact on the generation of RE. The methods can be implemented in real life however there is weak robustness against critical scenarios.

Table 10. Decision matrix for price based coordination strategies

| Decision parameter | Real-Time Pricing | Time of Use Tariff | Critical Peak Price | Peak Time Rebate | Dynamic Price-Based Coordination Methods |
|---|---|---|---|---|---|
| Amount of necessary measurements | 4 | 5 | 4 | 5 | 5 |
| Grid-friendliness | 4 | 7 | 5 | 4 | 6 |
| Practicability (technical feasibility) | 3 | 7 | 3 | 6 | 3 |
| Necessary additional ICT infrastructure | 4 | 5 | 4 | 5 | 4 |
| Efficiency | 5 | 6 | 6 | 6 | 4 |
| User acceptance | 4 | 6 | 5 | 7 | 3 |
| Security | 4 | 5 | 4 | 6 | 5 |
| **Sum** | **95** | **146** | **107** | **137** | **101** |

### 2.3.10 Fleet Control

Fleet control is applicable to public/private passenger buses, logistic vehicle fleets, and heavy-duty commercial fleets. Its control and coordination are motivated for specific objectives, such as maximize the EV charging during off-time, maximize the RE utilization, and finding optimal coordination between charging sessions and travelling trips. Centralised strategy is majorly used for fleet control as it can schedule the fleet charging based on different objectives.

**Decision matrix for fleet control strategies**

Fleet control can be combined with different control approaches.

Table 11. Decision matrix for fleet control strategies

| Decision parameter | Fleet Control |
|---|---|
| Amount of necessary measurements | 2 |
| Grid-friendliness | 6 |
| Practicability (technical feasibility) | 5 |
| Necessary additional ICT infrastructure | 4 |
| Efficiency | 5 |
| User acceptance | 6 |
| Security | 6 |
| **Sum** | **125** |

Fleet control earns an average overall rating as it can be quite grid-friendly and accepted well by users, however a lot of measurements is necessary for its implementation.

### 2.3.11 Charging Station Coordination

Favourable coordination of charging stations within the network is necessary for optimal charging power sharing within the charging station after optimal allocation of power based on the grid's available power capacity and EV's energy requests at the network level. Optimal charging power coordination within charging station is determined by considering various objectives, such as, profit maximization of charging station, delivery of requested power within parking time slots and avoiding overloading of the charging station infrastructure. Charging station coordination requires a priority list of EV charging based on customer preference of smart charging, parking time and the difference between parking time and time required for charging with the maximum charging capacity. This prioritization helps coordinate charging stations as per the charging station operator's preference and EV owner's preference. Optimal charging power allocation and vehicle-to-charging station coordination is a combined procedure of performing smart charging for an EV.

**Decision matrix for charging station coordination strategies.**

Table 12. Decision matrix for charging station coordination strategies

| Decision parameter | Charging Station Coordination |
|---|---|
| Amount of necessary measurements | 3 |
| Grid-friendliness | 4 |
| Practicability (technical feasibility) | 5 |
| Necessary additional ICT infrastructure | 4 |
| Efficiency | 5 |
| User acceptance | 5 |
| Security | 6 |
| **Sum** | **115** |

This approach also only achieves an average rating, which is also due to the fact that such approaches might not be as grid friendly as others due to the focus of cost optimization in some variants of it. Additionally, lots of measurements and additional ICT infrastructure are necessary.

## 2.4 Ranking of strategies

After applying the decision matrix on the available smart charging strategies, the following strategies were scored accordingly.

Table 13. Ranking of Smart charging strategies

| Strategy name | Points |
|---|---|
| Random in window with fixed charging rate | 167 |
| Random in window with variable charging rate | 162 |
| Coordinated EV Charging and Distributed Generation Control in the Distribution Network | 157 |
| Time of Use Tariff | 146 |
| Peak Time Rebate | 137 |

| Strategy name | Points |
|---|---|
| Centralized EV Charging Coordination | 130 |
| Centralized Congestion Management | 130 |
| Hierarchical Centralized Control | 125 |
| Fleet Control | 125 |
| Decentralized Charging Coordination with Battery Degradation Cost | 118 |
| Decentralized Charging and Discharging Coordination | 118 |
| EV Charging Coordination Under Feeder Capacity Constraints | 115 |
| Charging Station Coordination | 115 |
| Distributed Power Profile Tracking for Heterogeneous Charging of Electric Vehicles | 111 |
| Critical Peak Price | 107 |
| Hierarchical Hybrid Control Strategy | 103 |
| Dynamic Price-Based Coordination Methods | 101 |
| Real-Time Pricing | 95 |
| Hierarchical Decentralized Control | 88 |
| Charging Coordination via Non-Cooperative Games | 87 |
| Artificial Intelligence/ Machine Learning-Based Charging Approach | 83 |
| Smart Charging Strategies Based on Optimization Algorithms | |
| e.g. Mixed-integer linear programming (MILP) | 83 |

## 2.5 Selected smart charging strategies

The selection of strategy (highlighted) for simulation is based on scoring and taking into consideration relative differences between classification of strategies.

Table 14. The selected Smart charging strategies

| Strategy | Classification |
|---|---|
| Local control-based strategy. | Random in window with fixed charging rate |
| | Random in window with variable charging rate |
| Objective based strategy. | Coordinated EV Charging and Distributed Generation Control in the Distribution Network |
| | EV Charging Coordination Under Feeder Capacity Constraints |

| Strategy | Classification |
|---|---|
| Price based coordination methods. | Time of Use Tariff |
| | Peak Time Rebate |
| | Dynamic Price-Based Coordination Methods |
| | Critical Peak Price |
| | Real-Time Pricing |
| Centralized control-based strategy. | Centralized EV Charging Coordination |
| | Centralized Congestion Management |

The selected smart charging strategies for simulation are the following:

Random in window with variable charging rate (RIW-VR): the start time of the charging sessions is set randomly within a predefined time window.

Time of Use Tariff (ToU): a static ToU electricity tariff is set, where electricity is charged at a different price for different periods of the day. However, these prices remain unchanged from one day to another and are not reflective of the current grid situation. CSs receive these price signals and can respond accordingly (e.g., reduce charging power when prices are high).

Dynamic price-based coordination methods: electricity prices are updated regularly to reflect the grid situation. CSs receive these price signals and can respond accordingly (e.g., reduce charging power when prices are high).

Coordinated EV Charging and Distributed Generation Control: the available charging power for the EVs is set depending on the amount of distributed generation. For instance, higher PV production at midday would increase the available power for charging the EVs.

Centralized EV Coordination: EV charging is scheduled by a central controller that monitors the grid state and defers EV charging to a later time when a critical grid state is observed.

The selected smart charging strategies described in the previous section have been classified according to these smart charging levels in Table 15.

Table 15. Classification of the selected smart charging strategies based on level of smartness.

| Smart charging strategies based on level of smartness | |
|---|---|
| Random in window variable charging rate | Level 1. Controlled charging (V1G) |
| Time of Use Tariff | Level 1. Controlled charging (V1G) |
| Centralized EV coordination | Level 2. Cooperative charging (V1G/H) |
| Coordinated EV charging and distributed generation control | Level 2. Cooperative charging (V1G/H) |
| Dynamic price-based coordination methods | Level 2. Cooperative charging (V1G/H) |

# 03 Simulation Studies

This chapter outlines the simulation of selected smart charging strategies. The smart charging strategies discussed in Chapter 2 are simulated to examine their effects on the grid infrastructure. The selected strategies are applied to datasets of realistic grid models (Data provided by the DISCOM) and EV charging time series to quantify their impact on the distribution grid. The impact on voltage profile, line loading, and transformer loading at the distribution grid level is investigated through simulation analysis.

## 3.1 Key Elements for the simulation Analysis

### 3.1.1. Input data for simulation

The data collected for this study from the DISCOM comprised of the network elements, loads in the network and transformer linkage between low and medium voltage levels. The provided grid models contain information about the topology of the grid including lines, buses, transformers, and the external grid. The following prosumers[3] were considered within this simulation:

- Private households
- Other building types (industries, public buildings, commercial loads)
- Private electric vehicle charging stations.
- Public electric vehicle charging stations.
- Photovoltaic systems

### 3.1.2. Type of feeder selected for simulation.

The characteristics of distribution-level feeders can vary based on factors like capacity, type of consumers connected, capacity, loading level etc. To comprehend the impact of the chosen strategies on diverse distribution-level, data from different feeder types under the DISCOM were deliberately collected. Specifically, data pertaining to total number of consumers, total line length of different feeders under the selected DISCOM was collected to conduct the simulation.

---

[3] Battery swapping stations and Battery energy storage systems can be considered as prosumer. In this study, due to lack of load profile representing these type of prosumers, they have not been considered.

Table 16. Type of feeder selected for simulation.

| Feeder Name | Feeder Type | Feeder Properties |
|---|---|---|
| Feeder 1 | Urban Residential Feeder | 829 customers*,<br>29 transformers,<br>824 lines (total line length: 28.08 km),<br>853 buses |
| Feeder 2 | Rural Residential Feeder | 2420 customers*,<br>12 transformers,<br>1280 lines (total line length: 44.73 km),<br>1293 buses |
| Feeder 3 | Industrial Area Feeder | 364 customers*,<br>50 transformers,<br>636 lines (total line length: 8.39 km),<br>687 buses |
| Feeder 4 | Public Building | 503 customers*,<br>6 transformers,<br>436 lines (total line length: 18.38 km),<br>443 buses |

** Several customers can be connected to one bus*

### 3.1.3. Scenarios and addition of EV and PV elements into the feeder

Table 16 provides feeder information without the inclusion of any future EV or PV elements under existing conditions. Thus, the base case refers existing feeder condition with its current customer loads and PV generators and corresponding profiles. To assess the potential future impact of smart charging strategies, three distinct scenarios are simulated, namely, low, medium, and high. These scenarios correspond to different levels of penetration of PV and EV, allowing for an analysis of potential future influences on the distribution grid.

The electric vehicle penetration scenarios are derived from the NITI Aayog Target-2030[4]. Basing on the year 2019 the rise in energy demand caused by electric vehicles until 2030 is predicted. Consequently, penetration percentages is calculated for the different scenarios low, medium and high. For the photovoltaic scenarios the method is similar. Considering an installed PV capacity of 46.2 GW[5] in 2021 the different percentages are calculated according to the solar target 2030.

Table 17. Photovoltaic penetration scenarios

| Scenario Name | Growth of PV plants [%] | Installed Capacity [GW] | Explanation |
|---|---|---|---|
| Low | 216 | 100 | Meet 2022 target in 2030 |
| Medium | 411 | 190 | Meet half of the target for 2030 considering that the target for 2022 was met |
| High | 606 | 280 | Meet target 2030 |

---

[4] The summary of the chosen feeders, with the PV and EV penetrations under the different scenarios, is provided below. EV penetration source: ALL CASE SCENARIO as per NITI Ayog Target-2030

[5] https://www.pv-magazine.com/2021/12/13/india-hits-46-2-gw-of-installed-pv-capacity/

The base case elements refer to the value provided by the DISCOM. As the provided feeders contained no EV locations and almost no PV locations, these numbers were increased for the sake of the scenario creation to enable scenarios with higher penetrations. Next, the resulting PV and EV elements and penetrations for the low, medium and high scenarios were determined as follows.

PV:

$$\mathit{PV}\ \text{elements}_{\text{scenario}} = \frac{\mathit{PV}\ \text{growth}_{\text{scenario}}}{\mathit{PV}\ \text{growth}_{\text{base}}} \cdot \mathit{PV}\ \text{elements}_{\text{base}}$$

$$\mathit{PV}\ \text{penetration} = \frac{\mathit{PV}\ \text{elements}}{\text{Customer buses}}$$

Illustrative example:

For determining the PV values for the high scenario for the feeder1, where there are seven PV elements in the base case and the PV growth for the high scenario is 606%.

$$\mathit{PV}\ \text{elements}_{\text{scenario}} = \frac{\mathit{PV}\ \text{growth}_{\text{scenario}}}{\mathit{PV}\ \text{growth}_{\text{base}}} \cdot \mathit{PV}\ \text{elements}_{\text{base}}$$

$$= \frac{606\%}{100\%} \cdot 7 = 42$$

This accounts that there are 42 PV elements in the high scenario based on the provided information. This results in the following PV penetration (household buses with PV):

$$\mathit{PV}\ \text{penetration} = \frac{\mathit{PV}\ \text{elements}}{\text{Customer buses}} = \frac{42}{123} \approx 0.34 = 34\%$$

EV:

$$\mathit{EV}\ \text{charging station elements}_{\text{scenario}} =$$

$$\frac{\mathit{EV}\ \text{growth}_{\text{scenario}}}{\mathit{EV}\ \text{growth}_{\text{base}}} \cdot \mathit{EV}\ \text{charging station elements}_{\text{base}}$$

$$\mathit{EV}\ \text{penetration} = \frac{\mathit{EV}\ \text{elements}}{\text{Customer buses}}$$

The process for determining the value for private and public EV is equivalent but the penetration is not needed for the public EV charging stations as the scenario generator works a little bit differently for the public charging stations and this value is not required.

Illustrative example:

For the high scenario in the feeder1. In the base case there are four private EV charging stations and two public EV charging stations based on the provided information. The EV growth for the high scenario is 892%.

### Private *EV*:

$$\mathit{EV}\ \text{charging station elements}_{\text{scenario}} =$$

$$\frac{\mathit{EV}\ \text{growth}_{\text{scenario}}}{\mathit{EV}\ \text{growth}_{\text{base}}} \cdot \mathit{EV}\ \text{charging station elements}_{\text{base}}$$

$$= \frac{892\%}{100\%} \cdot 4 = 45$$

This means that for the high scenario in the feeder 1, 45 private charging stations are assumed resulting in the following EV penetration (percentage of households with a private charging station):

$$\mathit{EV}\ \text{penetration} = \frac{45}{123}$$

### Public *EV*:

$$\mathit{EV}\ \text{charging station elements}_{\text{scenario}} =$$

$$\frac{\mathit{EV}\ \text{growth}_{\text{scenario}}}{\mathit{EV}\ \text{growth}_{\text{base}}} \cdot \mathit{EV}\ \text{charging station elements}_{\text{base}}$$

$$= \frac{892\%}{100\%} \cdot 2 = 18$$

This means that 18 public EV charging stations are assumed for the high scenario in feeder 1.

Table 18. Different levels of PV and EV penetration in the scenarios

| Scenario name | Feeder | Customer buses | PV growth [%] | PV elements | PV penetration [%] | Private EV growth [%] | Customer EV charging station elements | Customer EV charging station penetration [%] | Public EV growth [%] | Public EV charging station elements |
|---|---|---|---|---|---|---|---|---|---|---|
| base | Feeder 1 | 123 | 100 | 7 | 6 | 100 | 5 | 4 | 100 | 2 |
| | Feeder 2 | 450 | | 11 | 2 | | 11 | 2 | | 5 |
| | Feeder 3 | 180 | | 9 | 5 | | 3 | 2 | | 3 |
| | Feeder 4 | 183 | | 7 | 4 | | 3 | 2 | | 4 |
| low | Feeder 1 | 123 | 216 | 15 | 12 | 345 | 17 | 14 | 345 | 7 |
| | Feeder 2 | 450 | | 24 | 5 | | 38 | 8 | | 17 |
| | Feeder 3 | 180 | | 19 | 11 | | 10 | 6 | | 10 |
| | Feeder 4 | 183 | | 15 | 8 | | 10 | 5 | | 14 |
| medium | Feeder 1 | 123 | 411 | 29 | 24 | 551 | 28 | 23 | 551 | 11 |
| | Feeder 2 | 450 | | 45 | 10 | | 61 | 14 | | 28 |
| | Feeder 3 | 180 | | 37 | 21 | | 17 | 9 | | 17 |
| | Feeder 4 | 183 | | 29 | 16 | | 17 | 9 | | 22 |
| high | Feeder 1 | 123 | 606 | 42 | 34 | 892 | 45 | 37 | 892 | 18 |
| | Feeder 2 | 450 | | 67 | 15 | | 98 | 22 | | 45 |
| | Feeder 3 | 180 | | 55 | 31 | | 27 | 15 | | 27 |
| | Feeder 4 | 183 | | 42 | 23 | | 27 | 15 | | 36 |

## 3.2. Simulation Overview

The Python open-source tool pandapower is to be used for the simulations. The time series simulation for uncontrolled charging is carried out in all the feeder for the base case. These result serve as a foundational analysis to understand the initial effects before incorporating specific scenarios. Following, low, medium, and high scenarios are applied to each feeder and yearly simulations are conducted for uncontrolled charging. The results are analysed for the following:

- Investigate the impact of these scenarios on the grid parameters.
- Determine the worst cases for the low, medium, and high scenario, which are used to identify the time frames for the simulations with control strategies.

Subsequently, control strategies are applied, and weekly simulations are conducted for the timeframe surrounding the previously identified critical time steps (Worst cases). The simulation overview is illustrated below:

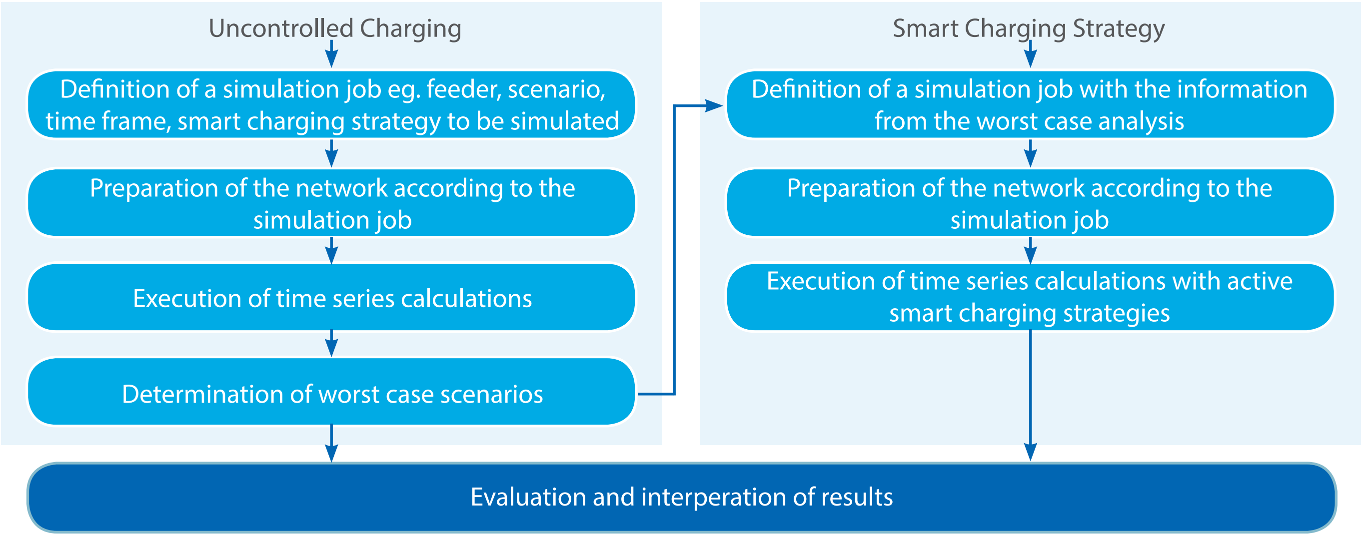


Figure 1. Simulation overview of smart charging strategy

The term "worst case" is used to describe the time steps at which the lines experience the highest level of loading, the transformer experiences the highest level of loading, or there is a drop in the bus voltage level. Identifying the worst-case scenarios is crucial for assessing the system's resilience and understanding the limits of power system components under extreme stress, aiding in effective planning and risk management in power infrastructure.

Additionally, the allocation of public EV charging nodes along the length of the feeder is an additional crucial factor that can significantly influence a worst-case. For every possible node the charging station connected to the shortest path to the nearest transformer station is determined. If the distance to the next transformer station is more than 144m, the possible location is considered as "far".

Table 19. Public EV station allocation investigation

| Category | Distance from bus to transformer station |
|---|---|
| Transformer station | Up to 5m |
| Near | 5 m up to 144 m inclusive |
| Far | More than 144 m |

The figure 2 illustrates a significant rise in worst-case line loading when public EV charging stations are distantly located from the transformer station. Given the critical importance of worst-case scenarios in grid planning, the public EV charging stations where deliberately positioned far from the transformer.

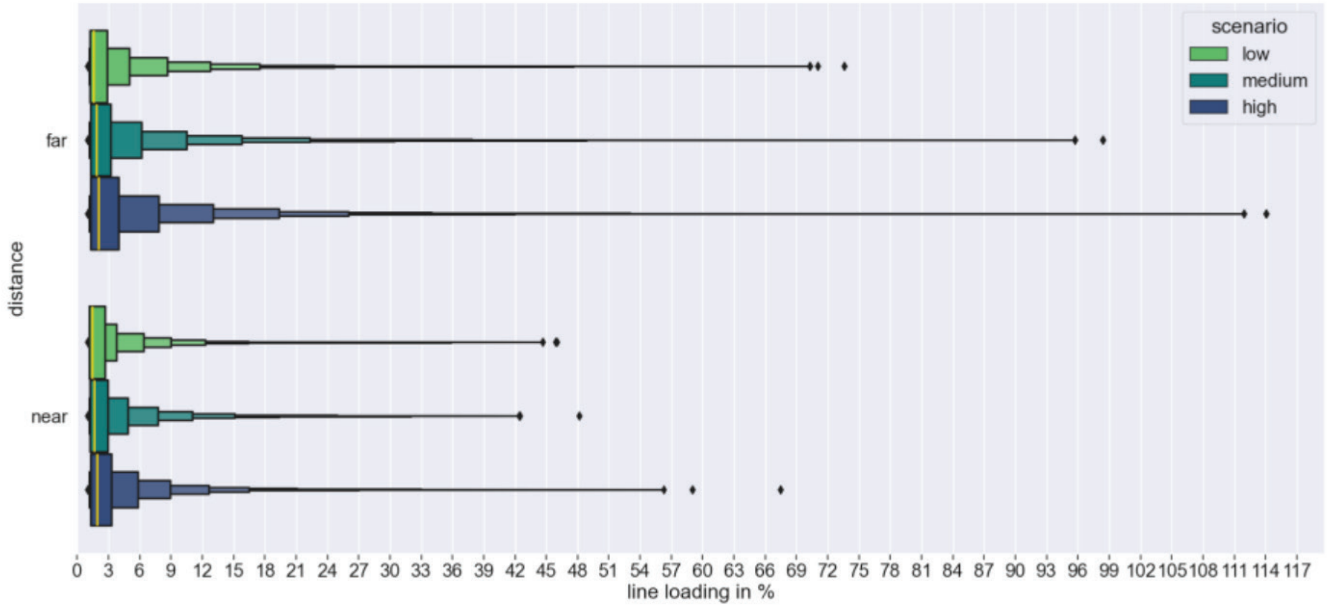


Figure 2. Line loading in % for different EV scenarios and EV charging station allocations.

## 3.3. Simulation results

The simulation steps described in 3.2 are carried out on all the 4 feeders and the results are as follows:

### 3.3.1. Feeder 1 – Urban residential feeder

Feeder 1 is an urban residential feeder with a meshed network topology. The feeder properties are given in Table 16. The topology and the network diagram are as given below.

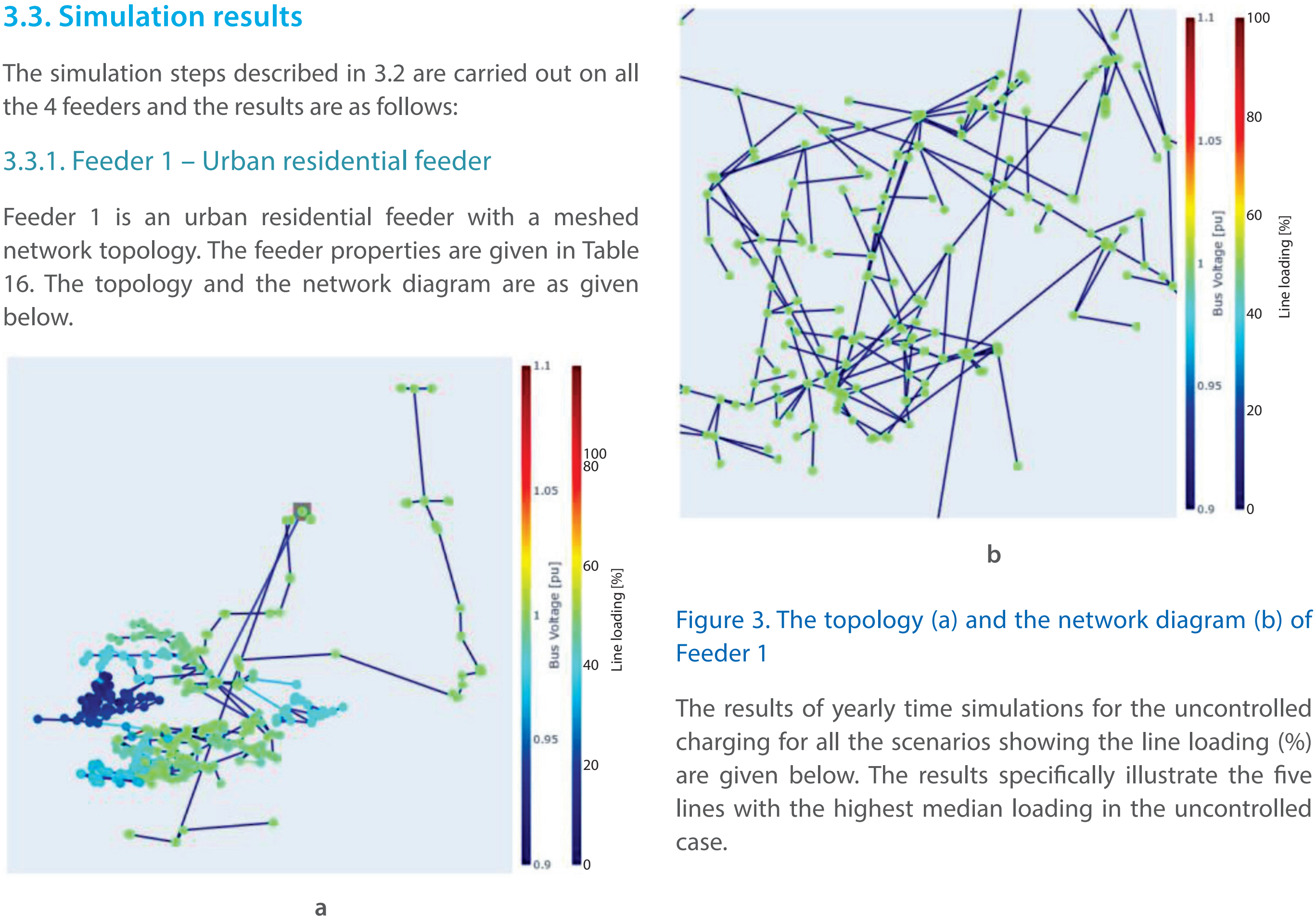


Figure 3. The topology (a) and the network diagram (b) of Feeder 1

The results of yearly time simulations for the uncontrolled charging for all the scenarios showing the line loading (%) are given below. The results specifically illustrate the five lines with the highest median loading in the uncontrolled case.

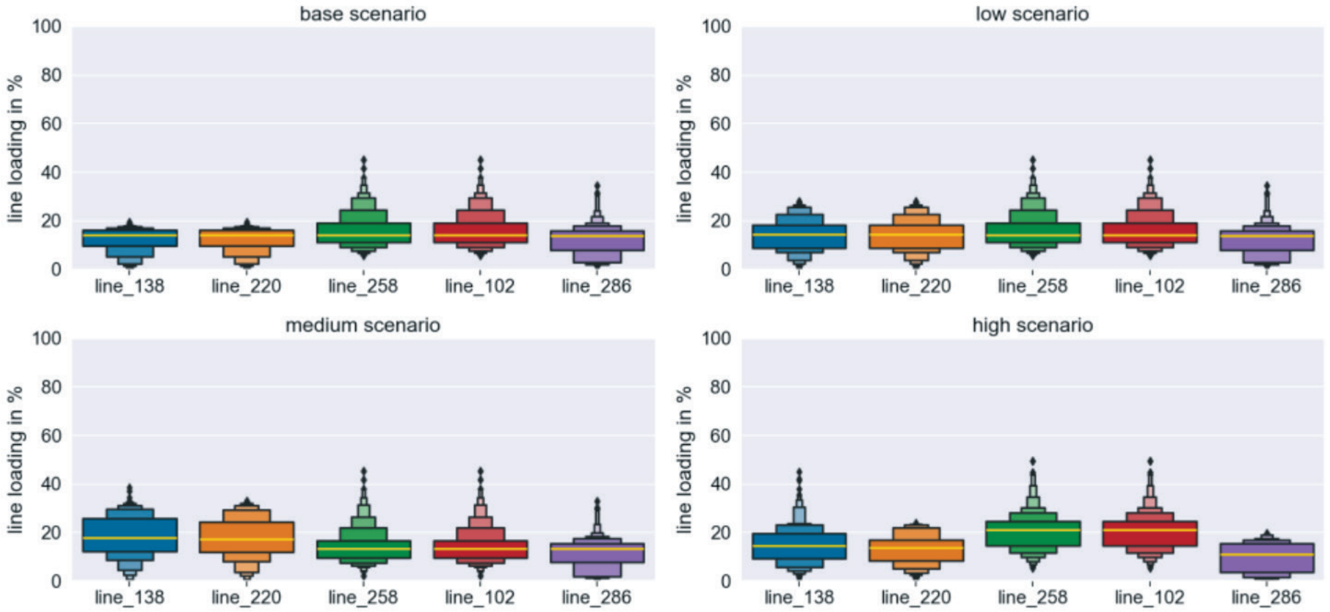


Figure 4. Yearly time simulations of Line loading for all the scenarios under uncontrolled charging.

The results of yearly time simulations for the uncontrolled charging for all the scenarios showing the transformer loading (%) are given below. The results specifically illustrate the five transformers with the highest median loading in the uncontrolled case.

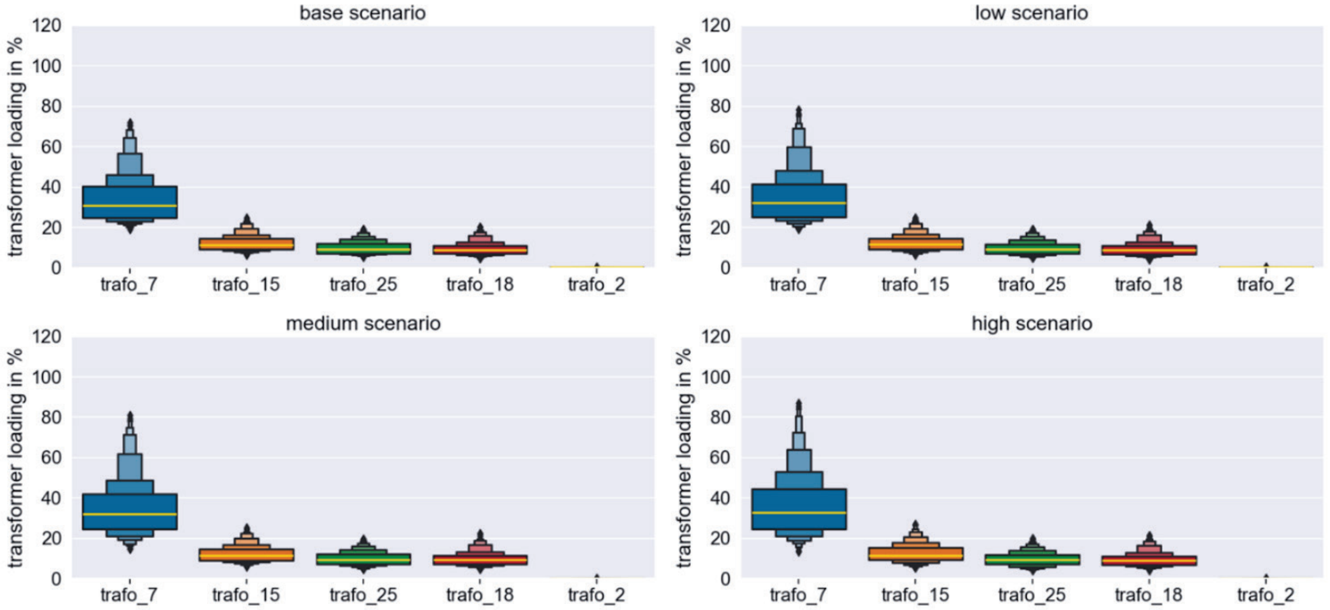


Figure 5. Yearly time simulations of transformer loading for all the scenarios under uncontrolled charging.

The bus voltages tend to decrease with an increasing load in the feeder. The results of yearly time simulations for the uncontrolled charging for all the scenarios showing the bus voltage (p.u.) are given below. The results specifically illustrate the five buses with the lowest median bus voltages in the uncontrolled case.

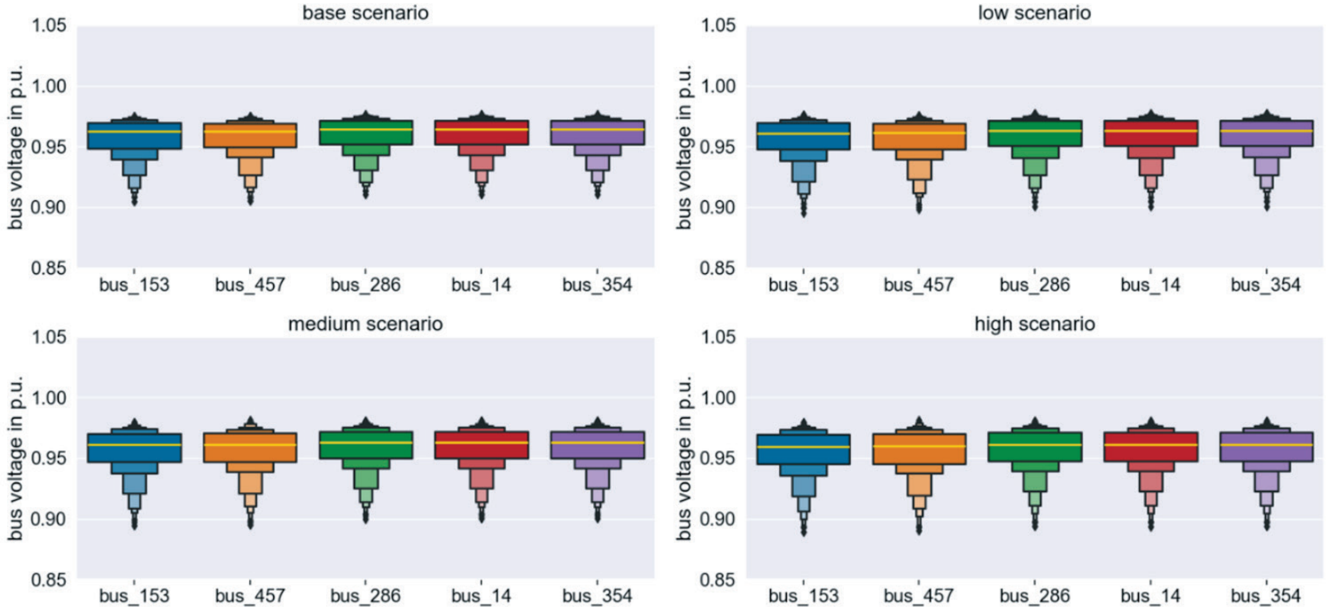


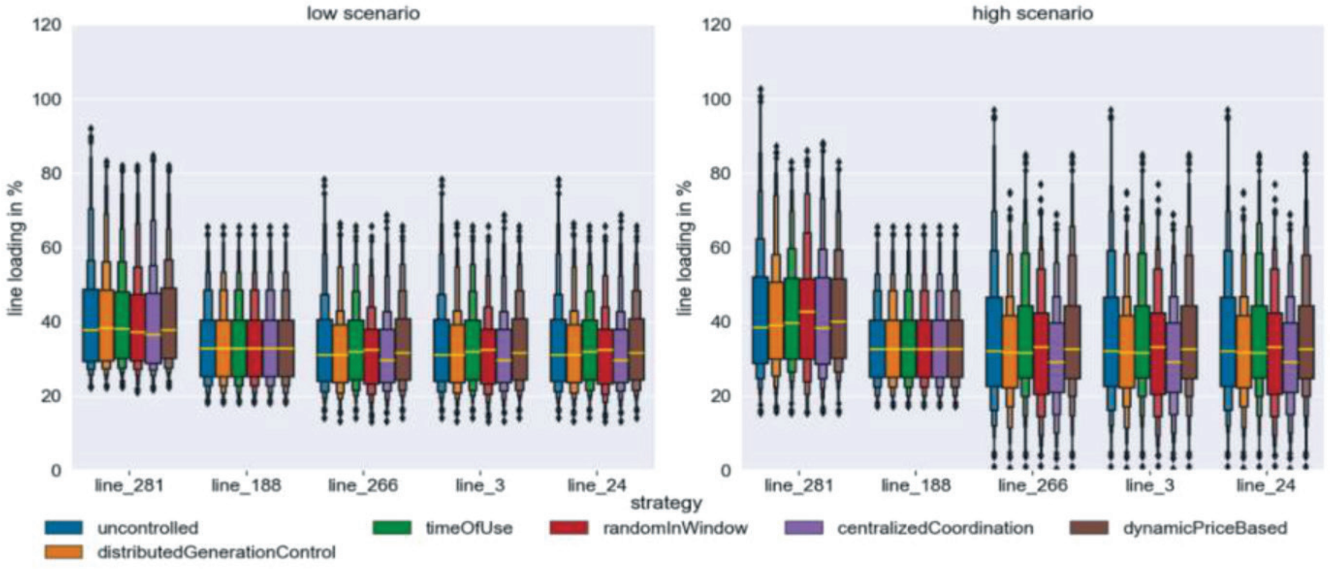
Figure 6. Yearly time simulations of bus voltages for all the scenarios under uncontrolled charging.

From the yearly simulations for uncontrolled charging, the timesteps for the worst cases are identified. The selected strategies are applied, and the simulation is carried out for the identified weekly timesteps.

**Results of Feeder 1**

**Feeder 1: Line loading (%)**

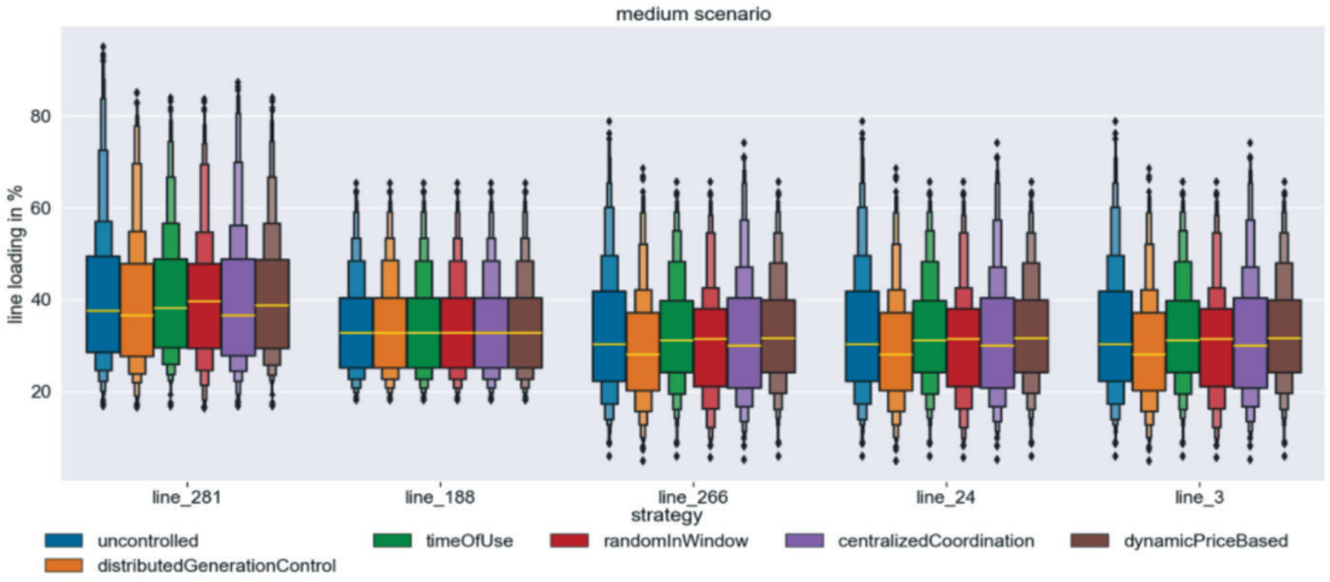
Figure 7 shows the line loadings (for low, medium, and high scenario) evaluated for 5 selected lines. A smaller value of line loading holds significant importance in mitigating violations, grid congestion, and the need for expensive grid extensions or reinforcements. Decreasing maximum line loadings via smart charging strategies is seen as a positive outcome. In here, all the smart charging strategies manage to contribute to the reduction of the maximum line loadings and therefore positively influence the grid situation.



a

b

Figure 7. Strategy overview of line loading in % for low (a) and high (b) scenarios for one week containing a worst case (selected lines)



c

Figure 7. Strategy overview of line loading in % for medium (c) scenarios for one week containing a worst case (selected lines)

To identify the impact of the strategies during the peak demand timesteps in the selected worst case, the line plots of line loading were plotted for the weekly timesteps. The following figures show the nature of line loading variations for the medium scenario in a for a worst-case week in the selected residential feeder.

While it is difficult to distinguish all different lines in the line plot below, all strategies manage to reduce the peak in the middle of the plot as well as the other peaks due to their individual properties. To highlight the behavior of the strategies a bit more, the figure is split into Figure 9 (price-based strategies) and Figure 10 (all other strategies).

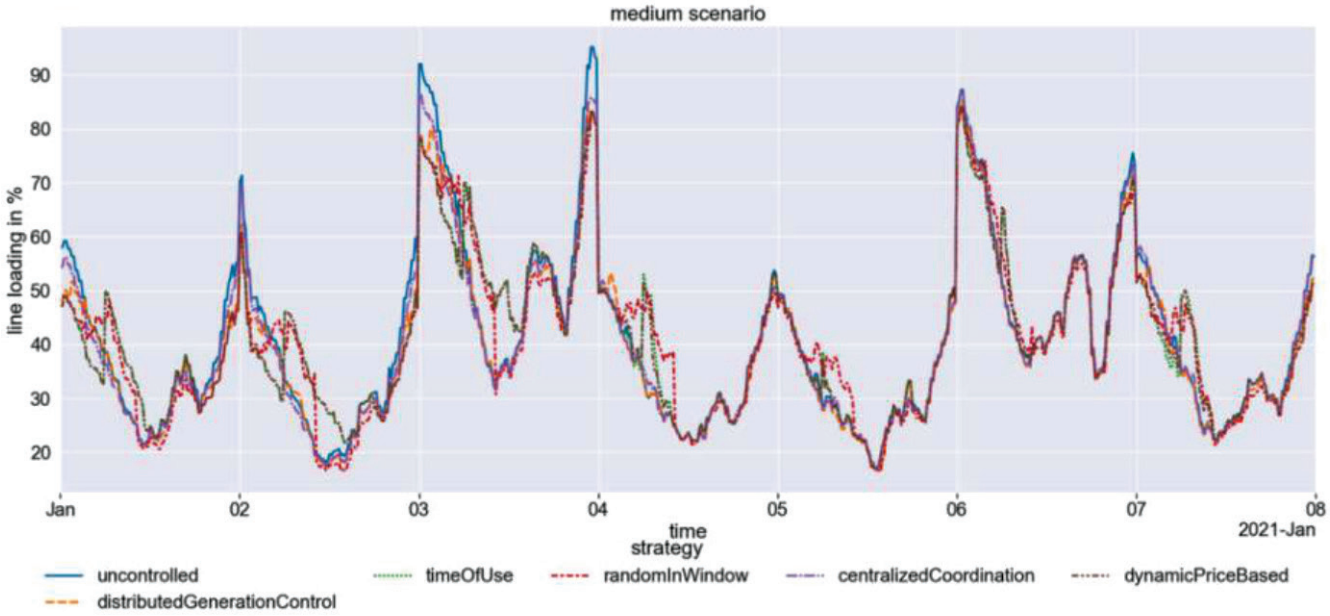


Figure 8. All strategies throughout one week (containing a worst case)

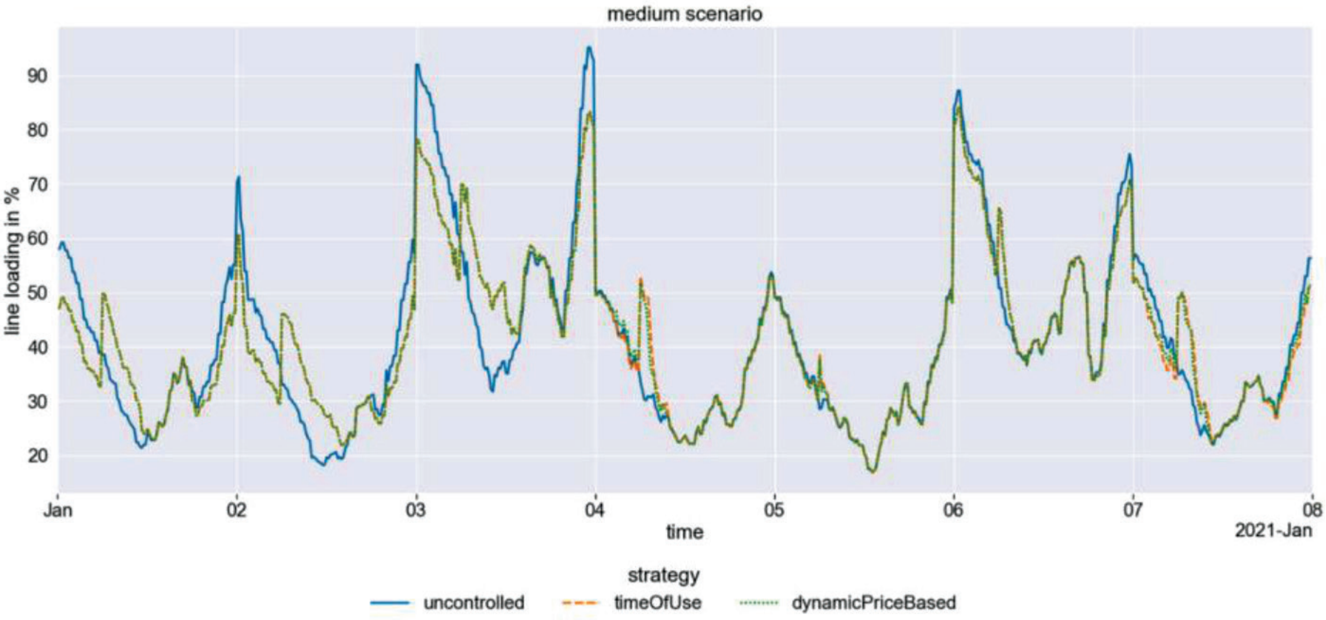


Figure 9. Price-based strategies throughout one week (containing a worst case)

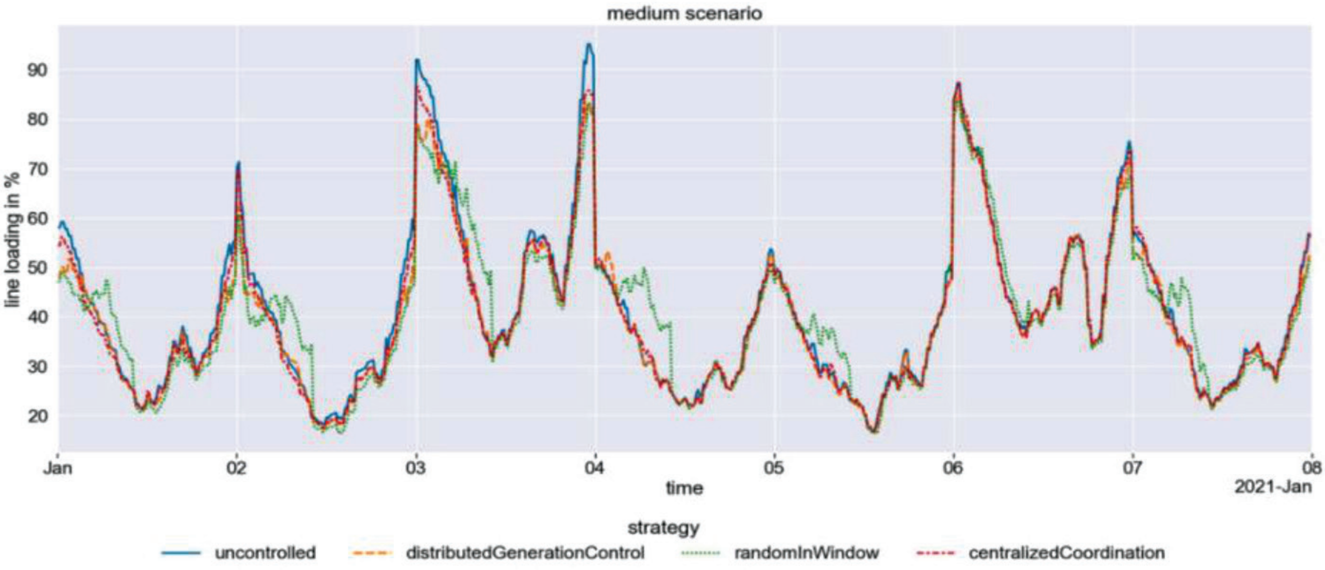


Figure 10. All other strategies throughout one week (containing a worst case)

**Feeder 1: Transformer loading** (%)

Figure 11 shows the transformer loading (for low and high scenario) evaluated for 5 selected transformers. A smaller value of transformer loading (minimum loading for efficient performance assumed) holds significant importance in reducing expensive transformer reinforcements. Decreasing maximum transformer loading via smart charging strategies is seen as a positive outcome.

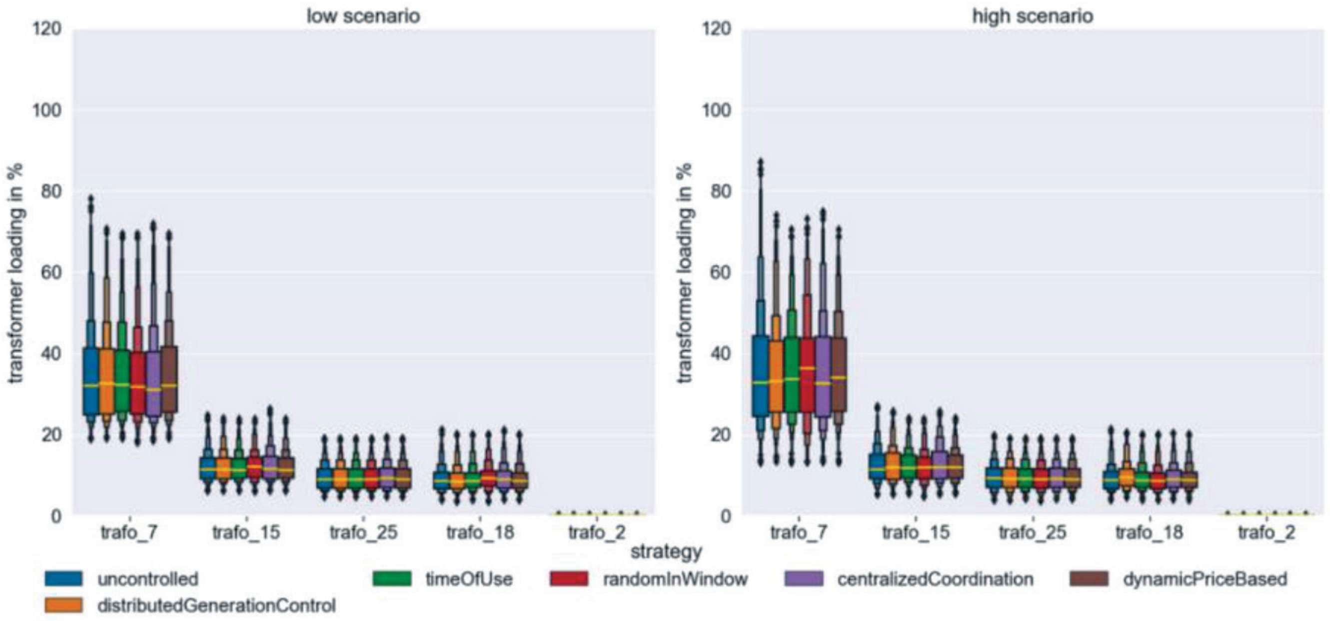


Figure 11. Strategy overview for two scenarios for one week containing a worst case (selected transformers)

**Feeder 1: Bus voltage (p.u.)**

Finally, the effect of the smart charging strategies on the bus voltages is assessed. As the increase of the load in a grid area, which is generally the case when many charging stations and EVs are added, leads to the reduction of bus voltages, the minimum bus voltage is of interest here (as opposed to the maximum loadings). Figure 12 shows the bus voltages of selected buses for low and high scenario for one week. It can be seen that the minimum voltage is raised by the smart charging strategies highlighting their positive effect on this urban residential feeder in this particular situation.

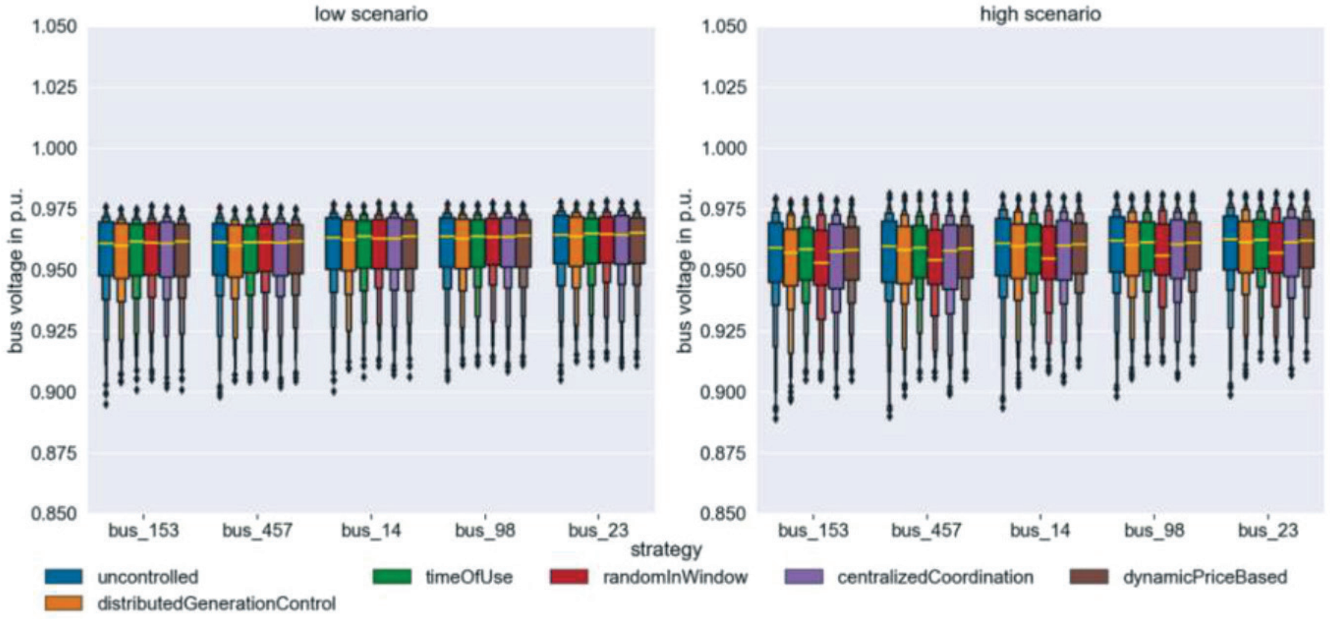


Figure 12. Strategy overview for two scenarios for one week containing a worst case (selected buses)

Similarly, the results of the smart charging strategies on all lines, all transformers and all buses simulated for a low and high scenerio is shown in Annexure II. A.

**Summary: Feeder 1 – Urban residential feeder**

The graph below depicts the overall comparison of performance (in terms of line loading, transformer loading and bus voltage) of the selected smart charging strategies on feeder 1.

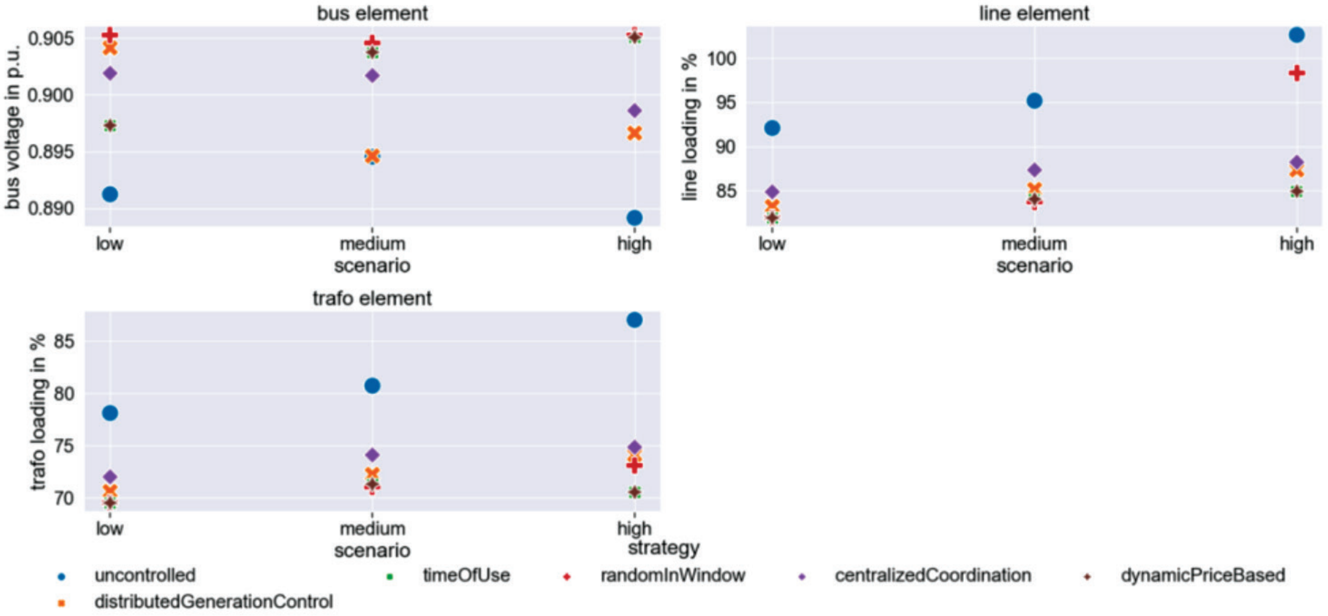


Figure 13. Overall comparison of performance (bus voltage, line loading, and transformer loading) of the selected smart charging strategies on feeder 1

- ❖ For the given urban residential feeder, the rise in the proportion of EVs and PV systems notably impacted the grid parameters.
- ❖ Application of smart charging strategies led to a reduction in the maximum line and transformer loadings in the presented time frames.
- ❖ The minimum bus voltages were also increased by the strategies (under voltages can be an issue in residential areas when many EVs are added)
- ❖ For the given urban residential feeder, more sophisticated strategies (dynamic price-based, centralized control) did not lead to significant improvement in the performance from the uncontrolled charging. To begin with, for an urban residential feeder, implementation of less sophisticated strategies such as the time of use tariff, distributed generation control and random in window might be the sensible approach.

### 3.3.2. Feeder 2 – Rural residential feeder

The feeder 2 is a rural residential feeder with a meshed network topology. The feeder properties are given in Table 16. The topology and the network diagram are as given below.

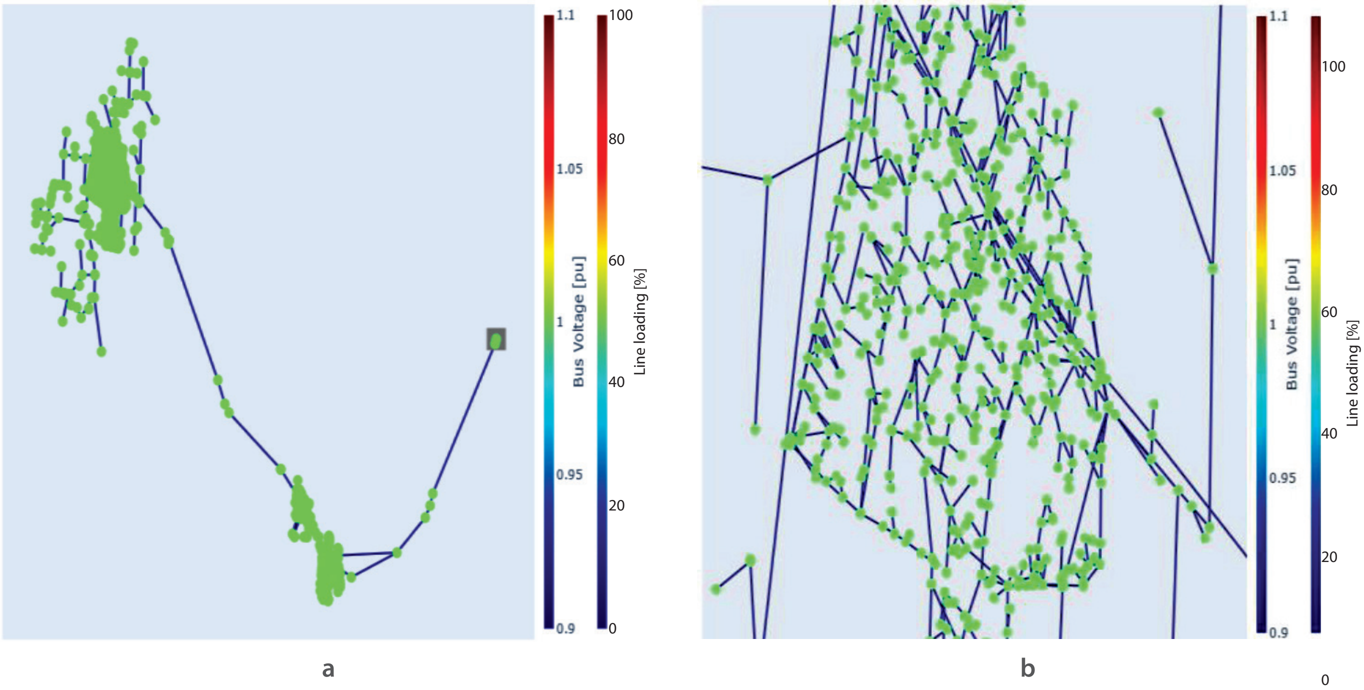


Figure 14. The topology (a) and the network diagram (b) of Feeder 2.

A similar simulation procedure (as described in 3.3.1) is carried out for feeder 2. For an uncontrolled charging simulation, the results showed a very less significant increase in line loading and transformer loading and reduction in bus voltage with increase in penetration of both PV and EV loads in low and medium scenario. This is due to the significantly larger number of customers within the feeder, proportionate to its size. Additionally in the base scenario the feeder is already highly loaded, hence the impact of a high scenario is more evident. Figure 15 depicts the line loading (%) for the uncontrolled charging for all the scenarios. Similarly, the variation in transformer loading and bus voltage with different scenarios for feeder 2 for an uncontrolled charging is given in Annexure II.B.

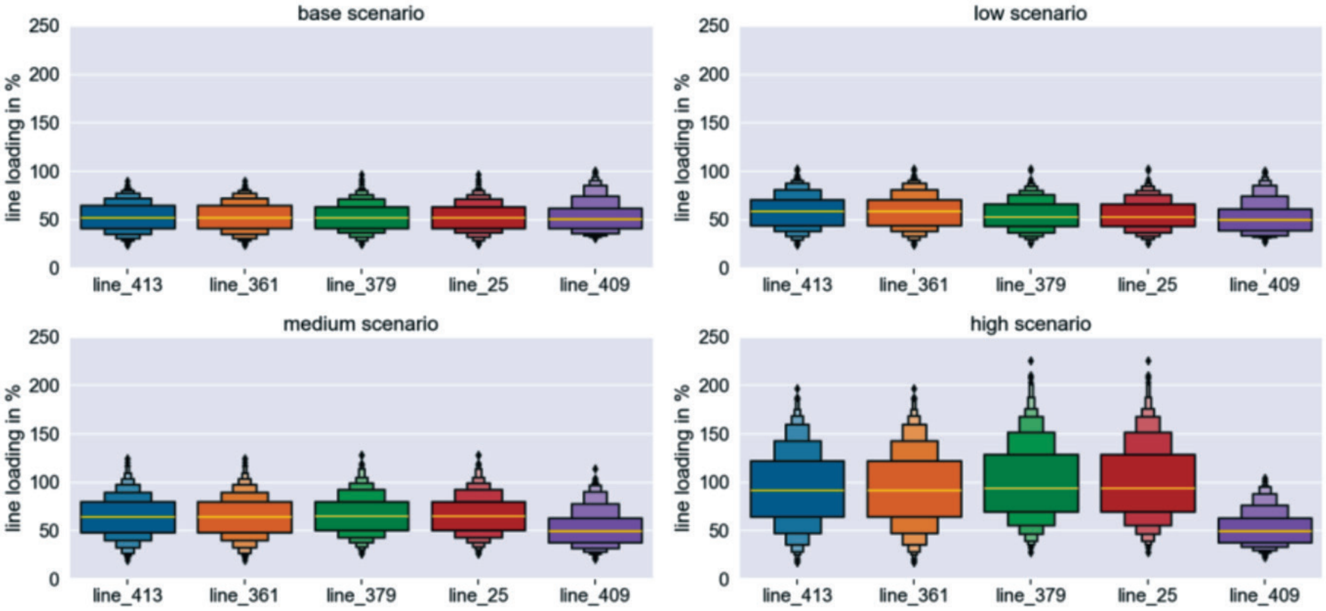


Figure 15. Yearly time simulations of Line loading for all the scenarios under uncontrolled charging.

### Results of Feeder 2

### Feeder 2: Line loading

Since feeder 2 had more customers already connected, the improvement in line loading with application of smart charging strategies was more prominent in the high scenario case. In here, the centralized coordination approach makes a notable difference due to its operational functionality, which involves curtailing charging powers (or curtailment of charging station loads) in the event of violations.

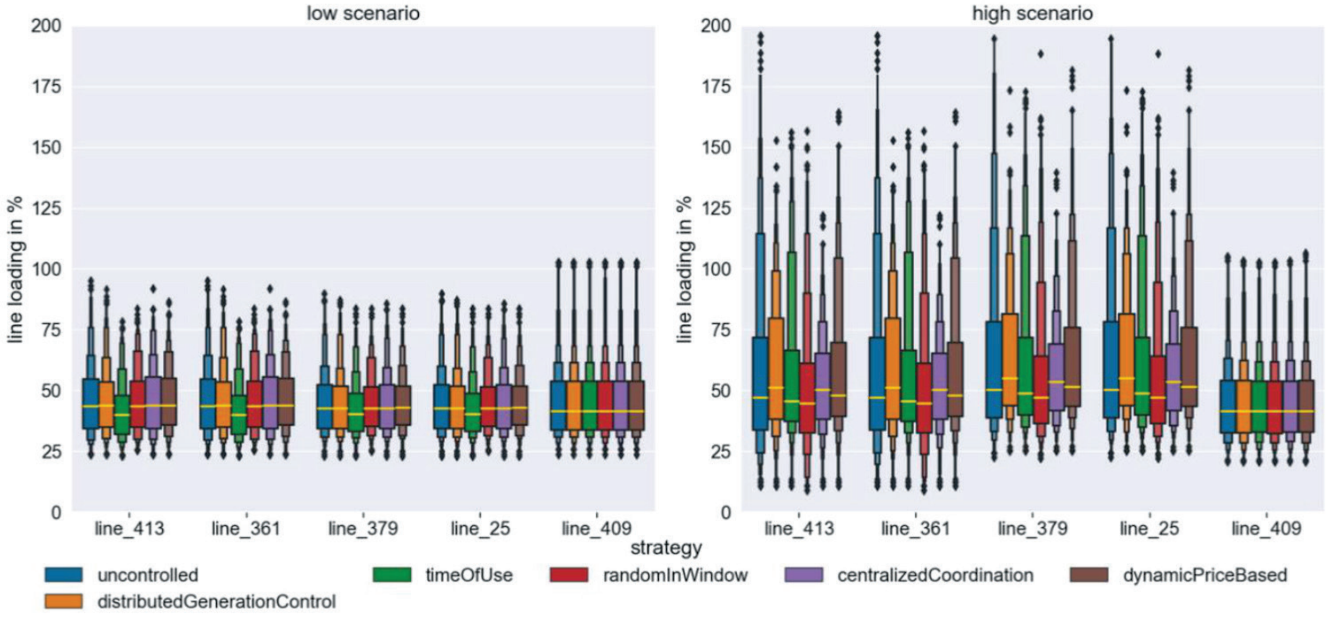


Figure 16. Strategy overview for two scenarios for one week containing a worst case (selected lines)

To better understand the behavior of the centralized coordination and why it can have such a large impact here, figure 17 is used to show the influence of this strategy on a line over time. The plots show the line loading of the line with the highest median value, which is also represented by the boxplots in the figure above.

While there are some differences between the uncontrolled and controlled line in the low scenario, the differences are especially prominent in the high scenario. Here, a violation in another element shortly before the large first peak most likely triggered the curtailment of charging stations, which lead to the reduction of the line loading of the illustrated lineline in figure 17.

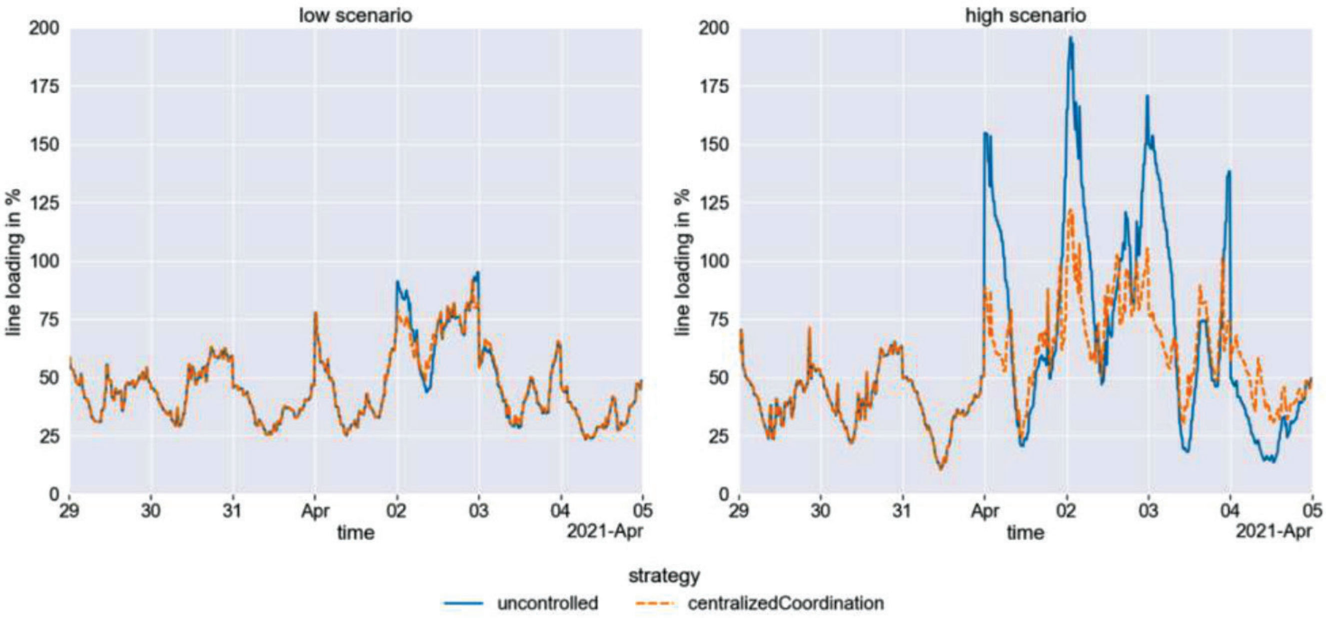


Figure 17. Centralized coordination throughout for one week (containing a worst case in low and high scenario)

**Feeder 2: Transformer loading**

Figure18 shows the results of the five transformers with the highest median loadings. Here, the impact of the scenarios is not as prominent but still noticeable. In almost all cases, the control strategies are able to reduce the maximum transformer loadings but, in some cases, this is not feasible for one of the transformers. In this particular case with the corresponding feeder configuration, this could mean that a transformer upgrade (replacement or additional, parallel one) might be something to consider.

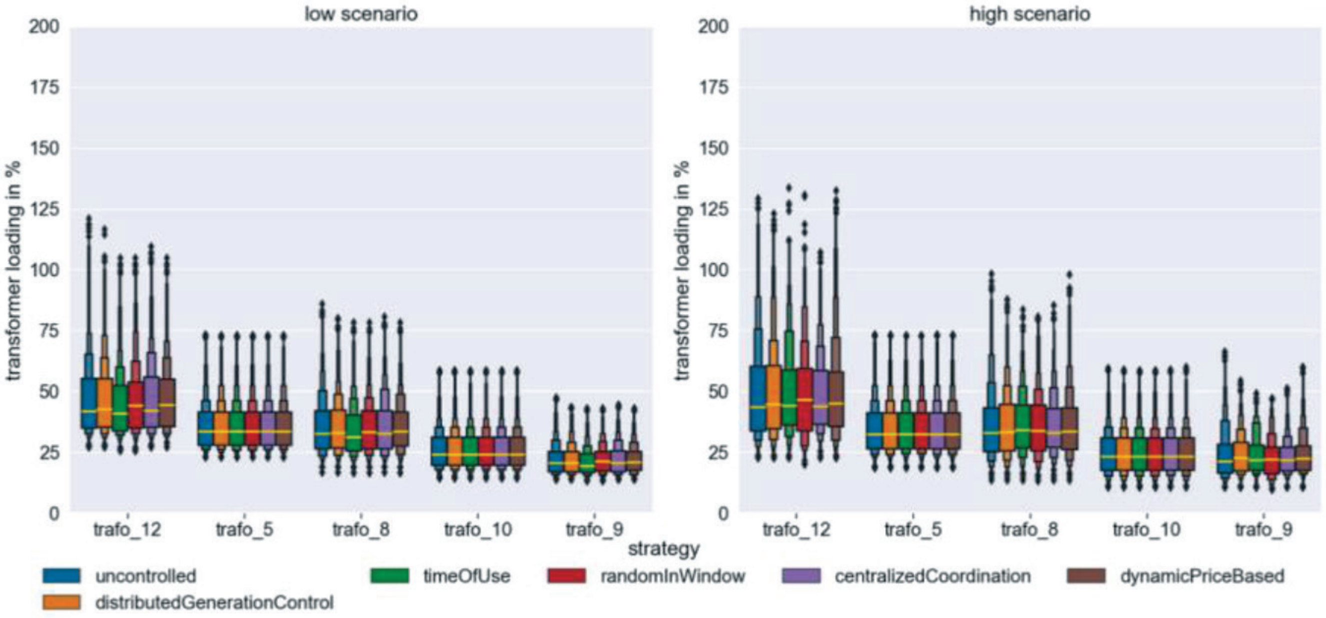


Figure 18. Strategy overview for two scenarios for one week containing a worst case (selected transformers)

### Feeder 2: Bus Voltages

Finally, the bus voltages of the buses with the lowest median values are shown in Figure 19. Here, the effect of the increase of the PV and EV penetration is also prominent. In the low scenario, all strategies are able to increase the minimum voltages in this particular case. In the high scenario, the effect of all strategies except the dynamic price based is also more substantial than in the low scenario and has a positive impact on the minimum bus voltage. It is possible that the dynamic price-based approach did not achieve more favorable results due to dynamic price adoption. This shows that such strategies need to be evaluated carefully before their real-life implementation.

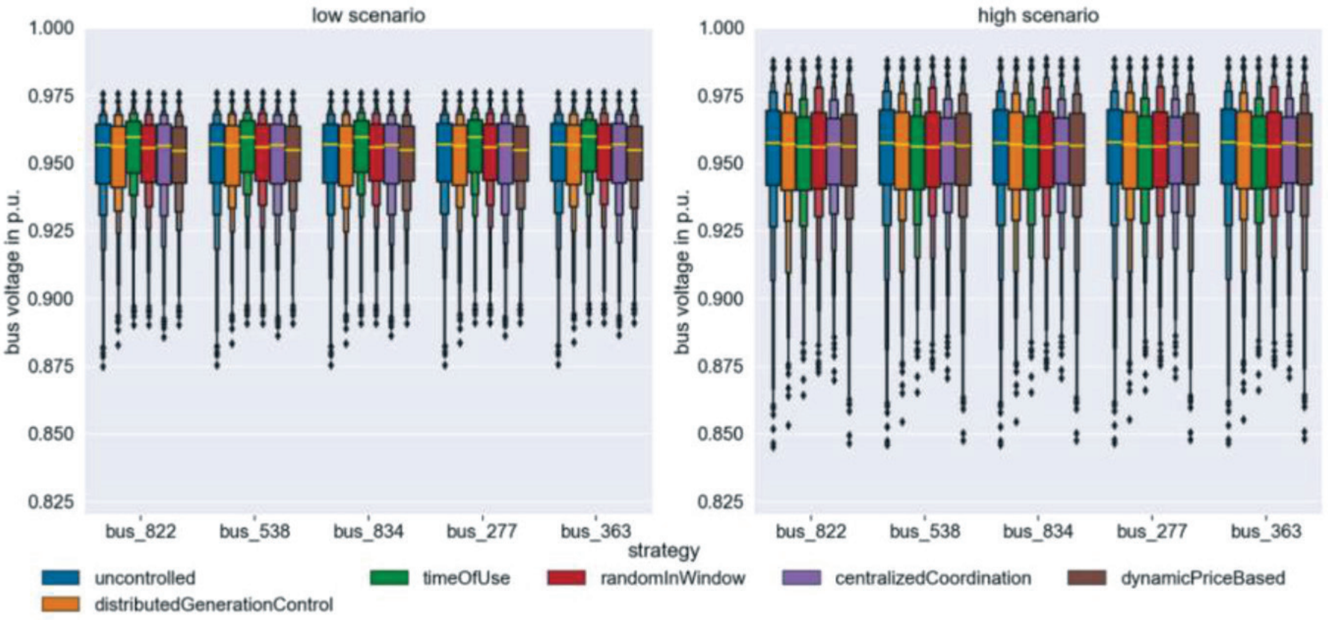


Figure 19. Strategy overview for two scenarios for one week containing a worst case (selected buses)

### Summary: Feeder 2 - Rural residential feeder

The graph below depicts the overall comparison of performance (in terms of line loading, transformer loading and bus voltage) of the selected smart charging strategies on feeder 2.

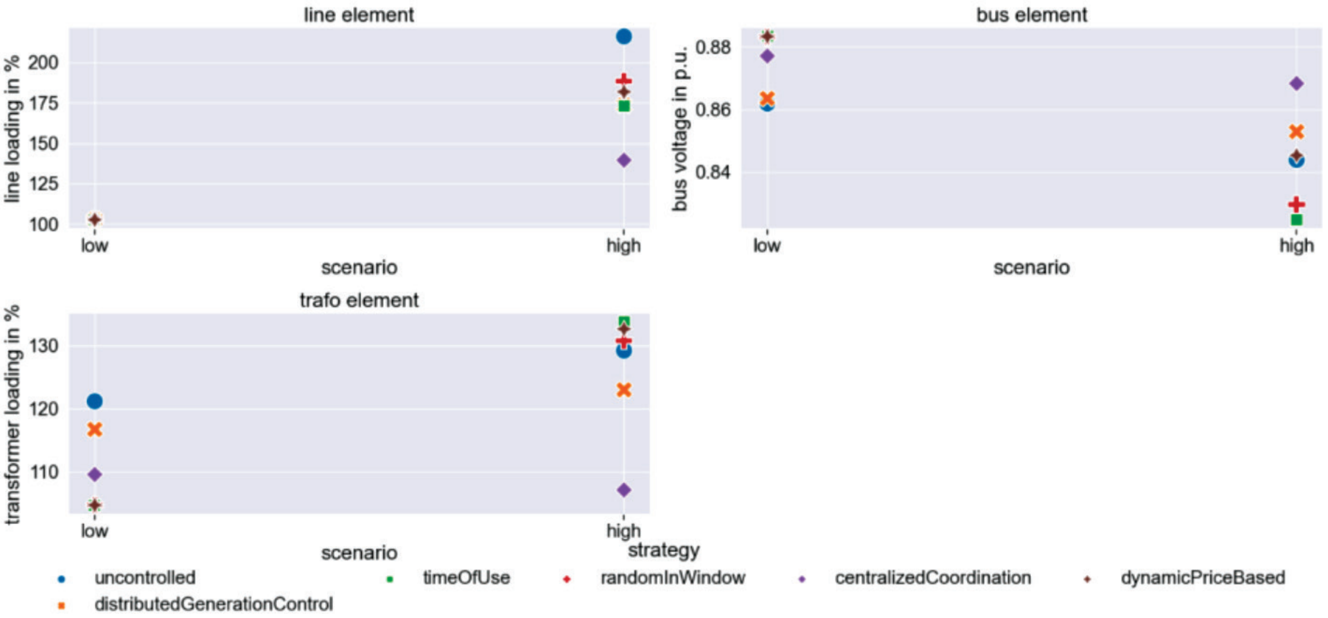
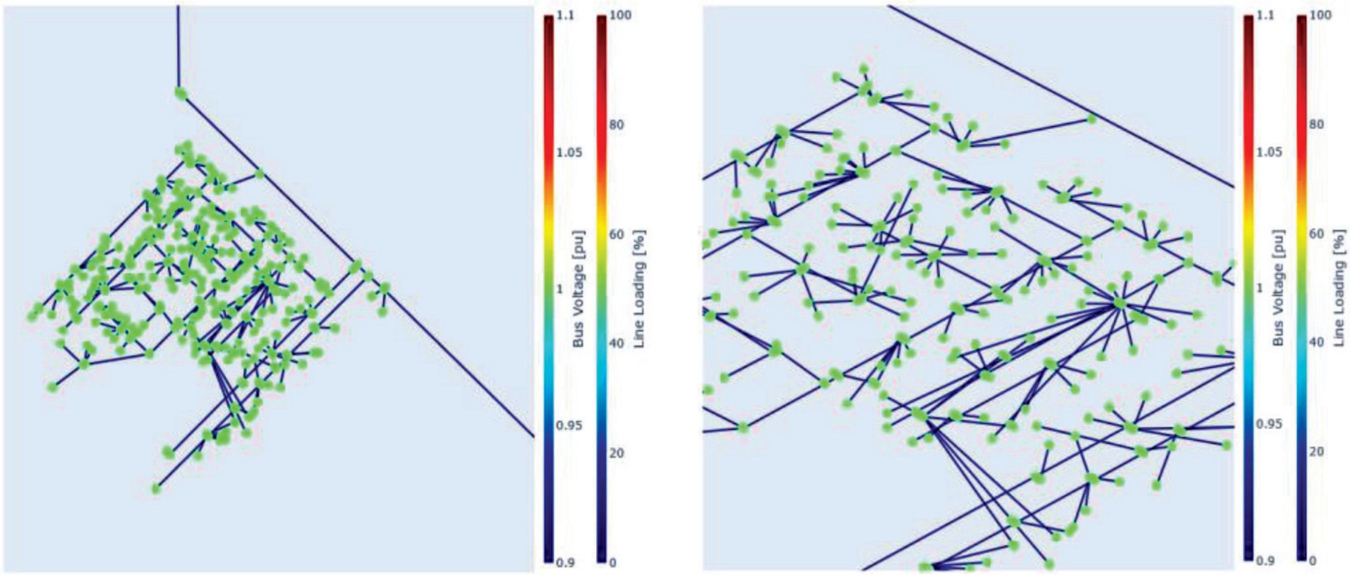


Figure 20. Overall comparison of performance (line loading, bus voltage, and transformer loading) of the selected smart charging strategies on Feeder 2.

- In the given rural residential feeder, the EV and PV scenarios (Specifically high) had a significant impact on the grid parameters leading to several violations in the simulated time frames. These violations are likely attributed to the substantial number of customers connected to the feeder.
- The strategies showed positive impact on the grid parameters notably for high scenario simulations.
- The centralized coordination approach has proven to be more useful for a high penetration scenario.
- The dynamic price-based approach did not have a large effect on the high scenario (more evident in case of bus voltage performance) in the portrayed simulation result.
- Grid independent Strategies (viz. those strategies that do not depend on the current or previous grid situation namely time of use, random in Window and distributed generation control) also exhibited positive performance.
- For a rural residential feeder, a combination of strategies (Grid independent and centralized coordination) would make more sense.

### 3.3.3. Feeder 3 – Industrial Feeder

Feeder 3 is an industrial feeder with a radial network topology. The feeder properties are given in Table 16. The feeder has fewer customers in relation to its size and the grid conditions are better. The topology and the network diagram are as given below.



a

b

Figure 21. The topology (a) and the network diagram (b) of Feeder 3

A similar simulation procedure (as described in 3.3.1) is carried out for feeder. For an uncontrolled charging simulation, all the scenarios had a significantly higher impact (relatively more evident than feeder 1 and 2) on the line loading, transformer loading, and bus voltages. This is due to the relatively low number of customers connected and better current grid condition. Figure 22 below depicts the line loading (%) for the uncontrolled charging for all the scenarios. Similarly, the variation in transformer loading and bus voltage with different scenarios for feeder 2 for an uncontrolled charging is shown in figure 23 and figure 24 respectively.

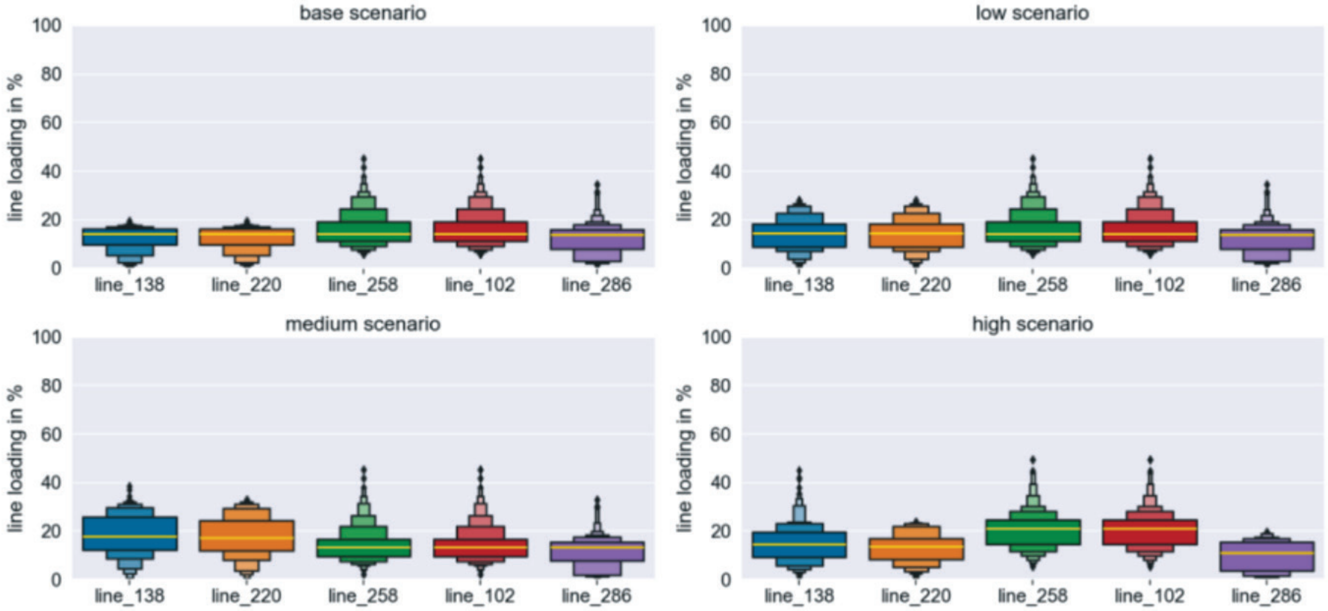


Figure 22. Yearly time simulations of Line loading for all the scenarios under uncontrolled charging.

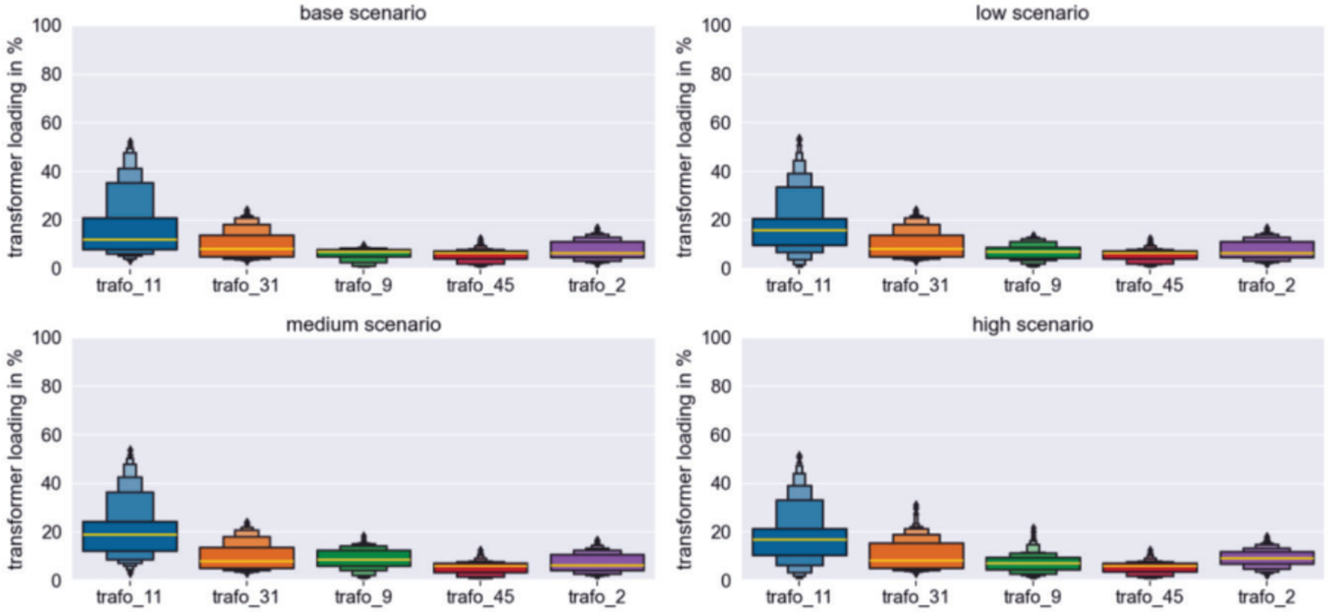


Figure 23. Yearly time simulations of transformer loading for all the scenarios under uncontrolled charging.

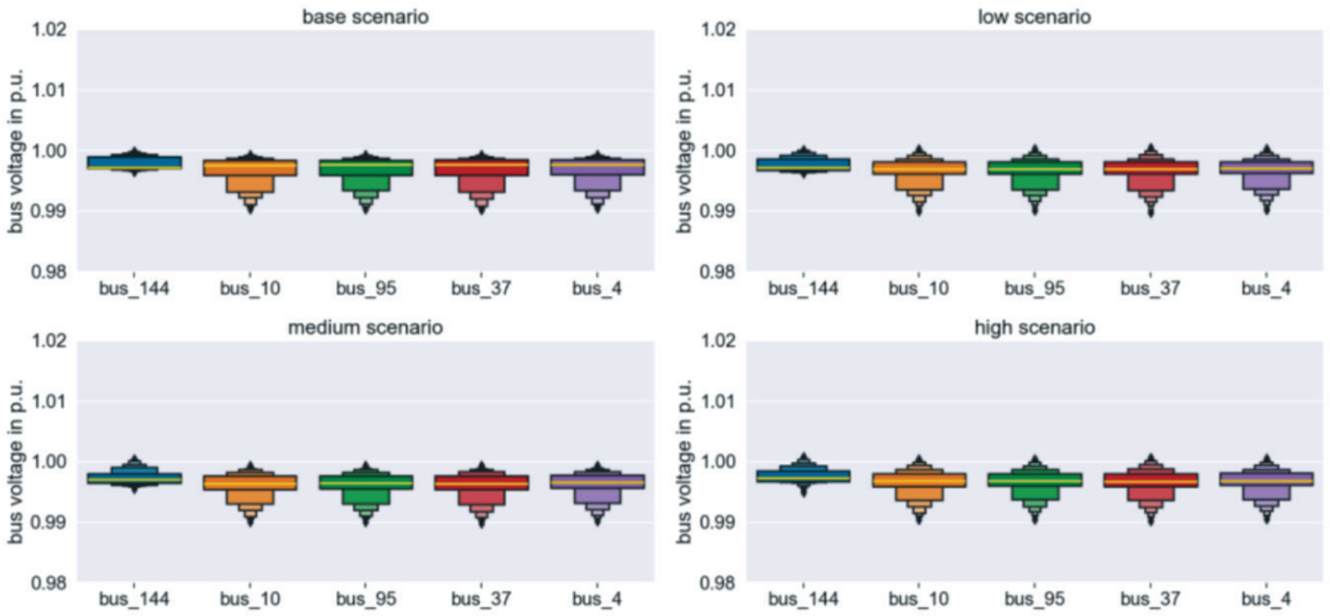


Figure 24. Yearly time simulations of bus voltages for all the scenarios under uncontrolled charging.

**Results of Feeder 3**

**Feeder 3: Line loading (%)**

Even under a high scenario, the uncontrolled charging exhibits no performance parameter violations, primarily because of the relatively small number of connected customers (comparatively lower customer to feeder size ratio). Thus, the centralized strategy has no effect on the line loadings. The findings indicate that implementing smart charging strategies on a line with relatively low load levels could result in unfavorable parameter violations. This occurrence arises from the load-shifting capabilities inherent in smart charging strategies. Some of the loads could be shifted irrespective of the current requirements of the grid. Therefore, it is crucial to carefully consider the characteristics of smart charging strategies, including their load-shifting capabilities and response to grid violations, alongside the current grid conditions before integrating them into the actual system.

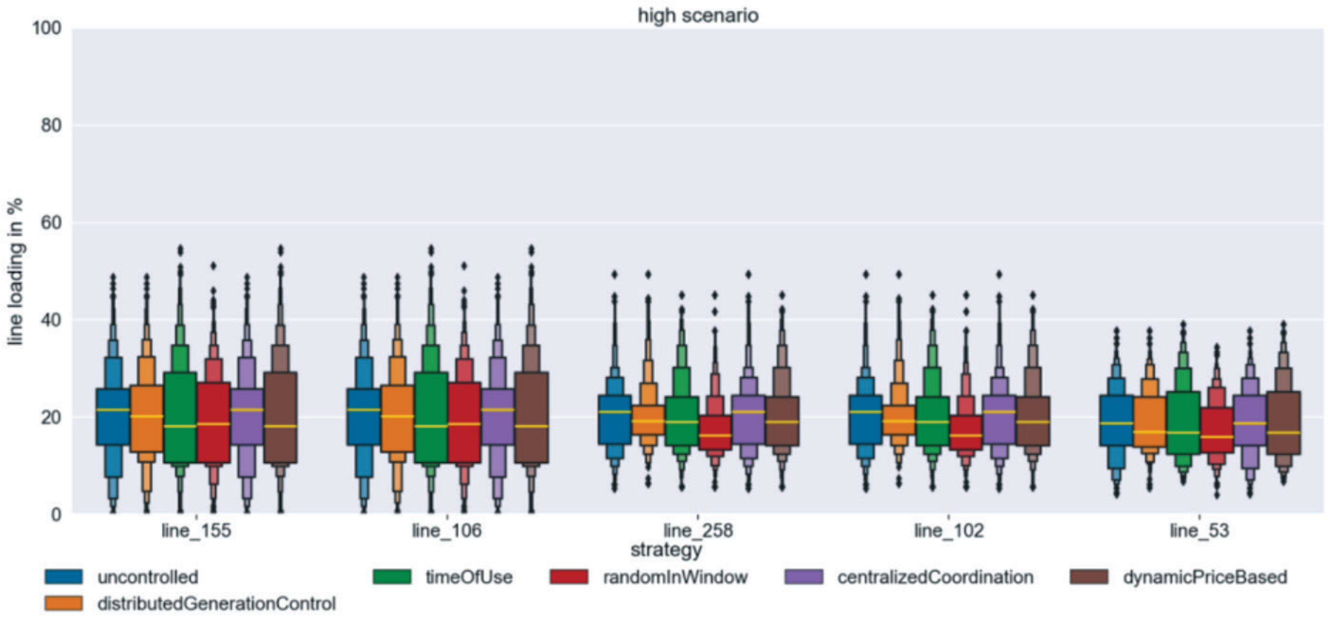


Figure 25. Strategy overview for one scenario for one week containing a worst case (selected lines)

In order to understand the significance of thoroughly assessing strategies before their real-world application and aligning them with specific grid conditions, consider the line loading of the line exhibiting the highest median value over time below.

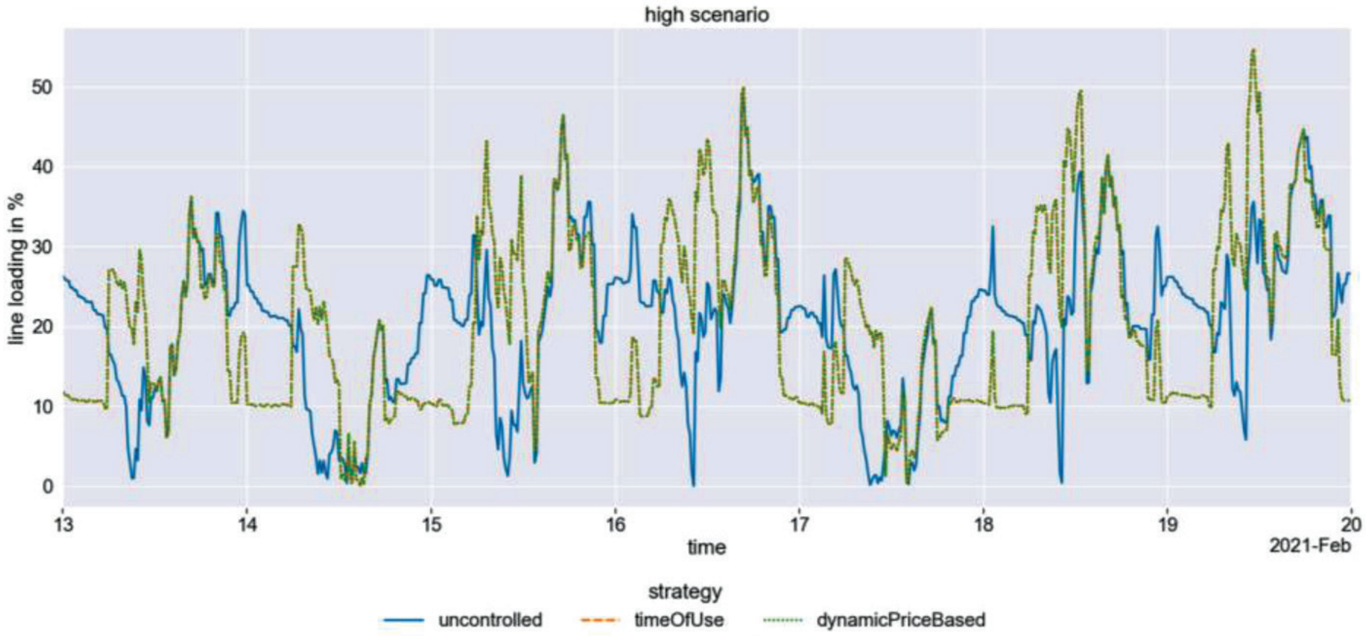


Figure 26. Price-based strategies throughout one week (containing a worst case, line with the highest median value)

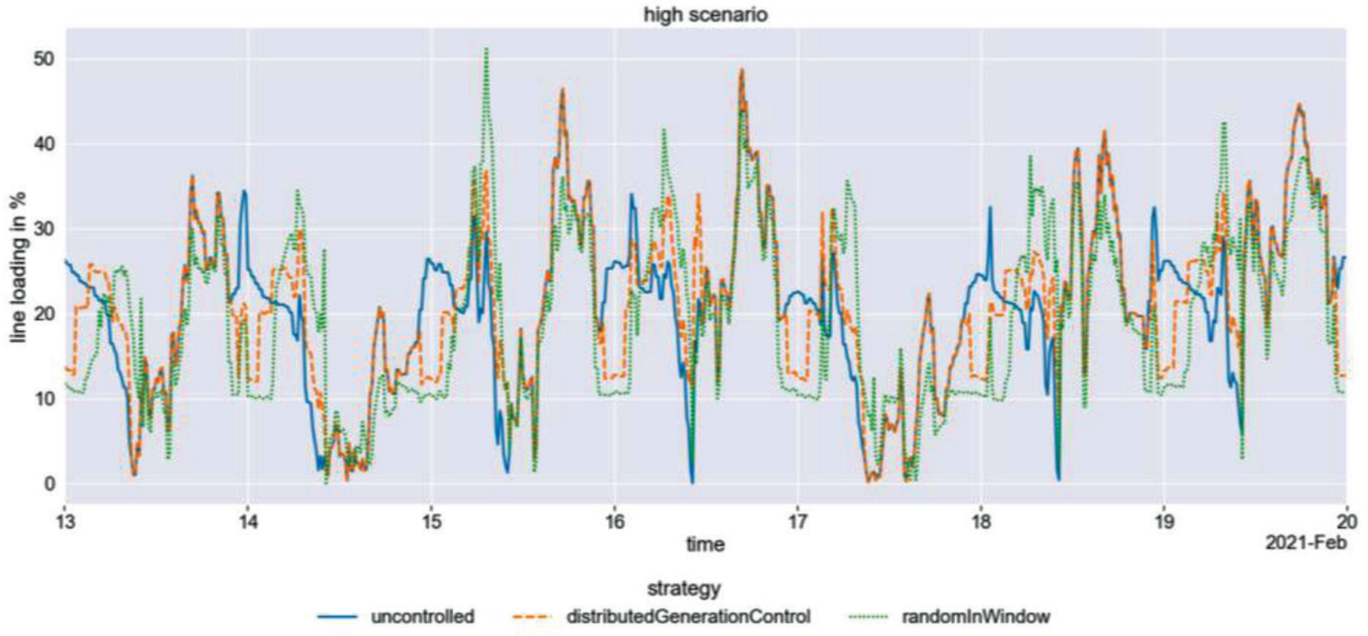


Figure 27. Time-dependent strategies throughout one week (containing a worst case, line with the highest median value)

**Feeder 3: Transformer loading and Bus voltage.**

The simulation results of transformer loading and bus voltages of the selected ones, for a low and high scenario is given below respectively. In both cases, the impact of smart charging strategies on the grid is not particularly significant, primarily due to the lower customer-to-feeder size ratio observed in feeder 3.

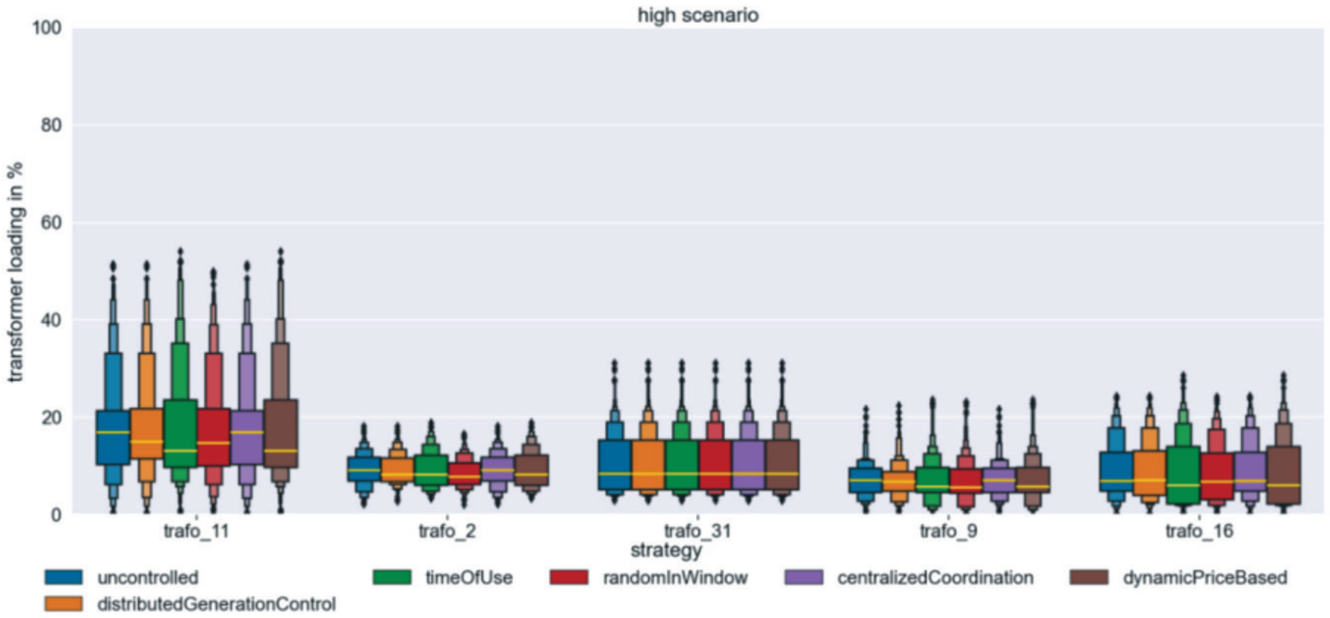


Figure 28. Strategy overview for one scenario for one week containing a worst case (selected transformers)

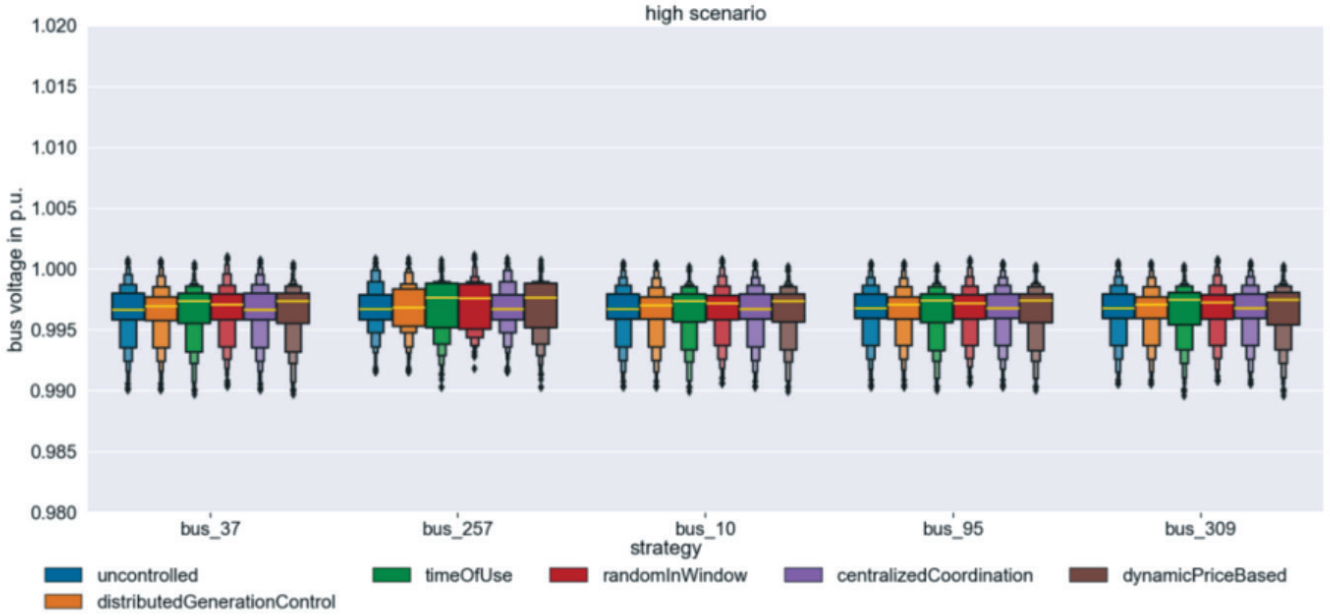


Figure 29. Strategy overview for one scenario for one week containing a worst case (selected buses)

- The impact of the scenarios on this industrial feeder was not particularly noticeable, likely due to the lower customer-to-feeder size ratio[6] and the generally good condition of the grid.
- Since no violations occurred, the centralized control approach had no discernible effect in this case.
- In this specific feeder during the simulated time frames, other strategies even had a slightly negative impact on grid parameters, possibly due to energy charging shifts implemented by these strategies. However, these shifts did not result in any violations within this feeder.
- Across the simulated cases for this feeder, where the grid parameters did not show many violations, all strategies appeared equally advantageous (Some of them exhibited a negative impact). In such scenarios, it becomes pertinent to evaluate the optimal timing and necessity for strategy implementation, considering potential additional costs such as infrastructure expenses.

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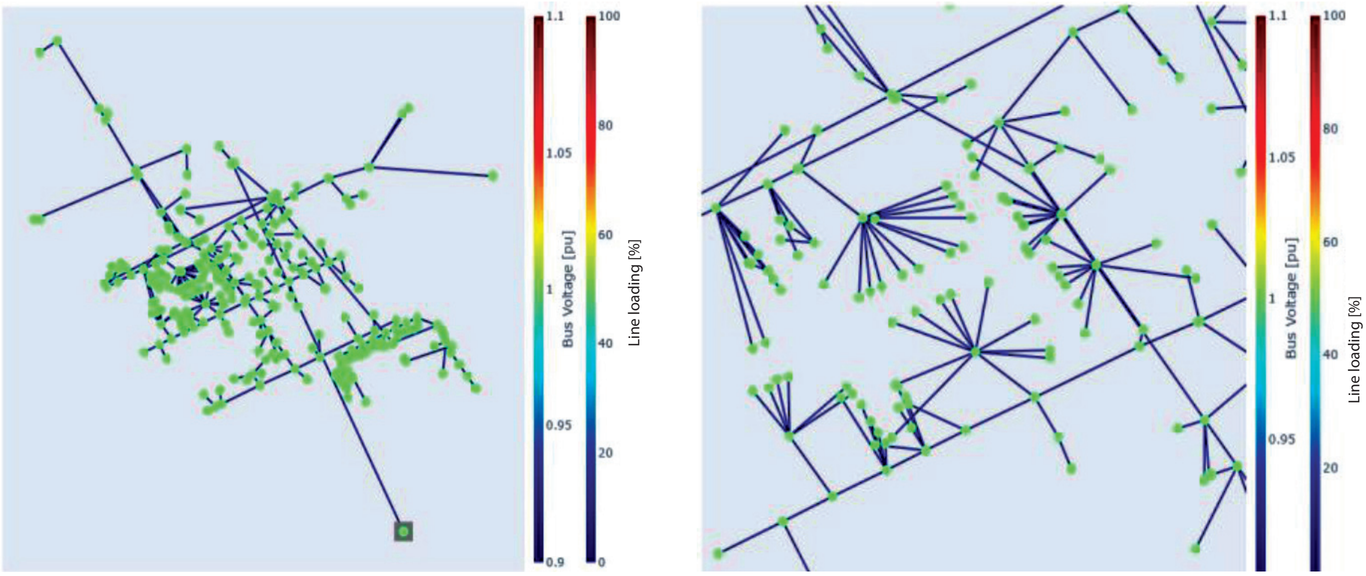
[6] This ratio may be due to fixed customers in industrial feeder.

### 3.3.4. Feeder 4 – Public building

The feeder 4 is a public building with a radial network topology. The feeder properties are given in Table 16. The feeder is relatively small in size and with a smaller number of connected customers. The topology and the network diagram are as given below.



a

b

Figure 30. The topology (a) and the network diagram (b) of Feeder 4

A similar simulation procedure (as described in 3.3.1) is carried out for feeder. For an uncontrolled charging simulation, the parameters had very less noticeable variations within the scenarios (low, medium, and high), but the impact is clearly visible from the base to low scenario. This could be because of the lower number of existing customers in the feeder. Figure 31 depicts the line loading (%) for the uncontrolled charging for all the scenarios. Similarly, the variation in transformer loading and bus voltage with different scenarios for feeder 4 for an uncontrolled charging is given in Annexure II.D.

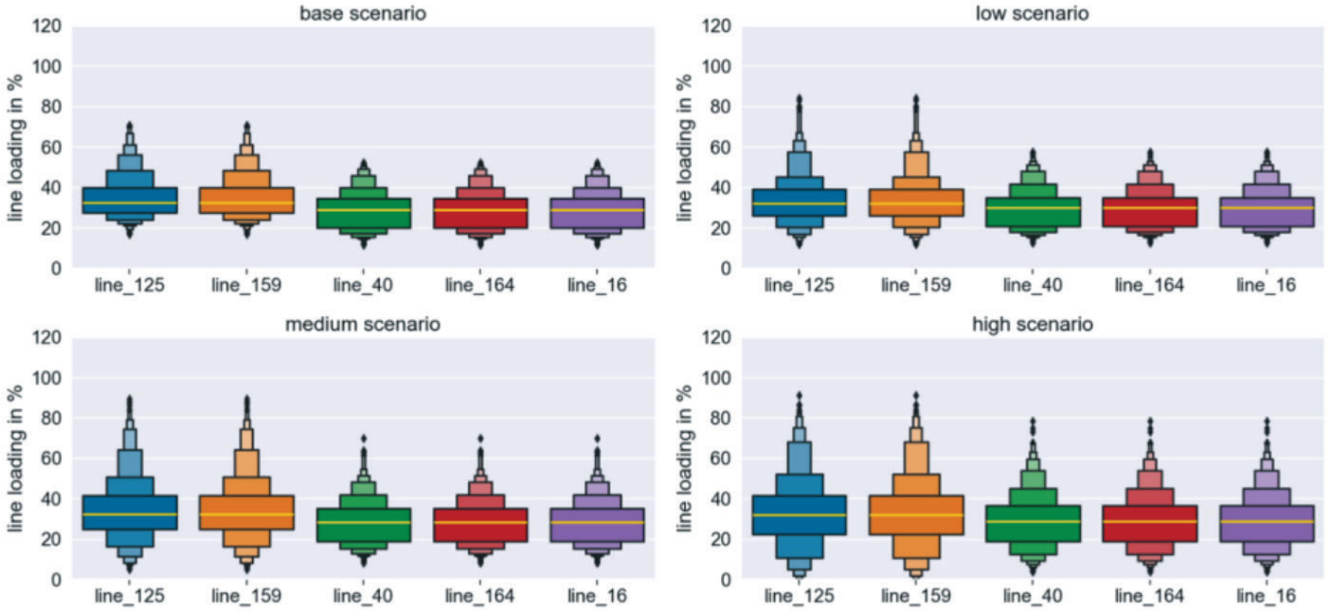


Figure 31. Yearly time simulations of Line loading for all the scenarios under uncontrolled charging.

Considering the fluctuating nature of the feeder (public building) and the varying weather conditions, two distinct worst-case weeks were chosen for simulation.

**Results of Feeder 4**

**Feeder 4: Line loading (%)**

The simulation results of line loading (%) for the 5 worst effected lines for two different weeks (week I, week II-high scenario)

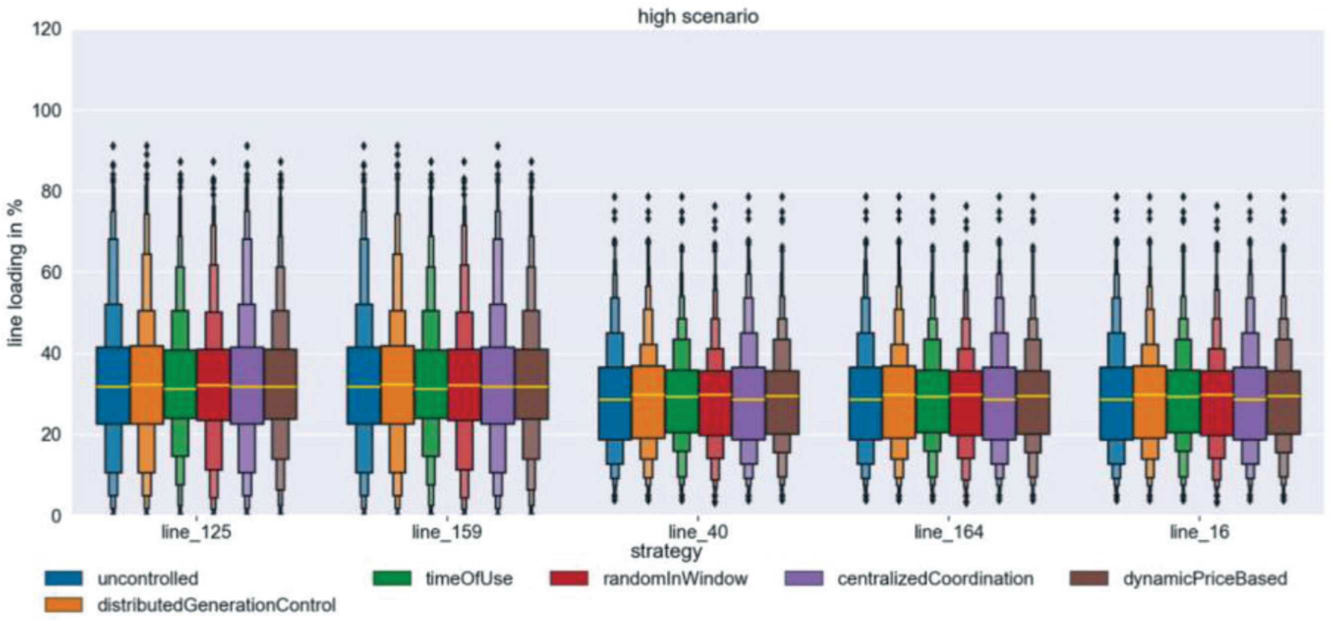


Figure 32. Strategy overview for one scenario for one week I (containing a worst case, five selected lines)

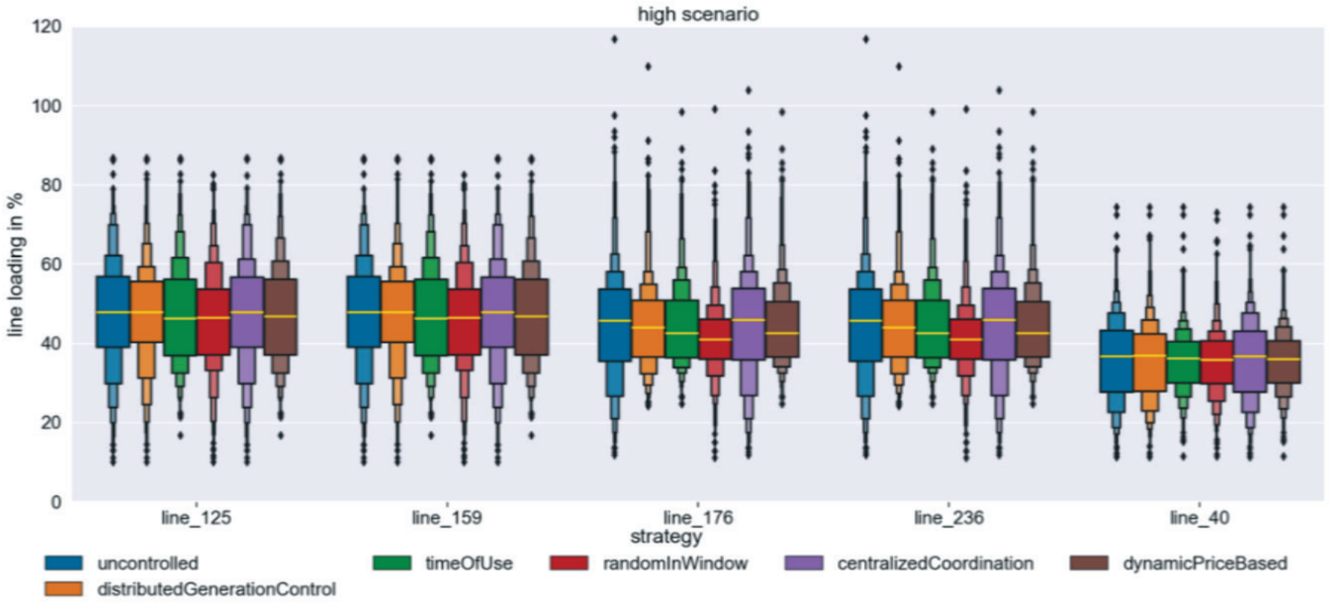


Figure 33. Strategy overview for one scenario for one week II (containing a worst case, five selected lines)

**Feeder 4: Transformer loading (%)**

The simulation results of transformer loading (%) for the 5 worst effected transformer for two different weeks (week I, week II-high scenario) are given below. In both the cases, small improvements are visible when employing smart charging strategies, particularly notable with the random in-window approach.

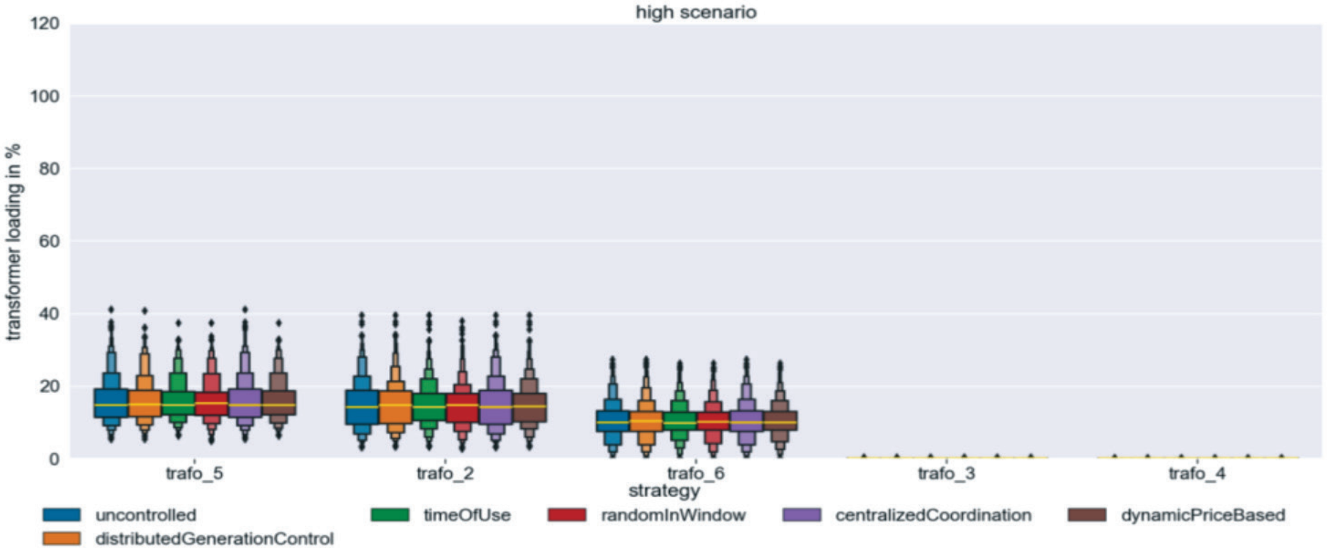


Figure 34. Strategy overview for one scenario for one week I (containing a worst case, five selected transformers)

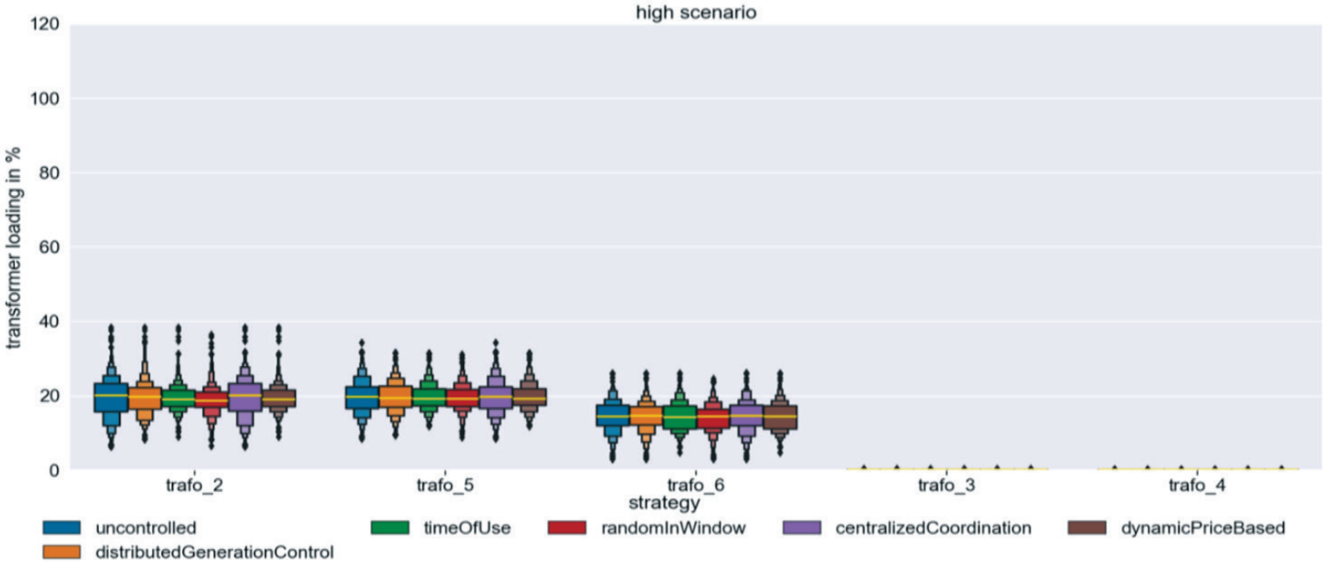


Figure 35. Strategy overview for one scenario for one week II (containing a worst case, five selected transformers)

**Feeder 4: Bus Voltages**

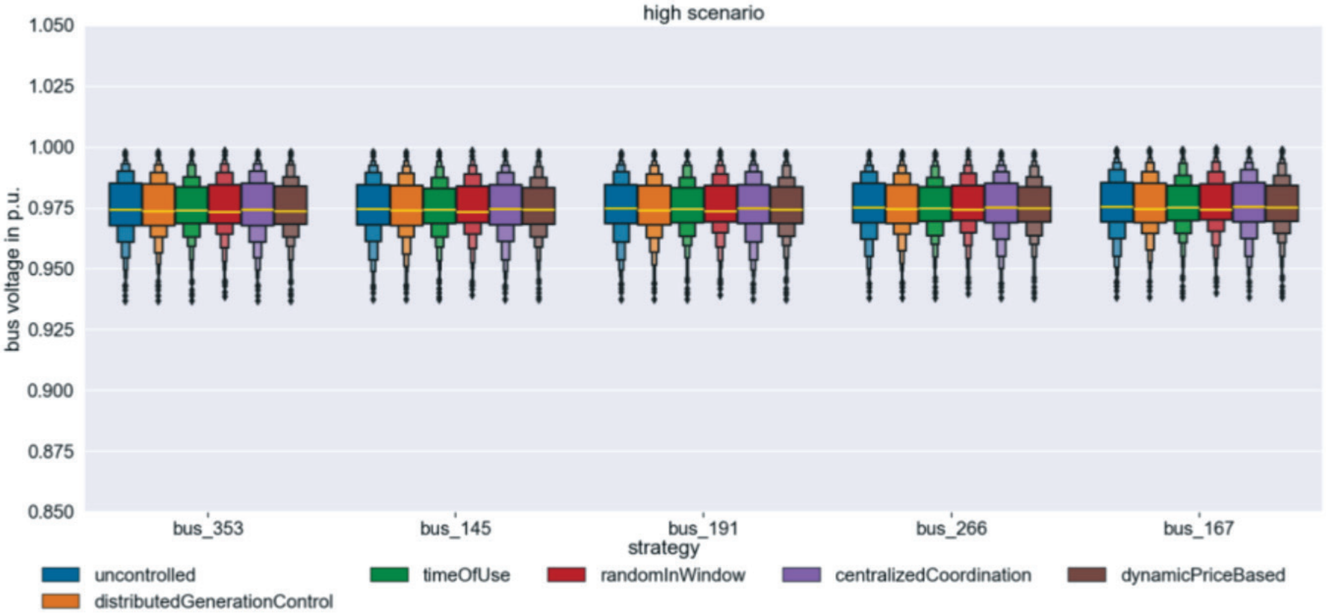


Figure 36. Strategy overview for one scenario for one week I (containing a worst case, five selected buses)

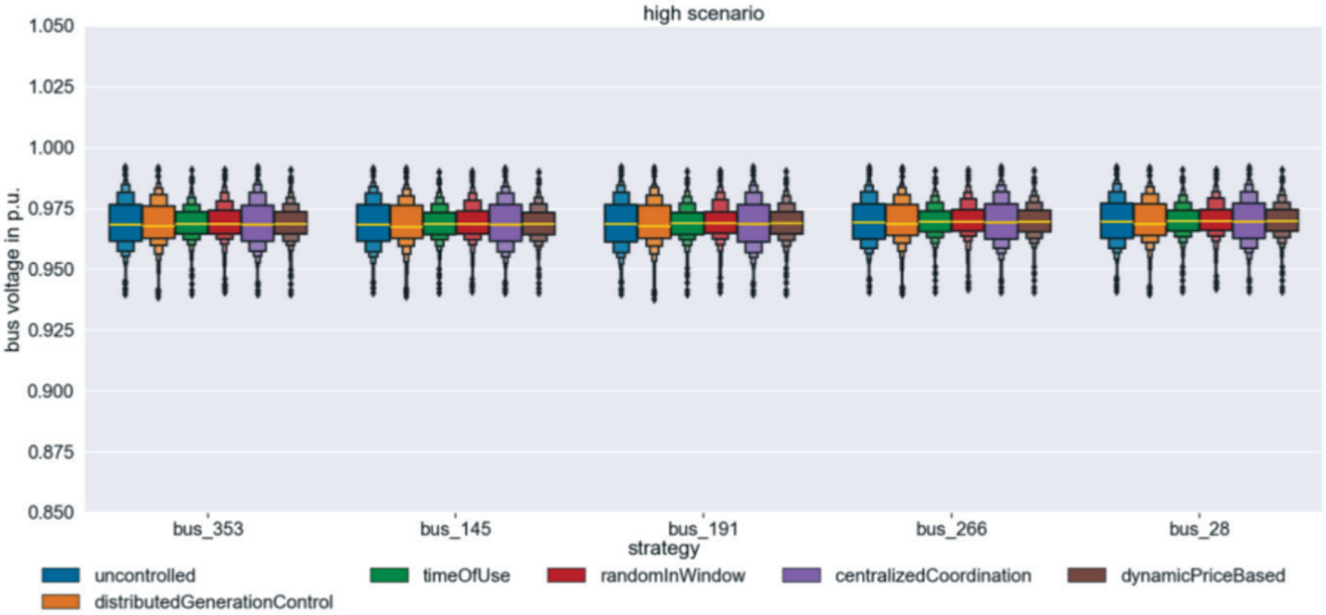


Figure 37. Strategy overview for one scenario for one week II (containing a worst case, five selected buses)

**Summary: Feeder 4 – Public building**

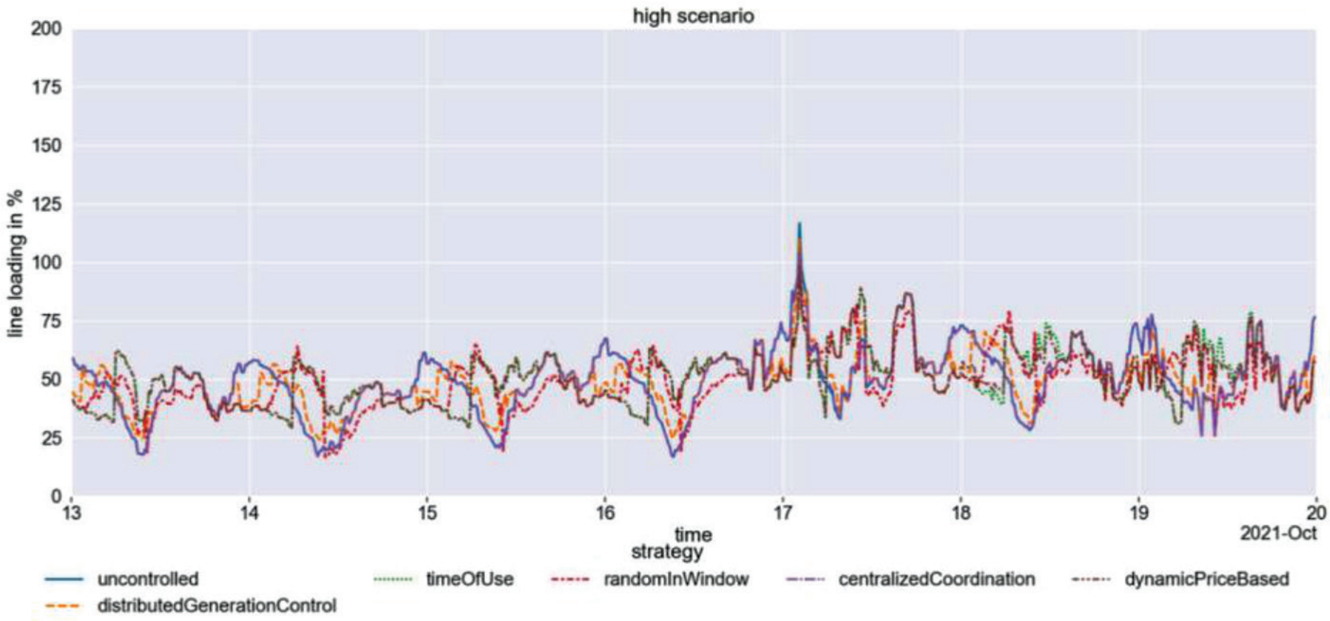


Figure 38. All strategies throughout one week II (containing a worst case, line with the highest maximum value)

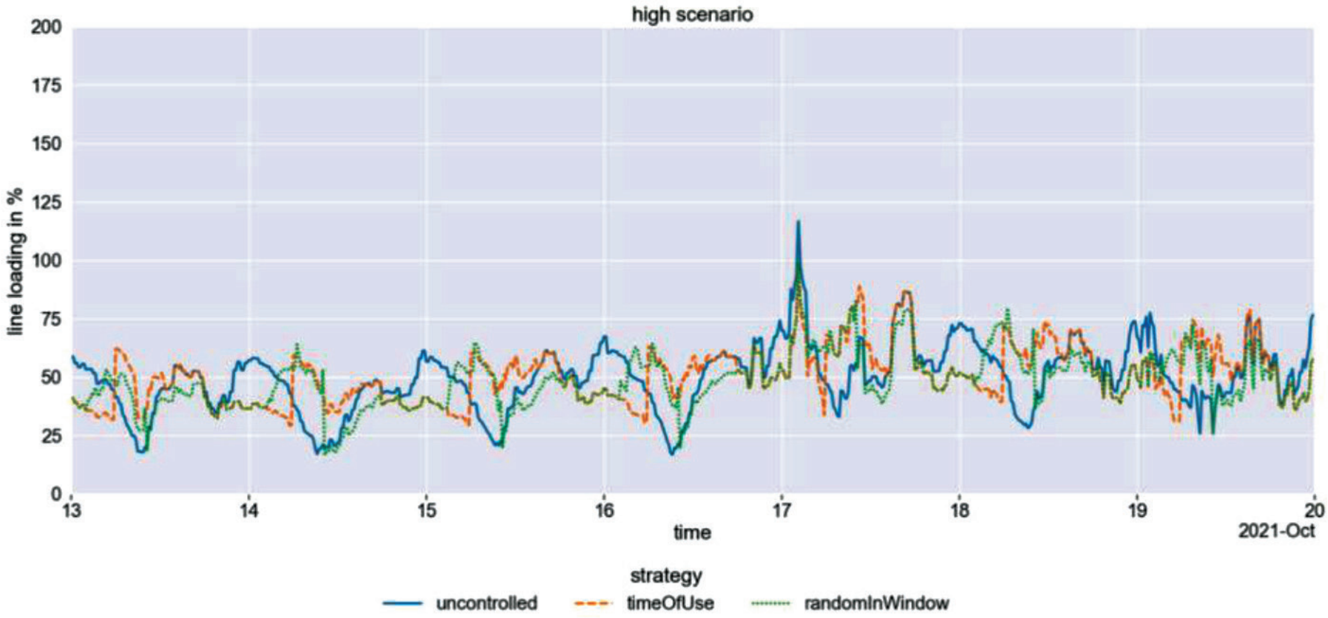


Figure 39. Price-based strategies throughout one week II (containing a worst case, line with the highest maximum value)

- While the strategies yielded a positive impact, it was less substantial compared to residential feeders due to fewer controlled charging stations relative to feeder size.
- The effectiveness of the strategies may vary on a weekly basis for a public building feeder, as seen in weeks I and II in the high scenario.
- "Simpler" strategies like random in-window and time-of-use could achieve favourable outcomes in the scenarios for a public building feeder.

## 3.4. Conclusion and recommendations from Strategy simulations

The following conclusions are derived from the simulation results of all the 4 types of feeders.

**I. Within the performed simulations, the strategies tend to have the biggest positive impact when a feeder was highly loaded.**

This conclusion is exemplified with results of Feeder 2, a rural residential feeder with the highest customer count and longest line length. The simulation results of line loadings for Feeder 2 in both low and high scenarios are shown in figure 40, focusing on the five lines with the highest median line loading. In the low scenario, line loading remains below 100%, reducible with all evaluated smart charging strategies, albeit by only a few percent. Conversely, in the high scenario, line loadings exceed 200% for uncontrolled charging, but a significant reduction of up to 75% is achievable. This emphasizes the substantial positive impact of smart charging strategies on highly loaded feeders, despite being unable to prevent threshold violations in such heavily loaded cases.

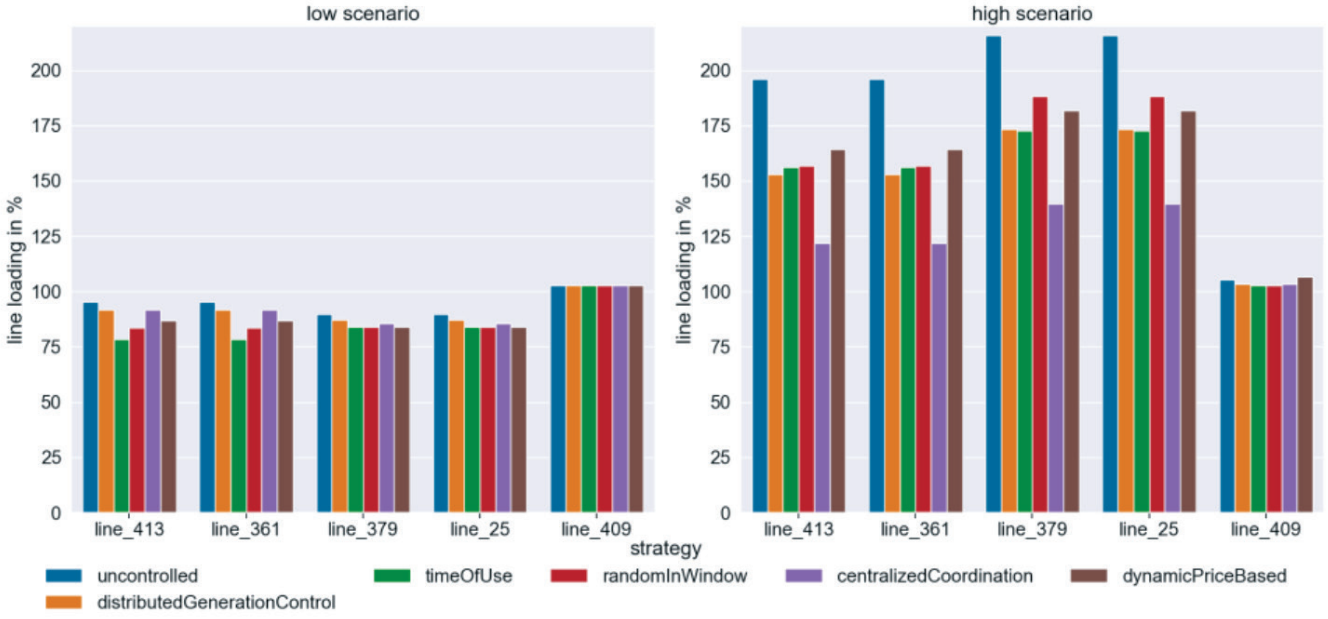


Figure 40. Maximum line loadings in the Feeder 2 – low and high scenario (one week surrounding a worst case, selected lines).

**II. In the simulations conducted, the centralized coordination control strategy demonstrates a notably more positive impact on grid parameters than simpler strategies in instances of high violations. However, simpler strategies still show significant positive impacts in most other cases.**

*Note: The term "simpler strategies" generally refers to strategies that can be implemented more easily in the real energy system.*

When assessing the effects of various smart charging strategies on grid elements, a positive influence is evident across all strategies. This suggests that even straightforward, easily implementable strategies can yield substantial grid enhancements. However, in highly loaded grids, such as those in Feeder 1 and Feeder 2 under high scenarios, the positive impact of the centralized coordination strategy becomes more pronounced. Thus, while simple strategies are suitable for initial implementations, as grid complexity, size, and load increase, a more advanced strategy like centralized coordination becomes increasingly necessary.

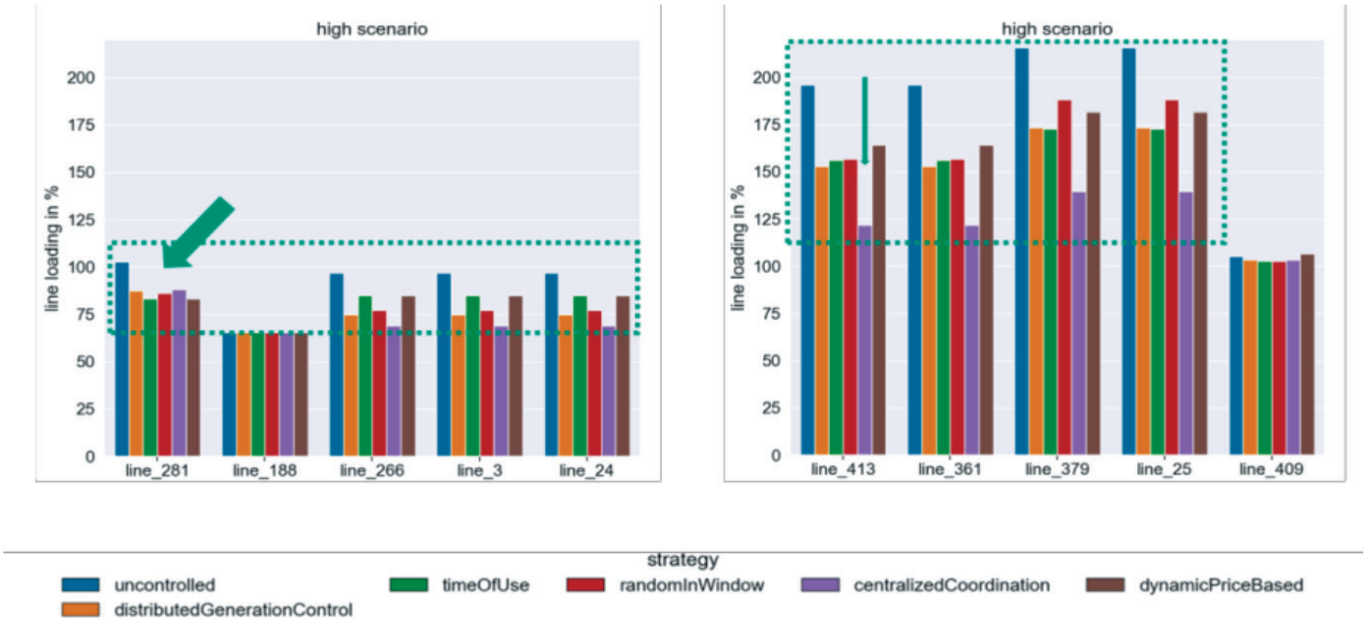


Figure 41. Maximum line loadings in Feeder 1 and Feeder 2 – high scenario (one week surrounding a worst case, selected lines).

**III. In some cases, the smart charging strategies can have a negative impact (increase in line loading) due to its load shifting capabilities.**

Smart charging strategies, especially those influenced by prices, can increase line loading by shifting loads to different time periods. For example, in the high scenario, the industrial feeder area of Feeder 3 illustrates this trend over a one-week period, as depicted in figure 42. Despite the rise in line loading, no threshold violations occur due to the feeder's low load. These results highlight the necessity of carefully selecting and continuously adjusting price signals, while also affirming the effectiveness of smart charging for load shifting.

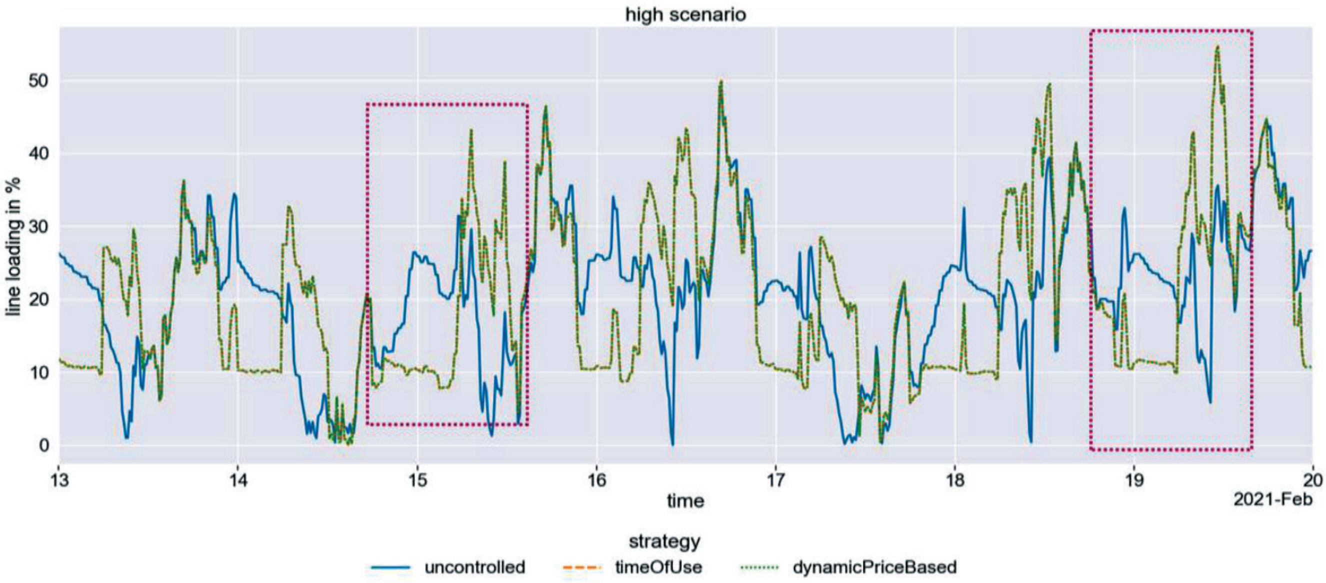


Figure 42. Maximum line loading in the Feeder 3 for different smart charging strategies –high scenario (one week surrounding a worst case, selected lines).

**IV. The simulations showed that in some cases control strategies can also lead to a worsening of the grid situation. This shows that the careful evaluation and preparation of strategies is highly important before their real-life implementation.**

In addition to their positive impact, smart charging strategies can also exacerbate grid conditions. This underscores the need for thorough evaluation and ongoing adjustment of strategies during implementation. For instance, the behavior observed in Feeder 3 in the high scenarios, as shown in figure 43, highlights this phenomenon. Thus, measurement campaigns and acquisition of additional data would be helpful to run further simulations that could consider in more detail user behavior, regionalization, longer time frames, larger distribution networks, among others.

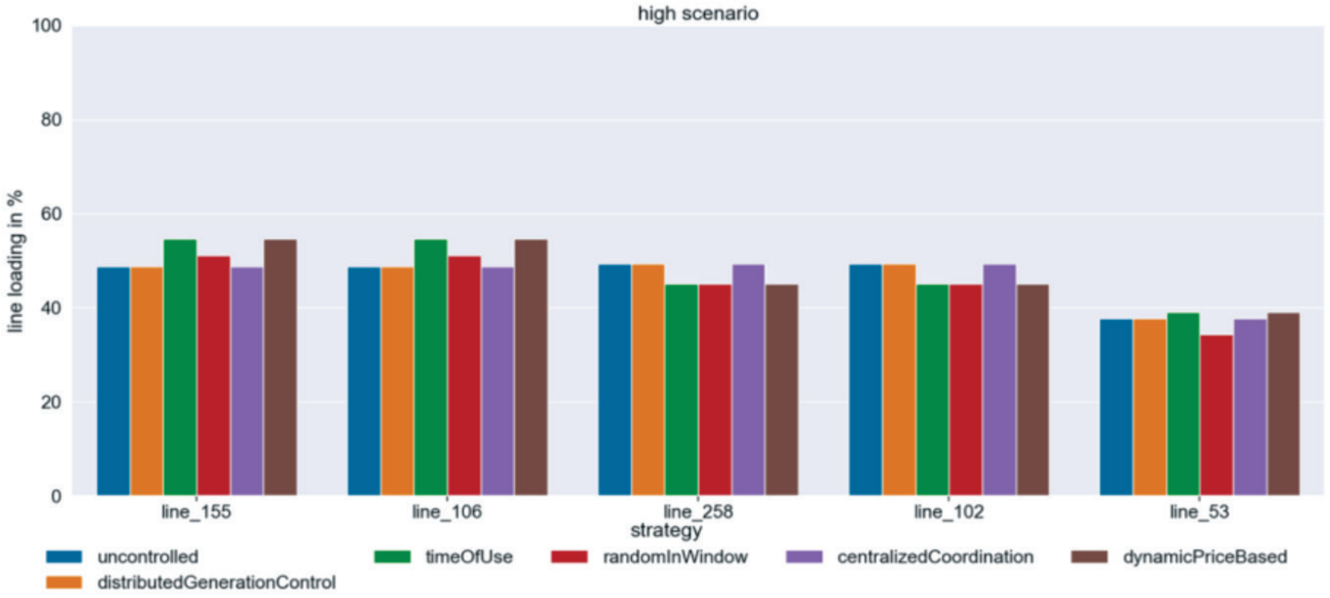


Figure 43. Maximum line loadings in Feeder 3 – high scenario (one week surrounding a worst case, selected lines).

In addition to the analyzed impacts of smart charging in the grid, the economic dimension of these smart charging strategies should also be investigated. For instance, a more complex smart charging strategy can have greater capital and operational expenditures. Still, at the same time, it might be able to reduce network costs by avoiding or deferring conventional grid reinforcements. Finally, prior to a nationwide roll-out of these smart charging strategies, field tests and pilot projects could be useful to validate the results of these simulations.

## 3.5. Simulation Analysis: Impact of EV integration on distribution system protection

In traditional distribution systems, the protection system is designed based on a radial configuration, where power flows from one end to the other. However, the integration of EVs and DGs introduces various challenges to the protection system.

The integration of EVs and DGs can lead to an increase in the short-circuit level of the system, which can exceed the limits/ratings of the existing protection devices. This can result in improper coordination between relays, leading to delayed or ineffective fault detection and isolation. Additionally, the integration of EVs and DGs can create islanded systems, where sections of the distribution network are electrically isolated from the main grid, further complicating the protection coordination.

The presence of EVs and DGs can also result in the issues such as blinding of overcurrent protection, where the protection devices are unable to accurately detect faults due to changes in the power flow direction and magnitude. This can result in inadequate fault clearance and compromise the safety of the system. Moreover, the integration of EVs and DGs can also lead to sympathetic or false tripping, where the operation of one protection device triggers undesired operation of other devices due to interdependencies and system interactions. This can lead to disruptions in power supply and affect the reliability of the distribution system.

To address these challenges, new protection strategies and technologies need to be developed to accommodate the non-radial configuration with EVs and DGs of the distribution system. This may involve the implementation of advanced protection schemes, adaptive relaying techniques, and enhanced coordination algorithms to ensure reliable and selective fault detection and isolation. Additionally, thorough system planning and engineering analysis are necessary to optimize the performance of the protection system and mitigate the potential issues arising from the integration of EVs and DGs.

**In order to investigate the effects of EV integration on the protection of distribution systems, specific simulation exercises given were undertaken. It is imperative to note that the data utilized in the subsequent simulation analysis**

**is not sourced from real-life scenarios and has not been provided by the DISCOM as mentioned in section 3.1.2.**

### 3.5.1 Short circuit level under EV penetration

To analyze the impact of EV integration on the protection schemes of the distribution network a real-life distribution network in India has been analyzed. The distribution feeder dynamic and steady state model has been used to perform this task. The influence of EVs on the system state protection level has been conducted for different EV charging technologies and for differed scenarios.

The short-circuit contribution of power electronic interfaced DG is limited compared to conventional alternators and is governed by the thermal limit of the semiconductor devices and switches. The fault current in converter interfaced sources is generally limited to 1 to 1.5 times the rated current so as to protect the power converters. In most cases, control strategies adopted in the power electronic converters are designed to provide positive sequence currents in case of symmetrical and unsymmetrical faults. Potential alterations to the grid code may necessitate future DGs to supply a negative sequence current for unbalanced faults. Figures below show the impact of EV integration for the test system under unidirectional vehicle to grid (V2G) charging scenarios, with and without consideration of distributed generation (DG).

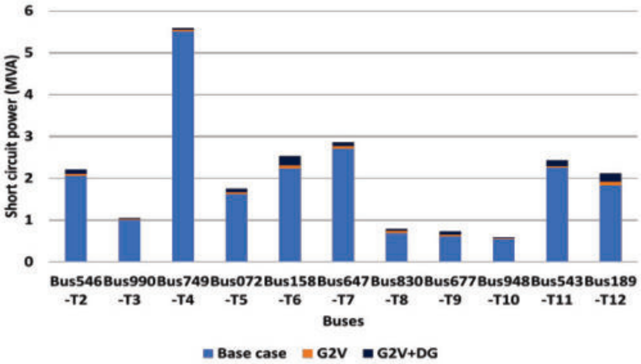


Figure 44. Comparison between impacts of G2V and G2V+DG cases on short-circuit capacity.

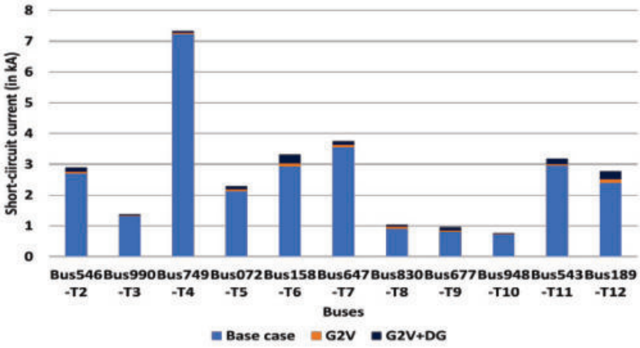


Figure 45. Comparison between impacts of G2V and G2V+DG cases on short-circuit current.

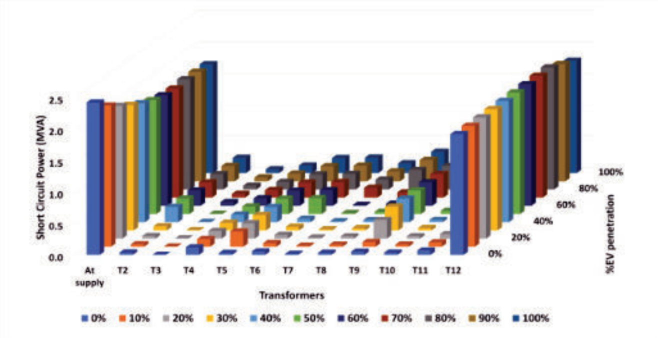


Figure 46. Impact of EV penetration on short-circuit power at different locations in G2V+DG case.

Introduction of EVs also results in distortion of the phase current during fault conditions. Figure 47 shows the phase currents for a LLL fault during 100% EV penetration. The fault occurred at 0.2s and sustained upto 0.25 s. From the figure it can be observed that during the fault period the phase current showed significant distortion. The comparative phase current for the same fault condition for 0% EV penetration is shown in figure 48. The introduction of distortion can be attributed to the non-linear characteristics of the EV load. Similarly, for a single LG fault, the phase currents are shown in figure 49, which also shows high amount for distortion with 100% EV integration.

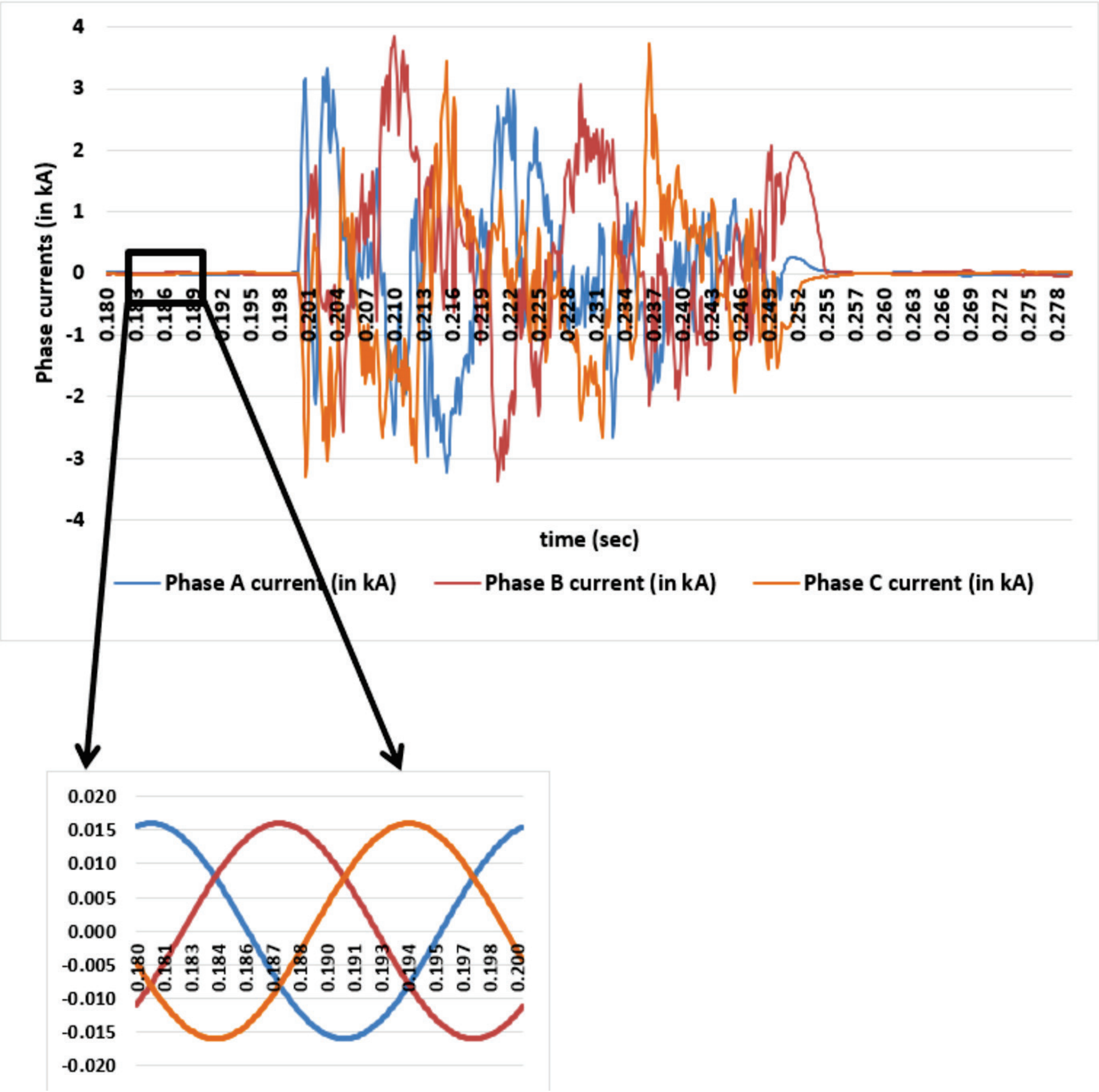


Figure 47. Phase currents during fault condition (LLL) for 100% EV penetration

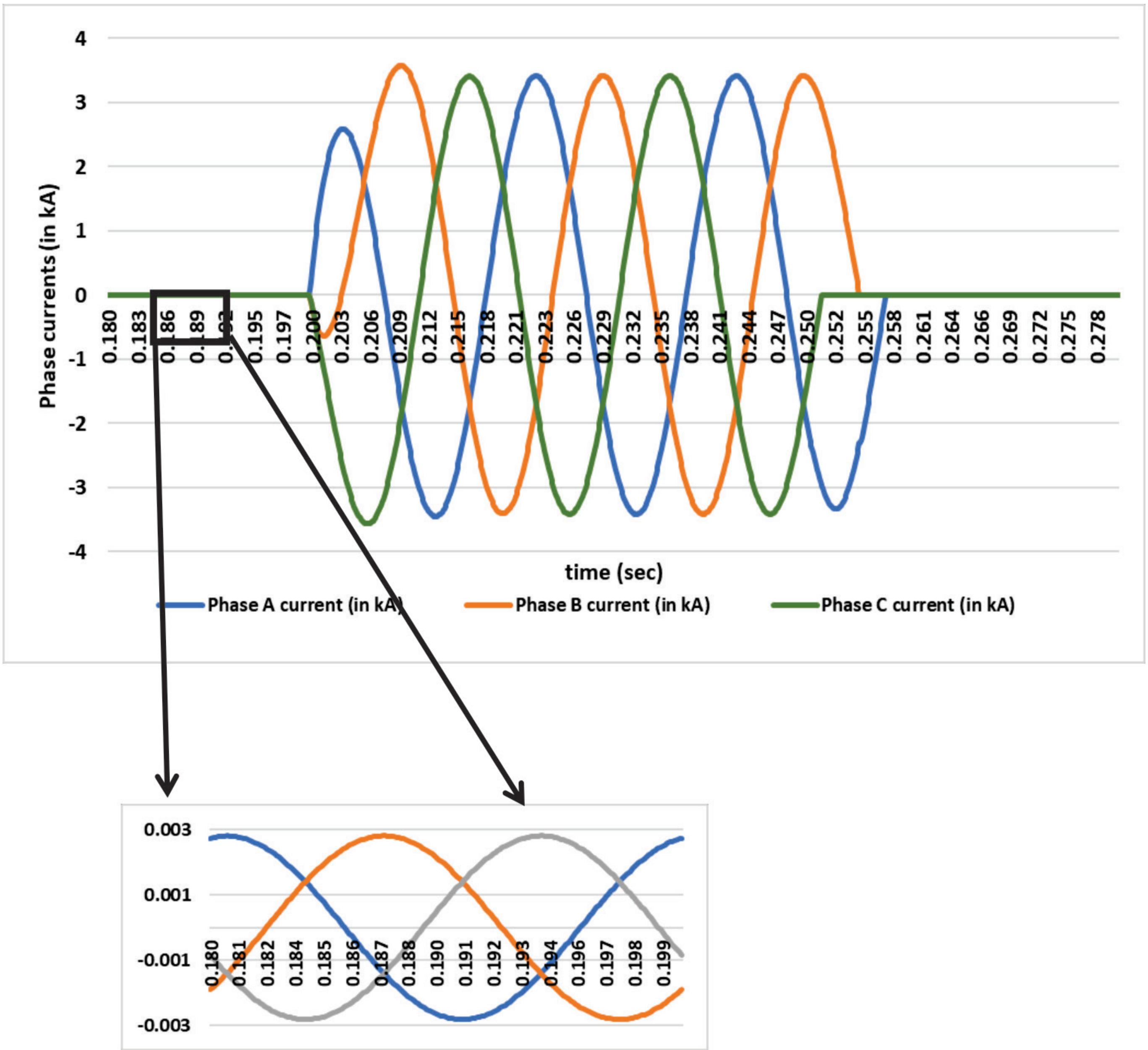
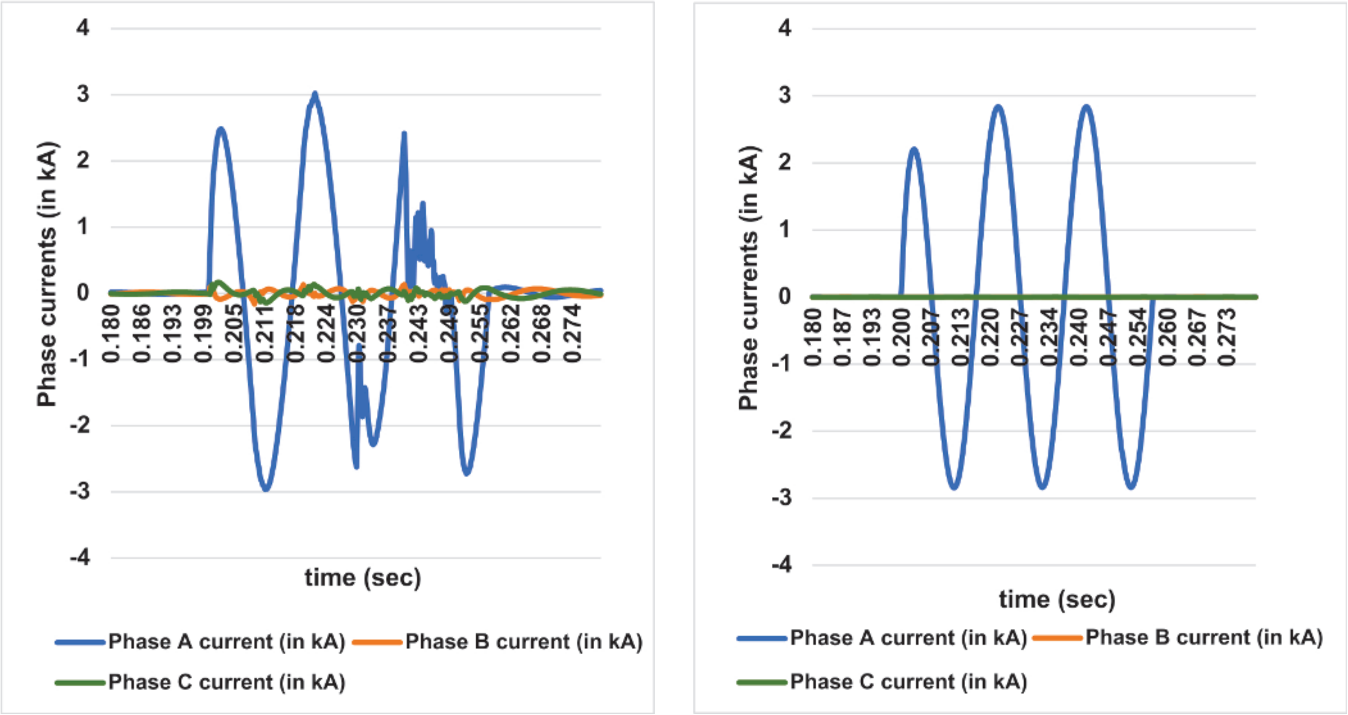


Figure 48. Phase currents during fault condition (LLL) for 0% EV penetration.

It is observed that the percentage increase in short-circuit power and short-circuit current level is 20.24% at Bus 677, 16 % at Bus 189, and 15 % at Bus 830 which are higher than the percentage increase in short-circuit power compared to other Buses. In case of G2V+DG, the order of percentage increase in short-circuit power and short-circuit current level has changed compared to the results obtained in G2V case only. This is due to the contribution of the DGs in the short-circuit power at the faulted bus.



a b

Figure 49. Phase current during fault condition (LG) for (a) 100% EV penetration and (b) 0% EV penetration.

The analysis of different scenarios involving EV charging and integration with led to the following observations:

- G2V case: The integration of EVs in the grid leads to an increase in short-circuit levels at each bus. This is due to the parallel connection of EVs, which reduces fault impedance and consequently increases short-circuit current and power. The magnitude of the short-circuit level varies depending on the number and location of EVs connected to the LV side of transformers.
- G2V+DG Case: The combined integration of EVs and DGs in the grid results in even higher short-circuit power and current levels compared to the G2V case. The impact is influenced by the cumulative contribution of both EVs and DGs to the short-circuit current.
- V2G case: When EVs are operated in V2G mode, they contribute to increased short-circuit levels, even in the absence of DGs connected to the network. The order of impact on short-circuit levels differs from the G2V and G2V+DG cases, with some buses being the most affected buses.
- V2G+DG case: The combined presence of EVs and DGs in the grid leads to the highest shortcircuit power and current levels among all scenarios. Bus 677, Bus 189, and Bus 830 demonstrate the most substantial increase in short-circuit levels.

Overall, the integration of EVs and DGs in the grid has a significant impact on short-circuit levels, with certain buses experiencing higher increases than others. The number and location of EVs and DGs connected to the LV side of transformers play a crucial role in determining the magnitude of short-circuit levels. Protection systems at highly impacted buses should be carefully designed to handle the increased short-circuit currents and powers effectively, ensuring the safety and reliability of the electrical system.

### 3.5.2 EV integration and Protection Coordination Schemes

The study of the impact of the addition of EVCS on the coordination of relays R02, R04, R09, R11 with R1268 is carried out. The representative figure showing the positioning of relays and EVCS is depicted in figure 50 . The EVCS integrated are of two types of rating 350 kW and 450 kW. Each type comprises 100 kW and 50 kW ratings of EV chargers. The EVCS are added on the upstream of primary relays R02, R04, R09, and R11. The secondary relay is coordinated with all four relays. The relay settings before the integration of EVCS are shown in Table 20.

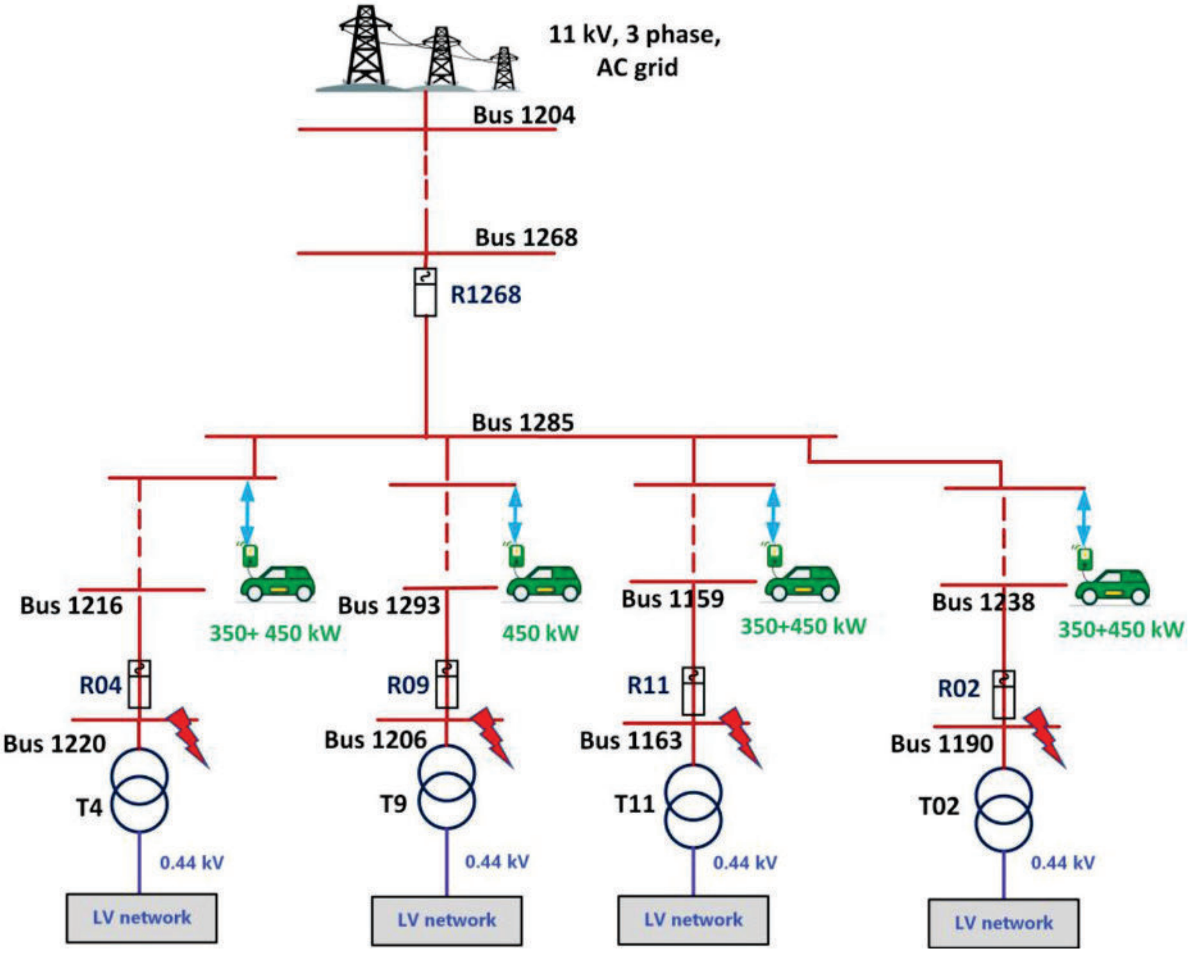


Figure 50. Representative figure showing the positioning of relays and EVCS.

Table 20. Relay coordination settings before integration of EVCS.

| Relay | Pickup current (A) | Maximum fault current (A) | Operating time (s) | TMS |
|---|---|---|---|---|
| R02 | 30.3 | 1064 | 0.190 | 0.1 |
| R04 | 11.1 | 1053 | 0.147 | 0.1 |
| R09 | 66.3 | 1058 | 0.221 | 0.09 |
| R11 | 27.3 | 1063 | 0.184 | 0.1 |
| R1268 | 508.5 | 1308 | 0.521 | 0.07 |

For the study of the coordination of relay R02 with relay R1268, the LLL short-circuit is performed on bus 1220. The time coordination curve (TCC) is plotted to analyze the CTI between the relays, as shown in figure 51. From the figure 51, it can be observed the CTI between R02 and R1268 is 0.315 seconds. As the coordination time is more than 0.3 sec, so there is no impact on the sensitivity of relay coordination. The fault current through the relays and the operating time of relays R02 and R1268 is tabulated in table 20. With the addition of EVCS, it can be observed that the fault currents have increased, and the operating time of relays has reduced as shown in table 20. The CTI is reduced to 0.216 sec which creates coordination issues as the selectivity of relays is impacted.

Similarly, when LLL fault is performed on bus 1220 before EVCS integration, the CTI is 0.315 seconds. With the EVCS integration, the CTI reduces to 0.216 seconds leading to the loss of selectivity among relays R04 and R1268. The TCC for R04 and R1268 coordination before EVCS coordination and after EVCS coordination is shown in figure 52. It can be observed from Fig. 6.6 that, CTI is 0.293 seconds which is acceptable. But with EVCS integration, CTI has reduced significantly from 0.293 seconds to 0.232 seconds as shown in figure 53 , which leads to the loss in relay coordination of

R09 and R1268. Similar observation can be made for relays R11 and R1268. As shown in figure 54a, the CTI before EVCS integration is 0.315 seconds, whereas after EVCS integration the CTI is reduced to 0.229 seconds as depicted in figure 54b.

It can be observed from table 21 that PSI index values for each relay pair are negative. It can be accessed that for PSI<0, operating time is increased which may require a change in protection settings. From table 22 it can be observed that OTI value is 1.24 for R1268. OTI value greater than 1 suggests a reduction in protection performance; therefore, protection settings must be adjusted.

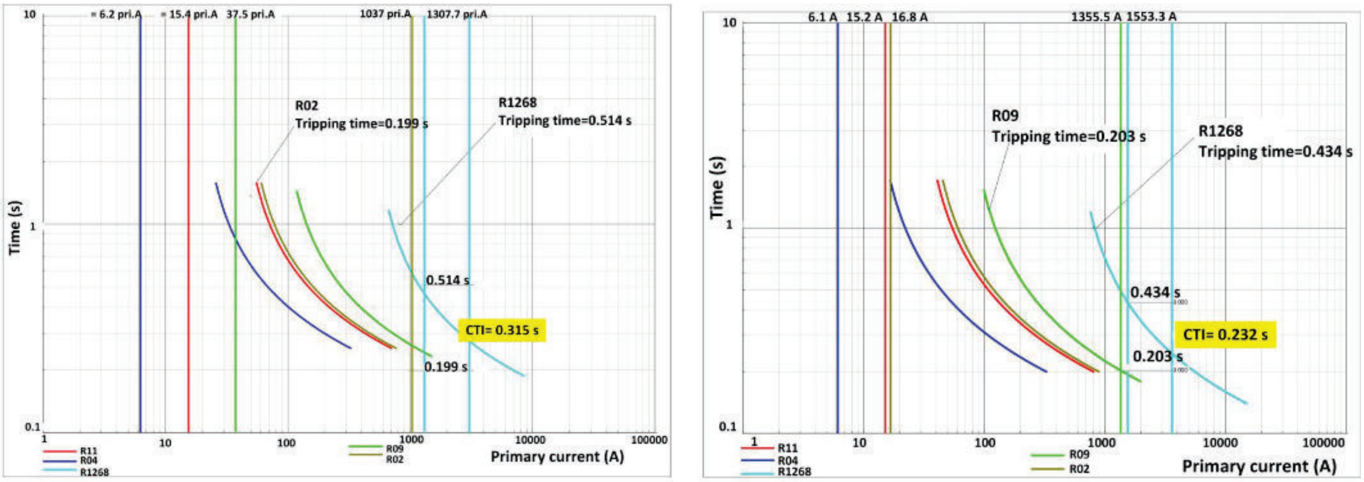
The case study shows the requirement to update the relay settings with the integration of EVCS. A proposed algorithm of an adaptive protection scheme is mentioned in the Chapter 5 to adjust the protection settings of relays with the change in the number of EVCS added to the network.

Table 21. PSI Index

| Relay pairs | Pickup current (A) |
|---|---|
| R02 - R1268 | - 0.177 |
| R04 - R1268 | - 0.184 |
| R09 - R1268 | - 0.156 |
| R11 - R1268 | - 0.165 |

Table 22. OTI Index

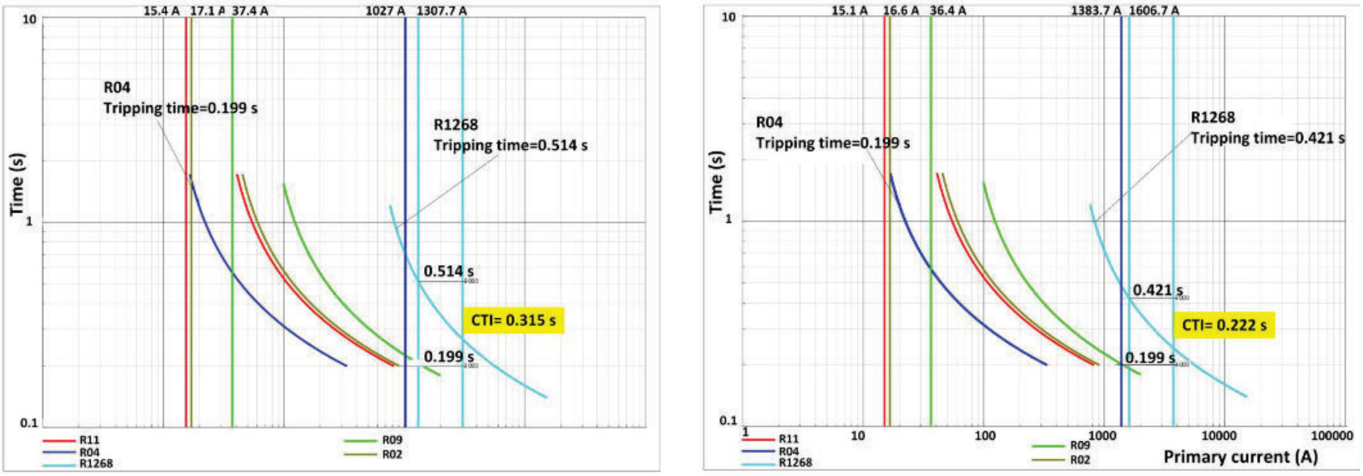
| Relays | V2G mode vs Not connected |
|---|---|
| R02 | 1 |
| R04 | 1 |
| R09 | 1 |
| R1268 | 1.24 |



a

b

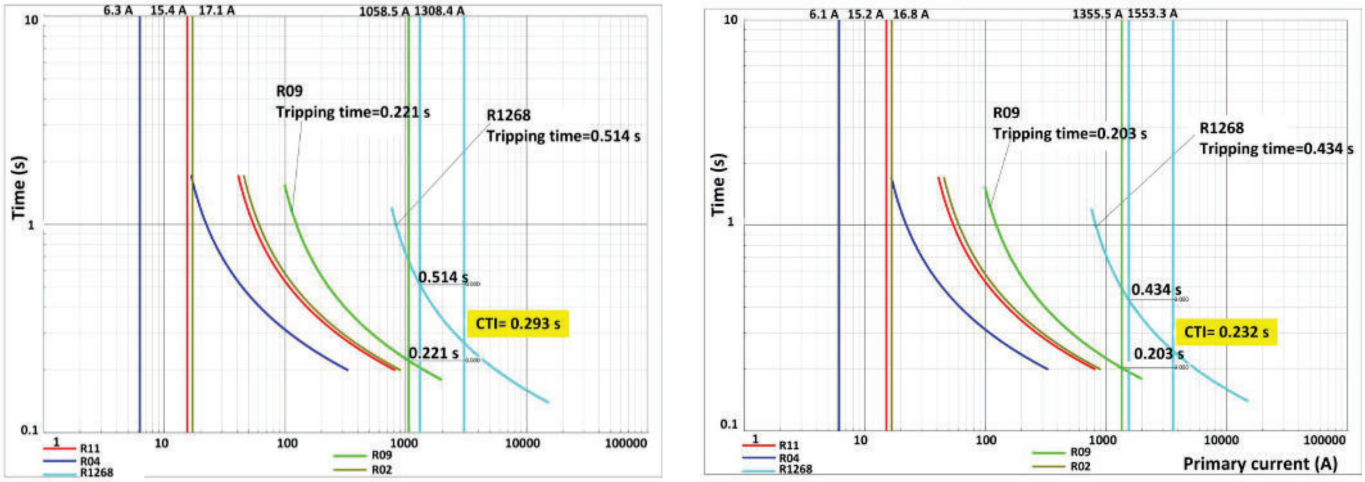
Figure 51. Time Coordination curve of R02-R1268 before (a) and after (b) EVCS integration



a

b

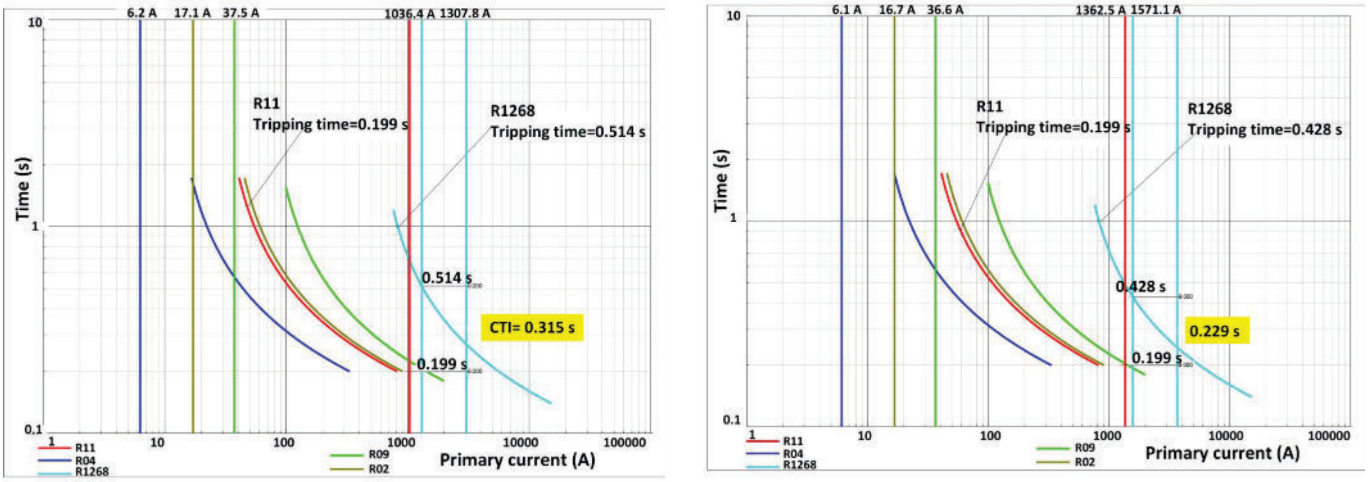
Figure 52. Time Coordination curve of R04-R1268 before (a) and after (b) EVCS integration.



a

b

Figure 53. Time Coordination curve of R09-R1268 before (a) and after (b) EVCS integration.



a

b

Figure 54. Time Coordination curve of R11-R1268 before (a) and after (b) EVCS integration.

# 04 Status quo of Smart charging ecosystem in India: Technical, economic and user perspective

## 4.1 Introduction

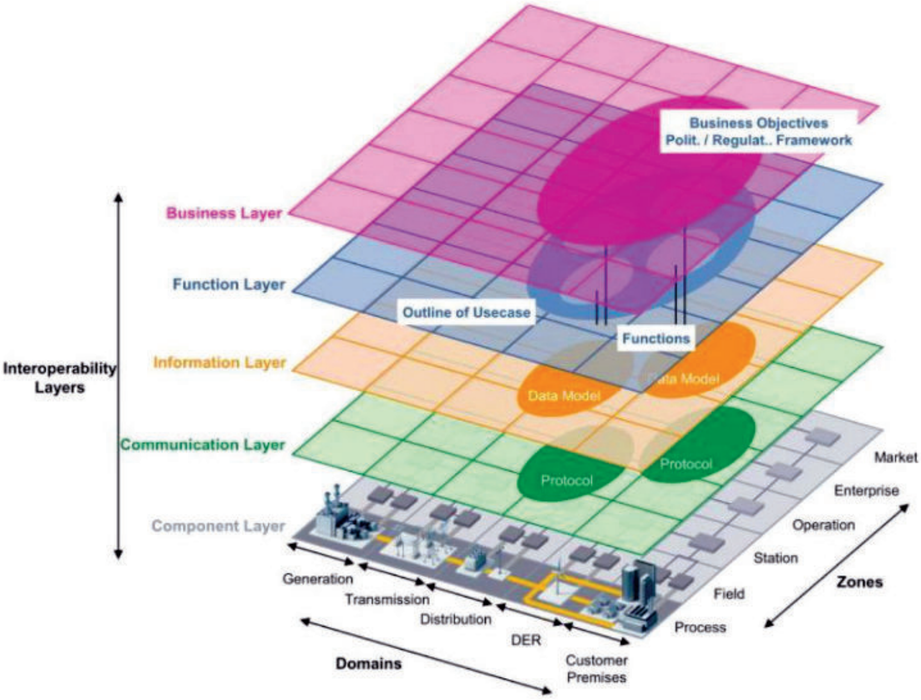


Figure 55. SGAM interoperability layers.

For the adoption of smart charging, the requisite infrastructure needs to be in place. The Smart Grid Architecture Model (SGAM)[7] has been taken as a reference to analyze the requirements for the implementation of smart charging at different layers. SGAM framework presents interrelation between elements over interoperability layer (Business-, Function-, Information-, Communication and Component Layer). Nevertheless, a complete characterization of the SGAM for EV smart charging is will not be provided in this document because the aim of this report is on the recommendations for the implementation of smart charging in India. This chapter provides an overview of the enablers of smart charging using the SGAM framework. For this study, the Business- and Functional layer has been considered under organizational layer, while the Information-, Communication and Component layers are considered under the Technical layer.

## 4.2 Organization layer

The organizational level describes the roles and responsibilities of the different stakeholders and analyzes their interaction. The development of smart charging requires integrated planning with participation from all players. In addition to the e-mobility and power systems sectors, regulatory bodies and EV users also play important roles in the EV smart charging ecosystem.

The smart management of EV charging involves coordination and communication among stakeholders in the e-mobility and energy sectors. Table 23 provides an overview of the most relevant entities, describing their roles and responsibilities in implementing smart charging based on (ISO, 2019; Neaimeh & Andersen, 2020).

Table 23. Overview of stakeholders in EV smart charging ecosystem.

| Abbreviation | Entity | Description |
|---|---|---|
| | Aggregator | Allows small DERs to provide services to the power system Provides flexibility services from the aggregation of EVs |
| CSO | Charging Station Operator | Centrally manages charging stations Determines the charging schedules |

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[7] Tool, S. I. CEN-CENELEC-ETSI Smart Grid Coordination Group.

| Abbreviation | Entity | Description |
|---|---|---|
| DSO | Distribution System Operator | Manages the distribution network Guarantees quality of supply and security |
| EMOCH | e-Mobility Clearing House | Provides roaming services among different EMSPs Mediate between EMSPs and CSOs |
| EMS | Energy Management System | Locally controls generation and demand from DERs<br>Optimizes energy consumption/generation at a location (e.g., house) |
| EMSP | e-Mobility Service Provider | Offers EV charging services to EV users<br>Validates the user and acts as an intermediary with CSO |
| EP | Electricity Provider | Purchases electricity in wholesale market and resales it to its clients Generates flexibility through electricity tariff design |
| EV user | Electric Vehicle user | Influences the charging patterns (e.g., driver, fleet operator, etc.) Provides information about driving needs (e.g., time of availability) |
| OEM | Original Equipment Manufacturer | The company that manufactures the product or component Comply with standards and regulations |
|  | Standards Organization | Develops and publishes publicly available standards Ensures interoperability among different systems |
|  | Regulatory Body | Legally regulate the activity in the EV smart charging ecosystem Defines requirements and ensures its compliance |

### 4.2.1 Function layer

The function layer describes use cases and services that are encompassed within the EV smart charging ecosystem. First, the functionality of smart charging infrastructure is defined. Then, these functionalities are mapped to analyze the relationships among the stakeholders and who is involved in the provision of the different smart charging use cases and services.

This section identifies, classifies, and describes smart charging services and use cases. The European Commission acknowledges (European Commission, 2021) that smart charging is key to achieve a cost-efficient integration of EVs in the electrical power system, given that the flexibility provided by smart charging reduces the necessity for investments in grid infrastructure and facilitates the integration of a higher share of renewable energy generation. In addition, European Commission, 2021 recognizes that the current Directive 2014/94/EU on the deployment of alternative fuels infrastructure vaguely supports the adoption of smart charging and recommends that additional requirements for smart charging infrastructure (e.g., EVSE and communication) are defined to fully enable the deployment of smart charging infrastructure. (Eurocities, 2020) suggests that the UK legislation could be taken as reference for this task. The “Automated and Electric Vehicles Act 2018” (UK Government, 2018) specifies the capabilities of smart charging stations:

- Receiving, processing, and sending information
- Respond to this information (e.g., adjusting current drawn/injected by the EV) to achieve energy efficiency.
- Monitoring and recording energy exchange with the grid.
- Being accessed remotely while complying security requirements

Considering the functionalities of smart charging, they are mapped in Figure 56 according to the stakeholders that take part in the provision of these services.

**Front-end services:** the communication link between the EV and EVSE is used to exchange information during the charging session. In addition, the EVSE can react to information signals by adjusting the current drawn/injected by the EV or updating the charging schedule times. Front-end communication as well as EV and EVSE components enable the following use cases:

- Charging modes: as defined by IEC 61851-1 (IEC, 2017) (e.g., slow or fast charging, AC or DC charging, etc.).
- Bidirectional Power Transfer (BPT): allows for bidirectional exchange (i.e., both consumption and injection) of electrical energy with the grid. This also enables the provision of further flexibility services to the grid (V2G) or home (V2H), given that the EV battery can be used to store energy that could be consumed or injected into the grid if it is required.
- Plug & Charge (PnC): identification mode in ISO 15118-1 (ISO, 2019) where all details of the charging session (e.g., load control, authorization, billing, etc.) are automatically handled with no direct intervention from the EV user.

**Back-end services:** interface between the EVSE and a third-party operator (e.g. CSOs or DSOs) for managing the charging schedules of the EVs.

**CS management:**

- Remote access by CSO.
- Load balancing
- Local smart charging
- Central smart charging
- Reacting to external control signals from third-party operators (e.g., DSO, HEMS).

**Grid management:**

- Demand response
- V2G services
- Pricing signals

EV roaming services: allow EV users to charge at charging stations operated by other entities using the same identification, i.e., electric mobility roaming (ElaadNL, 2016).

EV user services: EV users provide the necessary input data for scheduling the charging sessions (e.g., identification, expected departure time, desired battery SOC at departure, etc.) Besides, EV users are provided with the required data for making an informed decision on when and where to charge their vehicles (e.g., tariffs, availability of CS, etc.). These services are offered through a user interface such as a mobile application or a touchscreen on the CS.

Metering: monitor and record energy exchange of the EV with the grid. Energy measurements are needed for the implementation of most smart charging strategies to discriminate the consumption at different periods of the day. This can be achieved with smart meters.

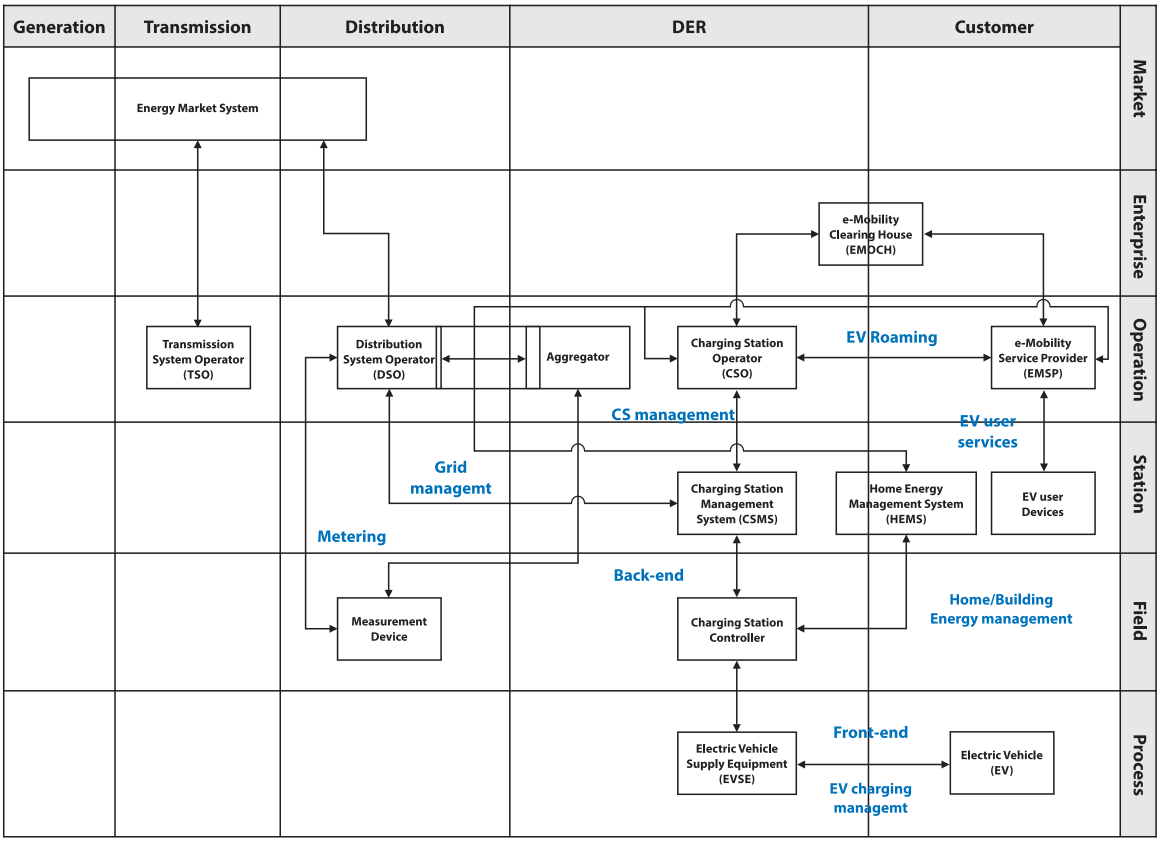

Figure 56. Function layer of smart charging

### 4.2.2 Business layer

The business layer within the Smart Grid Architecture Model (SGAM) serves as a comprehensive framework for integrating business aspects into smart charging ecosystem. It encompasses mapping business objectives, economic considerations, and regulatory constraints, while harmonizing roles and responsibilities across stakeholders. By hosting policies, business models, and use cases relevant to different actors, it facilitates strategic decision-making and managerial tasks. In this study, we look at the Indian states policies and regulations for adoption of EV's and smart charging as well an user behavior in response to pricing mechanisms.

In terms of regulatory constraints, the EV policies of Indian states does not address many aspects that are important for enabling EV smart charging in India. An in-depth analysis of the Indian states EV policies is analyzed from the viewpoint of smart charging can be found in (Rather et al., 2021). The key objectives of the policy guidelines and the tariff structure concerning smart charging of each state are explained in detail in the report "A Critical Review: Smart Charging Strategies and Technologies for Electric Vehicles"[8] . The analysis showed that smart charging ecosystem is limited in India and the smart charging implementation is through pricing mechanism, Time-of-Use. Hence, focus is given to the pricing mechanisms and user response to pricing mechanisms.

Following the selection of 5 smart charging strategies for simulation and reviewing the Indian states' EV policies, the viability of the selected strategies in the current policies of the Indian states is checked. Table 24 summarizes the viability of selected smart charging strategies in the current policies of Indian states (where √: Smart charging strategy is viable in current policies of an Indian state, ~ Smart charging strategy has limited viability in current policies of an Indian state, and × Smart charging strategy is not viable in the current policies of an Indian state).

The table shows that a few states' policies enable the use of smart charging strategy that is based on the Time of Use Tariff since they have ToU pricing mechanisms.

Coordinated EV Charging and Distributed Generation Control in the Distribution Network smart charging strategy has limited viability in a few state's policies. These states' policies encourage the supply of charging stations from locally generated electricity from renewable energy sources. However, to enable this smart charging strategy, a management system is needed to coordinate between the charging station and the local generation, which is not stated in the policies.

The Centralized EV Charging Coordination strategy has limited viability in Delhi policies since it has a central management system. The policies should state proper remuneration for EV owners that will enable the central management of their EVs to charge. No other Indian state has a central management system.

Many of the selected smart charging strategies are not viable in the current policies of most of the states. Therefore, modifications in the policies are required to implement these strategies.

Table 24. Evaluation of the viability of selected smart charging strategies in the current policies of Indian states.

| **Strategies**<br>States | **Centralized CS** | **RIW-VR CS** | **ToU CS** | **Coordinated EV and DG CS** | **Dynamic price CS** |
|---|---|---|---|---|---|
| Delhi | ~ | × | √ | ~ | × |
| Karnataka | × | × | √ | ~ | × |
| Maharashtra | × | × | √ | × | × |
| Andhra Pradesh | × | × | √ | ~ | × |
| Kerala | × | × | √ | × | × |
| Uttar Pradesh | × | × | √ | × | × |
| Gujarat | × | × | × | × | × |
| Tamil Nadu | × | × | × | × | × |

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[8] A Critical Review: Smart Charging Strategies and Technologies for Electric Vehicles: Single-resource - Digital Library on Green Mobility - DLGM (greenmobility-library.org)

| Strategies<br>States | Centralized CS | RIW-VR CS | ToU CS | Coordinated EV and DG CS | Dynamic price CS |
|---|---|---|---|---|---|
| Madhya Pradesh | × | × | ~ | × | × |
| Uttarakhand | × | × | × | × | × |
| Telangana | × | × | √ | ~ | × |
| West Bengal | × | × | × | ~ | × |
| Meghalaya | × | × | × | × | × |
| Punjab | × | × | √ | ~ | × |
| Bihar | × | × | × | × | × |
| Haryana | × | × | × | ~ | × |
| Chandigarh | × | × | × | × | × |
| Odisha | × | × | × | ~ | × |

*Centralized CS: Centralized EV Charging Coordination, RIW-VR CS: Random in window with variable charging rate (RIW-VR), ToU CS: Time of Use Tariff, Coordinated EV and DG CS: Coordinated EV Charging and Distributed Generation Control in the Distribution Network, and Dynamic price CS: Dynamic price-based coordination methods*

**Pricing mechanism**

Among regulatory priorities to achieve smart charging are pricing mechanisms that can influence EV charging patterns shift in both time and space and allow EVs to participate in ancillary service markets [IRENA, 2019]. These price mechanisms can be implemented by different means, and the experience of pilot projects, simulations, and real-world large-scale implementations can help decide which ones of them are a better fit for our case of study.

Demand response is how consumers change and shift the energy loads during certain time intervals by means of exposing them to cost-reflective price signals [IRENA, 2019]. ToU (Time-of-Use) tariffs send price signals to consumers to which they react voluntarily, thus achieving demand response. In ToU tariffs price signals vary in time, according to the power system balance or on short-term wholesale market prices.

A literature review (annexure III.A) summarizes the advantages and drawbacks of the different pricing mechanisms:

- RTP is the most studied pricing mechanism because it is the most advanced form of dynamic pricing, with a high level of time granularity. It allows for the most flexible management of charging. However, the communication infrastructure needs to be very sophisticated, and prices vary enough to raise uncertainty concerns among users.
- TOU (static) tariffs present a good trade-off between predictability and cost-reflectiveness, inducing changing in the charging trends that reduce the peak effectively. However, unified TOU tariffs across the territory can lead to an avalanche effect. The avalanche effect is the phenomenon by which all users switch to the least-costly time frame, therefore creating a new peak.
- CPP is more effective than TOU (avoiding the avalanche effect) because it can divide the demand among the least-costly time frame which is usually much longer than the peak period. However, it is only activated several days a year (normally below 20), which does not create a change in the habits of consumers.
- PTR is the preferred mechanism to avoid overloads during peak periods. Nevertheless, like CPP, it only works several days a year which does not contribute to the overall shift of the demand.

For all the aforementioned reasons, static ToU and RTP tariffs are the ones with the most potential for shifting the demand and creating charging habits that allow for the safe

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[9] CEER Paper on Electricity Distribution Tariffs Supporting the Energy Transition, 2020

and stable operation of the grid. However, CPP and PTR can effectively avoid overloads during rare peak periods.

For a pricing mechanism to be effective, it should comply with a number of criteria. A recent recommendation paper by CEER on distribution tariffs (CEER, 2020) , lists the following criteria:

- Cost-reflective: Tariffs to be paid by the users need to give the appropriate incentives so that future costs can be avoided.
- Non-distortionary: The way DSOs recover costs should not distort decisions that entail losses in access to the network.
- Cost recovery: DSOs are responsible for recovering their own costs by means of tariffs for the use of the distribution system, connection charges and regulated services.
- Non-discriminatory: Avoid discrimination between network users, in terms of where they live or the way they need to use the system.
- Transparency: Different tariffs concepts should be clear to consumers so that they can respond to the demand.
- Predictability: Estimating the cost of the distribution system is key to facilitate efficient long- term investment.
- Simplicity: Responding to the price signals requires understanding from the consumer side, which means that the way tariffs are built should be easy to follow and predict.

It is possible to estimate which price mechanisms respond better to each one of these criteria, which will be discussed later. In general terms, cost-reflectiveness is the one criterium that works against the rest. The more cost-reflective a tariff is, following market trends and short-term changes in price, the least understandable it is for the consumer. These opposition can be seen in Table 25, which depicts an initial evaluation of price mechanisms upon these criteria:

Table 25. Effectiveness criteria for pricing mechanisms.

| | Cost-reflectiveness | Non-discriminatory | Transparency | Predictability | Simplicity | Total score |
|---|---|---|---|---|---|---|
| Flat-rate | 1 | 1 | 1 | 5 | 5 | 13 |
| ToU | 4 | 3 | 3 | 4 | 3 | 17 |
| RTP | 5 | 4 | 4 | 1 | 2 | 16 |
| CPP | 3 | 2 | 3 | 3 | 4 | 15 |
| PTR | 3 | 2 | 3 | 3 | 4 | 15 |

**User Response: Modelling charging behavior**

The response of consumers when they are faced with a TOU tariff depends on the price-demand elasticity of charging. The price elasticity of the demand is defined as the ratio between the percentage change in the quantity demanded (Qd) and the corresponding percent change in price (see Formula 1). A high elasticity will mean that the demand is elastic thus it will suffer great changes when prices fluctuate. This is the case of goods that are easy to replace or avoid, like luxury goods. On the other hand, a low elasticity implies that the demand will remain almost constant even when the price changes. This is the case of goods that are hard to substitute or avoid, like first-need goods or in the case of transport, fuels.

$$\varepsilon = (\delta Q/Q^D)/(\delta P/P^D) \qquad (1)$$

$$\varepsilon = (\delta Q/Q^D)/(\delta P/P^D) \cong (\delta Q P^D)/(\delta P Q^D) \qquad (2)$$

Hence, if the price of charging changes over a period of the day, drivers will adapt their electricity demand by increasing or decreasing their demand in the same period. Given the need to charge the EVs, drivers will often shift their demands towards different periods of the day, as depicted in Figure 57. The amount of shifted demand will depend on the elasticity of consumers and the differences in prices between periods.

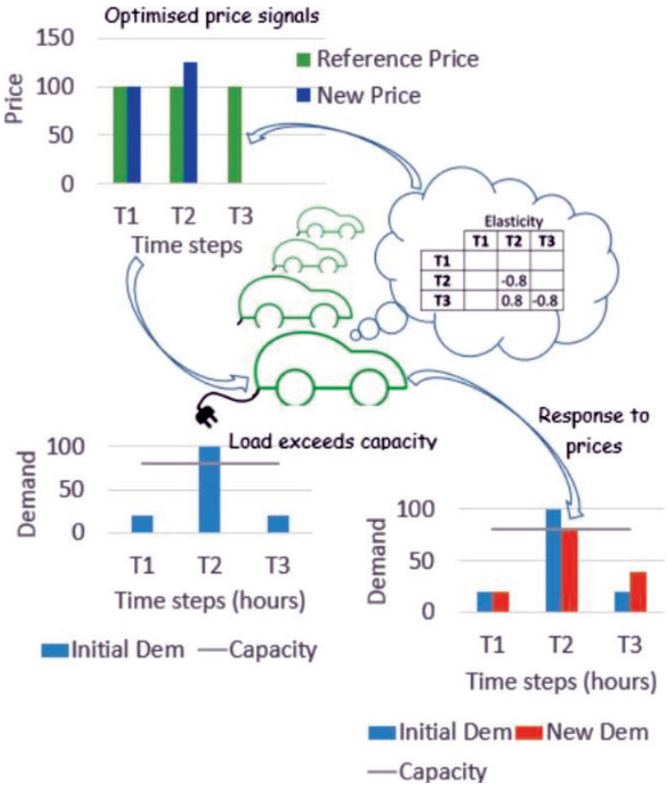


Figure 57. Load shifting between time periods, thanks to ToU tariffs.

A simplified optimization model in order to represent the behavior of agents has been presented in (Bordin etc.al 2021), where parameters are detailed in Figure 58.

$$minimize \sum_{t,h} Q^0_{t,h} - \sum_{t,h} q_{t,h}$$

$$\sum_h q_{t,h} \leq C_t \qquad \forall t : \sum_h Q^0_{t,h} \leq C_t$$

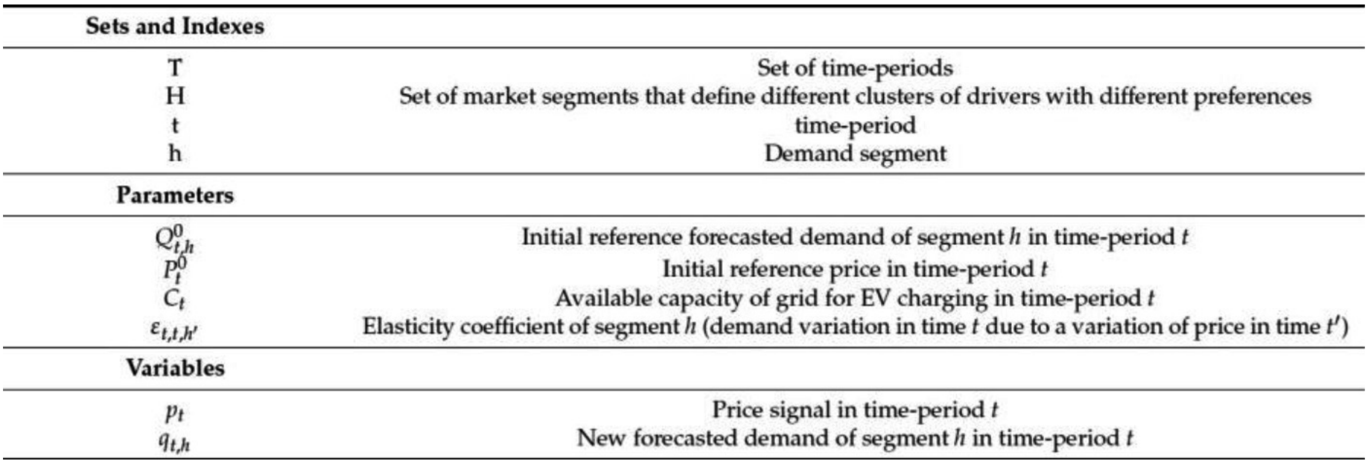
$$\sum_h q_{t,h} = C_t \qquad \forall t : \sum_h Q^0_{t,h} > C_t$$

$$\sum_{t,h} q_{t,h} \leq \sum_{t,h} Q^0_{t,h}$$

$$q_{t,h} = Q^0_{t,h} + \sum_{t'} \frac{Q^0_{t,h}}{P^0_{t'}} \varepsilon_{t,t',h}(p_{t'} - P^0_{t'})$$

$$\forall h, t : \sum_h Q^0_{t,h} > 0$$

Figure 58. Optimization model, consumer behaviour facing ToU. . [Bordin et.al, 2021]



| Sets and Indexes | |
|---|---|
| T | Set of time-periods |
| H | Set of market segments that define different clusters of drivers with different preferences |
| t | time-period |
| h | Demand segment |
| **Parameters** | |
| $Q^0_{t,h}$ | Initial reference forecasted demand of segment $h$ in time-period $t$ |
| $P^0_t$ | Initial reference price in time-period $t$ |
| $C_t$ | Available capacity of grid for EV charging in time-period $t$ |
| $\varepsilon_{t,t,h'}$ | Elasticity coefficient of segment $h$ (demand variation in time $t$ due to a variation of price in time $t'$) |
| **Variables** | |
| $p_t$ | Price signal in time-period $t$ |
| $q_{t,h}$ | New forecasted demand of segment $h$ in time-period $t$ |

Figure 59. Optimization model parameters.

In 7, this model sweeps different price elasticities of the consumers as it is normally

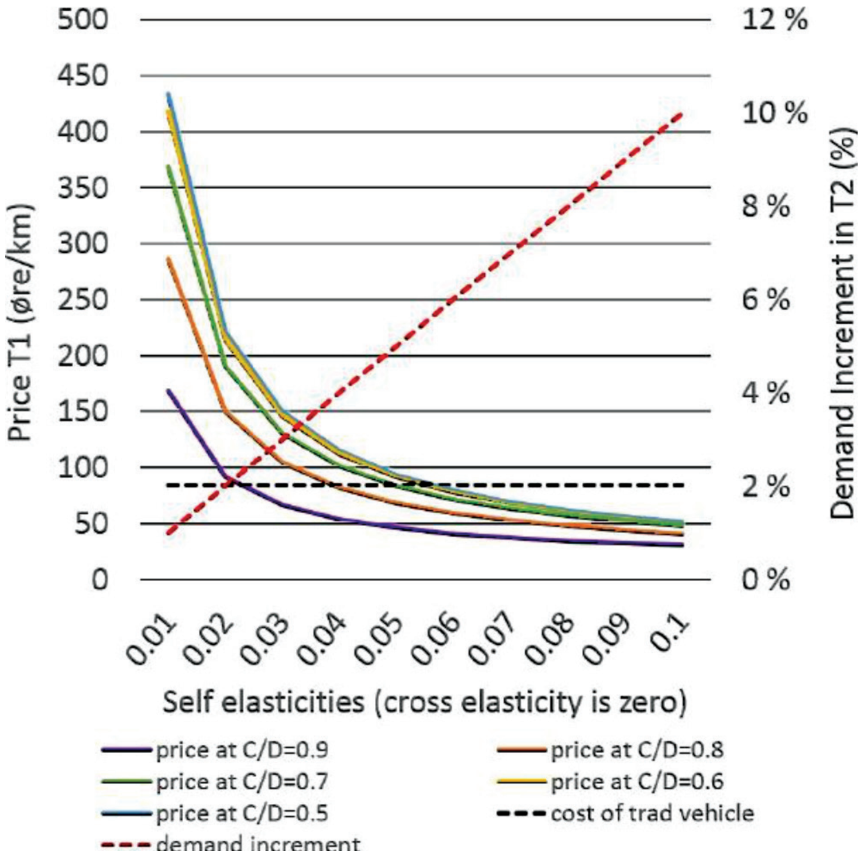


Figure 60. Incentives needed to shift charging demand from period T1 to T2, under the effect of different price elasticities considered. . [Bordin e.al, 2021]

unknown parameter. If we have two charging periods (T1 and T2), in which the demand in T1 is desired to shift towards T2 (the demand in T2 is originally lower), the price elasticities of the demand will determine the minimum amount of the incentive to actually move the demand forward. We can see how an increasing elasticity involves a lower incentive amount (in Norwegian krone, 100 øre = 1 NOK) for a given C/D relationship (Capacity over Demand). The C/D ratio refers to the amount of demand to be shifted. The horizontal dotted line (cost of trad vehicle) represents the cost per km of a conventional ICE car, to see the minimum elasticity from which the EV is competitive (in this case, around 0.05).

In brattle group, 2017, different consumer elasticities are considered as well, and the higher the elasticity of the demand, the more the TOU tariffs can shift the demand flattening the peak and reducing the cost of charging. In Figure 61, we can see how an inelastic demand wouldn't be affected by price mechanisms, while a higher demand shifts the peak towards the cheapest hours during the night.

Price mechanisms can have multiple outcomes depending on the consumers and on the type of demand they are affecting. For that reason, designing the right regulatory mechanisms needs the understanding and quantification of the perceived cost of charging by consumers. The way these prices mechanisms reach are presented, and the amount of the incentives will determine their effectiveness. However, billing more than necessary will not just shift the demand but discourage drivers in the purchase of EVs or even to follow price signals by acquiring fixed-cost subscriptions, which would jeopardize the goal of price mechanisms as a whole.

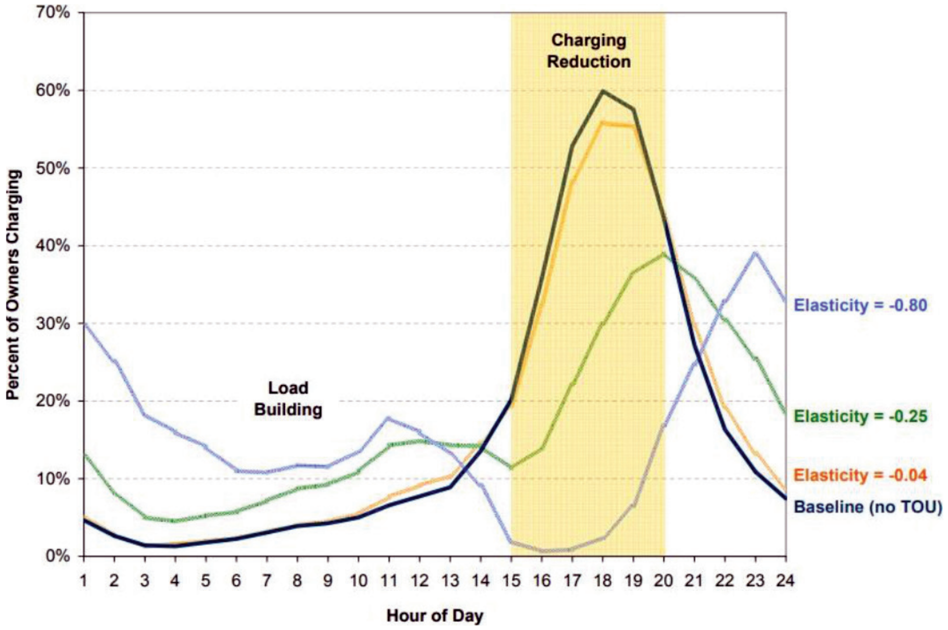


Figure 61. Influence of price elasticity of the demand on the potential of TOU tariffs to shift charging during the day. Source: The Brattle Group 2017

**Price-elasticity estimates**

As mentioned above, the elasticity of consumers is a parameter that is hard to obtain and estimate. It is highly dependent on socio-economic features and not easily generalized for a population. Studies can differ giving values within very different orders of magnitude. In Labandeira et. Al, 2017, they have estimated generalized values of elasticity from a meta-analysis and established a correlation with the main difference drivers:

- Type of energy product: Electricity, natural gas, car fuels, etc.
- Type of consumer: Residential, Industrial, Commercial
- Country: Net energy importer/exporter, developed/developing
- Other features related to data collection.

Although different ways of gathering the data can lead to different elasticity values, they are all within the same order of magnitude and relate well with the hypothesis of elasticity. In the short-term, it is harder to change demand habits, while consumers present a higher elasticity in the long-term. Also, electricity demand has a higher elasticity than other energy products like car fuels or natural gas.

Table 26. Average elasticities for the different energy goods.

| | Average elasticity | |
|---|---|---|
| **Good** | **Short term** | **Long term** |
| Energy (general) | -0.201-0.149 | -0.572 |
| Electricity | -0.201 | -0.513 |
| Natural gas | -0.184 | -0.568 |
| Car fuels | -0.180 | -0.372 |
| Gasoline | -0.195 | 0.526 |
| Diesel | -0.157 | -0.391 |
| Heating oil | -0.188 | -0.535 |

Enabling technologies for implementing price mechanisms in smart charging

The Danish EV Alliance and DTU recommend three specification requirements for EV chargers to enable smart charging (Dansk, 2020):

1. Charger communication must be through open standard while the data and the communication must be protected through cyber-security.

2. Charger controls must be fast responsive and able to adjust power exchange at higher granularity than ON/OFF.

3. Charger data must be accessible for operational management, and for later settlement to reward EV owners that delivers flexibility to the electricity grid.

Summing up technology requirements to send price signals to the EV users, we can divide into:

Table 27. Minimum enabling technology requirements to send price signals to the EV users. . [Bhagwat et al., 2019]

| | Solutions | Minimum enabling technology |
|---|---|---|
| Energy tariff | Time of day tariff | Smart meter |
| | Real-time pricing | Smart meter and smart charger |
| Demand charges | Time-varying demand charges | Smart meter |

The recommendations from the Danish EV Alliance are further supported in (Dansk, 2020) by a valuation of smart charging divided into three control mechanisms enabled by the charger requirements listed above.

- Consumer control Multiple chargers that share a point of common coupling to the electricity grid share the available capacity. The charging power of each charger depends on the number of chargers in use. The distribution of available capacity across the chargers can be balanced or can depend on the EV conditions, e.g. the relative state of charge,
- Energy control If chargers are included in local energy management, these can be controlled ac- cording to other local resources and flexible consumption. Such control can minimize the power exchange with the electricity grid by maximizing the use of local resources.
- Aggregation An aggregation of an EV fleet, not limited by the geographic location, can be controlled by a third party to support the operation of the electricity grid through provision of ancillary services in exchange of profit.

## 4.3 Technical layer

The transition to electric mobility introduces new challenges for the electricity sector such as an increasing and volatile demand on distribution grids. Smart charging introduces synergies among both sectors, mobility, and electricity, to reduce the impact of EV charging on the grid. The implementation of smart charging strategies requires that ICT systems are integrated in EVs and charging infrastructure to enable smart energy management and the interaction among several systems and stakeholders (e.g., EV user's, CSOs, DSOs, etc.). The technical layer includes the information-, communication-, and component layer. Detailed analyses of the technical layer have been conducted in the Fundamentals of Electric Vehicle Charging Technology and its Grid Integration report[10] and hence will not be included in this section. A cost analysis is carried out to determine which of the commercially available chargers in the Indian market would be more suitable for implementing the proposed smart charging strategies.

Information layer: The information layer maps the information flow and represents the information objects and common semantics that enable interoperability and information exchange among the different devices and stakeholders (Kirpes et al., 2019). Information protocols in the EV smart charging ecosystem can be divided into front-end, back-end and roaming protocols (Neaimeh & Andersen, 2020). While front-end protocols are used to exchange information between the EV and EVSE, back-end protocols define the interface between the EVSE and a third-party operator (e.g., CSOs or DSOs). The latter allow EV users to charge at charging stations operated by other entities using the same identification, i.e., electric mobility roaming (ElaadNL, 2016).

Communication layer: For utilizing smart charging, and for provision of billing and roaming facilities etc., communication among the different EV stakeholders is vital. These communications include communication between EV and EVSE, EVSE and CPO, CPO and CMS, CPO with DSO, etc. For each different communication layer different communication protocols have been developed, with each protocol having its own set of functionalities. For example, there is a separate protocol that takes care of billing of the user based on the time the vehicle plugged in, the time the vehicle plugged out, the energy consumed, as well as the electricity tariff; similarly, there is a different communication protocol to enable demand response in EV charging.

Component layer: The component layer comprises all the physical components (e.g., equipment, infrastructure, or hardware) that are necessary to implement the functionality of the smart charging strategies.

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[10] Single-resource - Digital Library on Green Mobility - DLGM (greenmobility-library.org)

Table 28. Summary of technical requirements for each level of smart charging.

| | | Level 0 Uncontrolled charging | Level 1 V1G Controlled charging | Level 2 V1G/H Cooperative charging | Level 3 V2H/V2B Bidirectional charging | Level 4 V2G Aggregated (bidirectional) charging |
|---|---|---|---|---|---|---|
| Description | | Compliant with local regulations, safety standard, grid codes | Remote on/off control Variable charging power Centralized control | Third parties (e.g., DSO, HEMS), EV-EVSE negotiation, Automatic authorization | Bidirectional power transfer Behind the meter applications Integration in HEMS (e.g., PV) | Bidirectional power transfer Ancillary services (e.g., frequency regulation) |
| Mode | | Mode 1 (AC) | Modes 3 (AC) & 4 (DC) | Modes 3 (AC) & 4 (DC) | Modes 3 (AC)* & 4 (DC) | Modes 3 (AC)* & 4 (DC) |
| Connectors | | IEC 60309 | IEC 62196: Types 1 & 2 | IEC 62196: CCS | IEC 62196: CCS | IEC 62196: CCS |
| Communication | | | PWM (Networked) | PLC Networked | PLC Networked | PLC Networked |
| Protocols | Front-end | | IEC 61851, DIN SPEC 70121 | ISO 15118-2 (Ed.1) | ISO 15118-20 (Ed.2) | ISO 15118-20 (Ed.2) |
| | Back-end | | OCPP 1.6 | OCPP 2.0, IEC 63110, IEC 61850, OSCP, OpenADR, IEEE 2030.5 | OCPP 2.X, IEC 63110, EEBus, IEEE 2030.5, | OCPP 2.X, IEC 63110, (EEBus), IEEE 2030.5, |
| | Roaming | | OCPI, eMIP, OCHP, OICP, IEC 63119 | OCPI, eMIP, OCHP, OICP, IEC 63119 | | |
| | Maturity | High | Partial market deployment | Partial market deployment | Advanced testing | Advanced testing |

** AC bidirectional power transfer is also allowed in ISO 15118-20, but the on-board charger would have to be able to operate under different grid codes.*

## 4.4 Economic analysis

In this section, the cost and smart charging features for a selection of commercially available chargers in India are compared to determine which type of EV charger would be the most suitable for the roll out of new smart chargers in India. A summary of the cost and characteristics for each model are provided in Table 28. Besides, the selected chargers from the Indian market have been classified according to the type of charger (Table 29):

**AC Light EV:** AC normal power charger with IEC 60309 connector (BEVC-AC001 standard).

**DC Light EV:** DC normal power charger with GB/T 20234.3 connector (BEVC- DC001 standard) and front-end communication based on IEC 61851-24B (CAN bus).

**AC Parkbay:** AC normal power (22 kW) charger with Type 2 connector and front- end communication.

**DC Parkbay:** DC normal power charger with CCS and/or CHAdeMO connectors and front-end communication.

**DC Charging station:** DC high power charging station with CCS and/or CHAdeMO connectors and front-end communication.

However, in Table 28 some AC chargers have not been assigned to any of the categories defined in Annexure III of (MoP, 2022). These chargers, which have been grouped under the type “Other AC chargers”, are AC chargers equipped with an IEC 62196-2 Type 2 connector and have a single-phase connection with an output power of 3.3 or 7.4 kW. Thus, they have not been considered as “AC Parkbay” chargers, given that PCS with a Type 2 connector should have a 22 kW power output according to Annexure II in (MoP, 2022) and that (DST, 2021) specifies that “AC Parkbay” chargers have a 3-phase connection. Besides, they have not been classified as “AC Light EV” since they have different connectors and a physical communication link between the EV and the EVSE.

Furthermore, each charger in Table 28 has been assigned to the levels of smartness, which were defined in Section 2.2, according to the following criteria:

Level 0. No communication between EV and EVSE, mainly due to the use of the three-pin IEC 60309 connector as part of the BEVC-AC001 standard. In addition, chargers lacking proper back-end communication, i.e., non- networked or OCPP version 1.5 which does not include smart charging support.

Level 1. Chargers with communication between EV and EVSE (PWM as per IEC 61851-1 for Type 2 and CCS or CAN for CHAdeMO and GB/T 20234.3 connectors). Besides, all these chargers are networked and use OCPP version 1.6 for back-end communication with the CSO.

Level 2. Chargers that provide support for ISO 15118 (including PnC) and can be upgraded to OCPP 2.0.

Table 29. Classification of commercially available EV chargers in India.

| Manufacturer | Model | Type no. | Power [kW] | Connector | Level Smart. | Cost |
|---|---|---|---|---|---|---|
| Amplify Mobility | BHARAT AC 001 | 1 | 3,3 | IEC 60309 | 0 | ₹42.500 |
| TVESAS Electric | BHARAT AC- 001 | 1 | 3,3 | IEC 60309 | 0 | ₹44.000 |
| Evlion Technologies | Bharat AC001 | 1 | 3,3 | IEC 60309 | 0 | ₹50.000 |
| Verde mobility | Bharat AC 001 | 1 | 3,3 | IEC 60309 | 0 | ₹51.750 |
| Okaya Power | Bharat AC EV Charger | 1 | 3,3 | IEC 60309 | 0 | ₹55.000 |
| Magenta power | Charge grid Ulta AC 001 | 1 | 3,3 | IEC 60309 | 0 | ₹63.200 |
| Uznaka Solutions | TRONX-AC001 | 1 | 3,3 | IEC 60309 | 0 | ₹70.000 |
| Exicom | BHARAT EV /15kW/20kW | 2 | 15 | GB/T 20234.3 | 1 | ₹130.000 |
| Delta India | DC001 Bharat Charger | 2 | 15 | GB/T 20234.3 | 1 | ₹200.000 |
| Okaya Power | Bharat DC EV Charger | 2 | 15 | GB/T 20234.3 | 1 | ₹230.000 |
| Evlion Technologies | Bharat DC 001 | 2 | 15 | GB/T 20234.3 | 1 | ₹300.000 |
| EVFast | EVFAST LiteAC Charger | * | 3,3 | Type 2 | 0 | ₹29.500 |
| Magenta power | Charge grid Polo | * | 7,4 | Type 2 | 1 | ₹48.000 |
| Exicom | Type-2 AC Charger (Compact) | * | 3,3 | Type 2 | 1 | ₹48.900 |
| TVESAS Electric | Type 2 | * | 7,4 | Type 2 | 1 | ₹59.000 |
| Axonify | Atom AC Wallbox | * | 7,2 | Type 2 | 1 | ₹59.000 |
| Exicom | Type-2 AC Charger | * | 7,4 | Type 2 | 1 | ₹65.000 |
| ABB India | Terra AC wallbox | * | 7,4 | Type 2 | 1 | ₹69.000 |

| Manufacturer | Model | Type no. | Power [kW] | Connector | Level Smart. | Cost |
|---|---|---|---|---|---|---|
| Okaya Power | AC Wallbox Charger | * | 7,4 | Type 2 | 1 | ₹75.000 |
| Uznaka Solutions | AC Wall-box | * | 3,3 | Type 2 | 0 | ₹80.000 |
| Verde mobility | Single Gun AC Charger | * | 7,4 | Type 2 | 1 | ₹80.000 |
| Delta India | AC Mini plus | * | 7,4 | Type 2 | 1 | ₹89.200 |
| Brightblu | Jolt | 3 | 22 | Type 2 | 1 | ₹100.000 |
| Okaya Power | AC Wallbox Charger | 3 | 22 | Type 2 | 1 | ₹100.000 |
| Verde mobility | AC dual gun | 3 | 22 | Type 2 | 1 | ₹125.000 |
| Delta India | AC Max | 3 | 22 | Type 2 | 2 | ₹130.000 |
| ABB India | Terra AC wallbox | 3 | 22 | Type 2 | 1 | ₹130.000 |
| RRT Electro Power | DC Wallbox | 4 | 25 | CCS, CHAdeMO | 1 | ₹590.000 |
| Okaya Power | DC Wallbox Charger | 4 | 20 | CCS, CHAdeMO | 1 | ₹700.000 |
| Uznaka Solutions | DC Wall-box | 4 | 24 | CCS, CHAdeMO | 1 | ₹800.000 |
| ABB India | Terra DC wallbox | 4 | 22 | CCS, CHAdeMO | 2 | ₹850.000 |
| Okaya Power | Single Gun Quick DC Charger | 4 | 40 | CCS, CHAdeMO | 1 | ₹1.100.000 |
| Delta India | DC City Charger | 5 | 50 | CCS | 2 | ₹1.120.000 |
| Delta India | DC Quick EV charger | 5 | 150 | CCS, CHAdeMO | 1 | ₹1.955.000 |
| ABB India | Terra 54 DC fast charger | 5 | 50 | CCS, CHAdeMO | 2 | ₹2.000.000 |

** Other AC chargers: 3.3/7 kW and Type 2 connector.*

The cost of commercially available chargers in the Indian market has been studied in Figure 62 based on the data provided in table 29. From this analysis, it can be concluded that the key drivers for EVSE cost are the rated power output, the location of the power converter and the additional equipment required for managing the charging event. For instance, the cost of a 22 kW AC charger from ABB is 88% greater than a 7 kW charger from the same manufacturer. Moreover, the cost of ABB's 22 kW DC charger is 6.5 times higher than their AC charger with an equivalent power output.

The cost analysis of commercially available chargers in India performed in Figure 62, reveals that the most economical chargers are type 1 "AC light EV" chargers. However, they are not capable of smart charging since they lack a communication link with the EV. Although uncontrolled charging (denoted as Level 0) is only used in slow AC charging, there are other slow AC chargers with support for Level 1 smart charging functionality that are commercially available in the market. These chargers have an EV-specific connector, usually a Type 2 connector, which has a physical communication link with the EV that allows the CS to control the charging power and start/stop the charging event. As aforementioned, these chargers were classified as

"Other AC chargers" since they have a monophasic 3.3/7kW connection while type 3 "AC Parkbay" chargers have a 3-phase 11/22kW connection. Even though Figure 62 illustrates that chargers following the BEVC-AC001 Indian standard have a similar cost as the ones grouped under "Other AC chargers", BEVC-AC001 chargers can charge 3 EVs at the same time while latter only have one charging gun. Therefore, there is an additional cost associated to the hardware required for controlling the charging event.

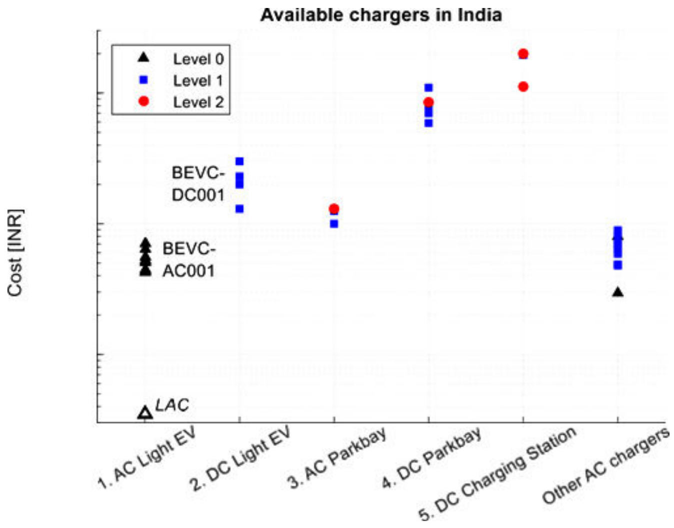


Figure 62. Cost analysis of commercially available chargers in India based on the type of charging point and level of smartness.

Regarding the communication standards, OCPP 1.6 de-facto standard for CS management in India. Several manufacturers state that their chargers can be upgraded to newer versions of OCPP, including OCPP 2.0. In addition, the sample of chargers that support ISO 15118 is small, but its adoption seems to be greater among high power CSs. This could be because high power CSs are usually intended for public use where its users could benefit more from the PnC functionality introduced in ISO 15118.

**Retrofitting of existing EV chargers**

In Europe and the USA, which have more mature EV markets, most of the new installed CSs already include support for smart charging technologies. For instance, the partner entities of the Living Lab Smart Charging in the Netherlands agreed that new PCSs must have smart charging functionalities, while older stations should progressively be retrofitted to be smart (IRENA, 2019).

Retrofitting "dumb" charging stations to support smart charging, could be considered as an alternative to the installation of new smart chargers. The main advantage of retrofitting would be a reduction of installation costs from utilizing existing physical locations and grid connection equipment. Installation costs are a significant portion of the upfront investment costs, comprising up to an additional 80% of the EVSE hardware costs (LaMonaca & Ryan, 2022).

The new components which would be required to transform an existing CS into a smart charger are:

**EV-specific connector** with dedicated communication pins to establish a physical commination link between the EV and EVSE (e.g., IEC 62196-2 or IEC 62196-3). This is the main issue that many "dumb" chargers such as the BEVC-AC001 face since they use a 3-pin industrial plug (IEC 60309).

**Back-end communication:** the charger should be networked (e.g., Ethernet, WiFi, 4G, etc.) and support OCPP 1.6 (or higher versions) to allow for remote management of the CS by the CSO and smart charging use cases.

**Charge controller** that can exchange information with the EV and CSMS and react to it by starting/stopping the charge event and regulating the current drawn by the EV.

Nevertheless, no details have been found on how retrofitting of older CSs is carried out in the Netherlands. Hence, the profitability of adding the required components and communication for smart charging to existing chargers should be assessed. Moreover, the number of existing PCSs in India, 934 in 2020 (CEEW, 2022), is small compared to the Netherlands, over 60000 in 2020 (Statista, 2021). This raises the question of whether the size of a potential market for retrofitting old CSs would of interest for any manufacturers of EVSE equipment.

## 4.5 Application of pricing mechanisms in India

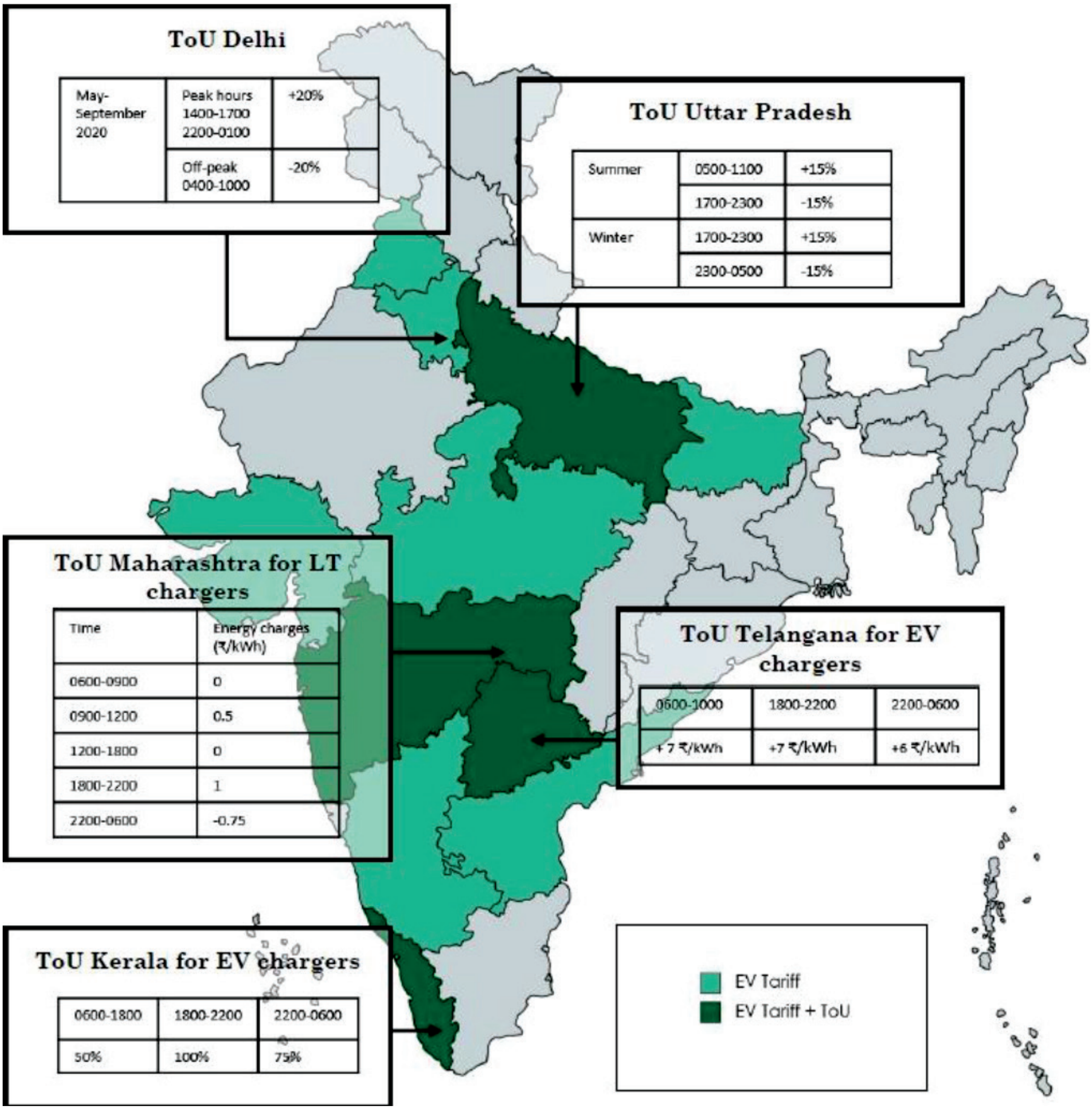
Having reviewed the international context of dynamic tariffs for EV charging and the principles of consumer demand response, it is now possible to assess the potential to influence smart charging in India.

### 4.5.1 Technology readiness in India

At the time of writing this report, the availability of smart meters in India is around 9% for consumers both between 200 and 500 kWh, and those above 500 kWh (MOP, Parameter Dashboard). The lack of smart metering can block progress towards sending price signals to the consumers. Nonetheless, the Indian Central Electricity Authority (CEA) established in 2016 the functionality requirements of Advanced Metering Infrastructure (AMI) (CEA 2016) and is already in deployment. This infrastructure enumerates a number of features, like: head-end system, meter data management system, web application update online data of consumer, and mobile app.

### 4.5.2 Electricity tariff regulatory framework in India

Although TOD tariffs are already practiced in India (Bhagwat et al., 2019), price signals are not as strong. Figure 63 summarized the TOD implemented by state (IIT Bombay et al. ,2021) (Pillai et al., 2019). States colored in light green correspond to those who have implemented specific electricity tariffs for EVs, and those colored in dark red the ones that have also adopted ToU tariffs applicable to the charging of EVs. States colored in light green correspond to those tariffs applicable to the charging of EVs.applicable to the charging of EVs.



**ToU Delhi**

| | | |
|---|---|---|
| May-September 2020 | Peak hours 1400-1700 2200-0100 | +20% |
| | Off-peak 0400-1000 | -20% |

**ToU Uttar Pradesh**

| | | |
|---|---|---|
| Summer | 0500-1100 | +15% |
| | 1700-2300 | -15% |
| Winter | 1700-2300 | +15% |
| | 2300-0500 | -15% |

**ToU Maharashtra for LT chargers**

| Time | Energy charges (₹/kWh) |
|---|---|
| 0600-0900 | 0 |
| 0900-1200 | 0.5 |
| 1200-1800 | 0 |
| 1800-2200 | 1 |
| 2200-0600 | -0.75 |

**ToU Telangana for EV chargers**

| 0600-1000 | 1800-2200 | 2200-0600 |
|---|---|---|
| +7 ₹/kWh | +7 ₹/kWh | +6 ₹/kWh |

**ToU Kerala for EV chargers**

| 0600-1800 | 1800-2200 | 2200-0600 |
|---|---|---|
| 50% | 100% | 75% |

Figure 63. ToU tariffs in the different states of India. Source: Self-elaboration.

### 4.5.3 ToU tariffs potential in India

The current ToU tariffs have, most surely, already shifted part of the demand from the peak hours to least-costly time periods. To evaluate the changes that these policies can have entailed, we have applied the methodology detailed in Section 3.

Table 30. ToU tariffs in India

| | Normal energy charges (Rps/ kWh) | Peak time price | Second peak price | Off-Peak price |
|---|---|---|---|---|
| Delhi | 4.5 | +20% | | -20% |
| Maharashtra | 5.06 | +1 | +0.5 | -0.75 |
| Kerala | 4.5 | * 100% | * 75% | * 50% |
| Uttar Pradesh | 5.9 | +15% | | -15% |
| Telangana | 6 | +1 | +1 | 0 |

First, we have calculated the load shift incentivized by these ToU tariffs in each of the states in which they currently in place. The state with the highest load shift rate is Delhi. The reason for Delhi to be ahead of the other states in load shifting could be the higher differnce between periods (20% with normal rates). Please note that these simulations use the short-term value of electricity demand elasticity, -0.201.

Table 31. Load shifting potential under the current ToU tariffs in the different states of India.

| | Load shifting (from Peak to others) |
|---|---|
| Delhi | 2.01% |
| Maharashtra | 0.50% |
| Kerala | 7.54% |
| Uttar Pradesh | 1.51% |
| Telangana | 1.68% |

In order to test whether higher differences in prices between periods can lead to a stronger shift, we have established a peak/off-peak coefficient relating both prices. With respect to this coefficient, two cases have been simulated, one for the short-term (less elastic) demand, and another for the long-term (more elastic) demand of electricity.

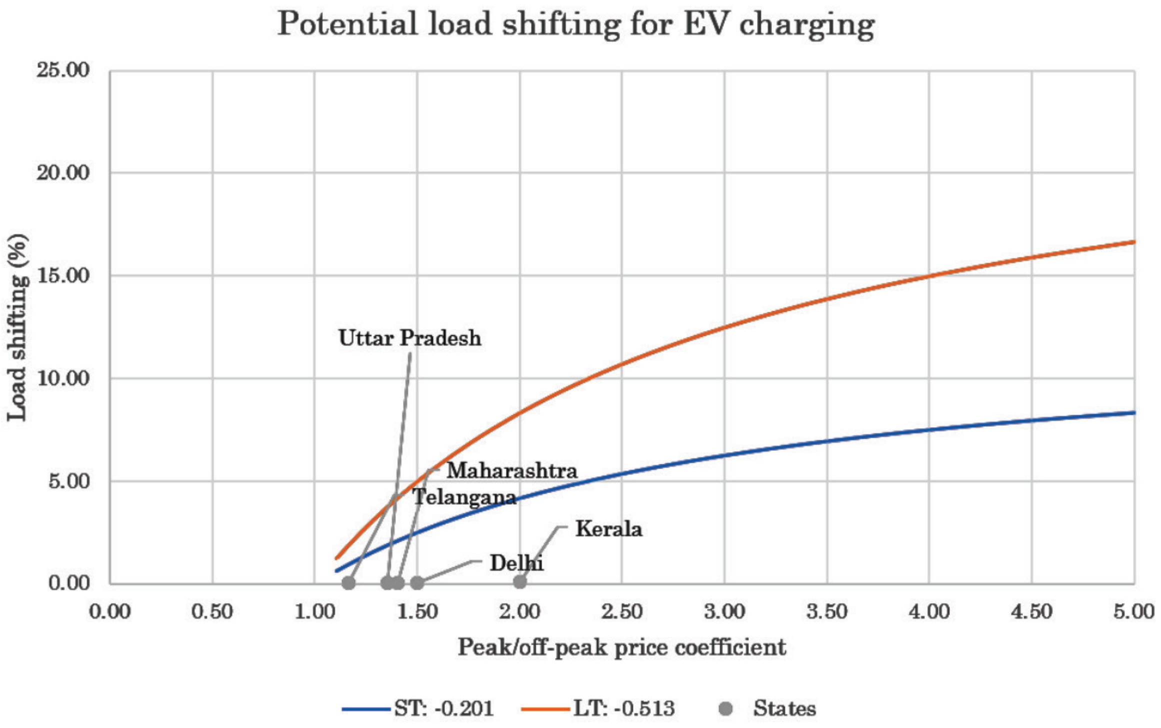


Figure 64. Load shifting potential with respect to the peak/off-peak prices coefficient. Short-term elasticity: -0.201, Long-term elasticity: -0.513. Current policies are depicted in dots, most of them with a low peak/off-peak coefficient thus a low load shift.

# 05 Recommendations for smart charging deployment in India

## 5.1 General recommendations to enable smart charging strategies in India.

This section provides a list of recommendations to enable the implementation of smart charging strategies in India. The following recommendations have been elaborated based on the outcomes of the project: (i) the interventions required in policies for smart charging, communication, and ICT strategies in India proposed in the previous report (Rather et al., 2021), (ii) the results from the simulations in chapter 3, (iii) the study on customer behavior and the analysis of the organizational and technological layer in chapter 4. The recommendations have been arranged into 6 categories: incentives, tariffs, mandates, data management, R&D, and standardization.

### 5.1.1 Incentives

I1. Provide financial incentives and land support for establishing a smart charging station.

I2. Subsidize the procurement of metering equipment, required software, and communication networks required for smart charging.

I3. Issue reward points or green certificates to EV owners using the smart charging option and charging their vehicles for more than pre-set aggregated charging energy (kWh). The green certificates can be used to avail free parking spaces at public/government parking spaces and receive concession in electricity bill against the reward points.

I4. Incentivize the use of management system to coordinate the EVs charging and local RESs to maximise self-consumption of local generation from RESs.

I5. Encourage local smart charging for using the locally controlled smart charging station by providing a small rebate on the monthly charging bills of the users.

I6. Provide special incentives for retrofitting older charging stations and fueling stations with smart charging stations.

I7. Prioritise the approval, land allocation, and incentives to smart charging stations over dumb charging stations.

I8. Allot incentives to purchase smart charging software and services such that it attracts the charging station operator.

I9. Incentivize the installation of smart chargers at residential and workplaces by subsidy to make their price comparable with dumb chargers.

I10. Run awareness programs to spread the benefits of EV, state's EV policy, and smart charging in reducing electricity bills and environmental welfare which will incentivize EV owners to use smart charging.

I11. Develop easy-to-use apps that provide information and enable the EV owners to set their preferences and use smart charging without affecting mobility needs.

I12. Smart charging also facilitates integration of renewable sources to the grid. Thus, incentivizing solar PV installation at home, society, and public sites can enhance the integration.

### 5.1.2 Tariff design

T1. Introduce smart charging and ToU incentive for residential EV customers. In this scheme, eligible customers will get an instant rebate of the appropriate amount for participating in this smart charging such that respective residential customers get a charge at a lower price as per time-of-use according to the availability of cleaner and cheaper energy.

T2. Allow private players to provide EV owners and fleet operators special offers for buying and participating in their smart charging using ToU or any other strategy.

T3. The price difference between peak and off-peak rates in the ToU tariff should be appropriate to encourage EV owners to shift to off-peak hours. However, ToU tariffs have to be maintained in time to make habits change.

T4. Besides ToU tariffs, other tariffs such as CPP and PTR could be developed to apply at occasional peaks (i.e., specific days of the year) in the power system.

T5. Develop local flexibility markets where aggregators can offer grid services (e.g., congestion management) from EV smart charging. In turn, EV users would receive revenue for the provision of these services.

### 5.1.3 Mandates

M1. Mandate Government offices to establish smart charging stations in the respective region and offices.

M2. Modify the building codes to mandate the installation of only smart chargers.

M3. Mandate relevant agencies to create a complete package of required logistics, software, network service providers, and training material. If a charging station owner wishes to opt smart charging strategy, he could directly avail of this complete package and establish a smart charging station.

M4. Mandate to establish and retrofit all the charging stations in government spaces and commercial, public charging stations to be smart, based on a time-of-use tariff.

M5. Agree on a common definition of smart charging functionality applicable to Indian conditions.

### 5.1.4 Data management

D1. DISCOMs should provide initial logistic support (viz, network information, access to required data, historical data of load, etc.) to implement a smart charging station.

D2. Security standards should be structured or adopted from any standard organisation to safeguard the user's, charging station's, metering, and sensing equipment's data to maintain users' privacy and charging stations to avoid cyber threats on users or charging stations.

D3. Communication network protection standards should clearly mention protecting the data while communicating over the network.

D4. Investigation of vulnerable nodes in the system must be done regularly.

### 5.1.5 Research and development (R&D)

R1. R&D funds should be allotted for research in the field of Vehicle-to-Grid (V2G) integration for national transportation, EV, and grid scenario.

R2. Grant R&D projects to investigate and develop modern information and communication technology (ICT) based integration and smart charging techniques for EV ecosystem in the presence of EV loads, smart grid, renewable generation, and digital billing.

R3. Incentivise eligible EV customers for participating in various pilot projects and case studies in due course of time.

R4. R&D funds to evaluate the smart charging strategies and define the most suitable strategies considering the current power system infrastructure and planned upgrades in the physical layer, ICT, management systems, electricity market, etc. for each state.

R5. R&D funds to evaluate the suitable ICT, management systems, etc. for the suitable smart charging strategies in India.

R6. R&D funds to evaluate the suitable EV tariff for different smart charging strategies.

R7. R&D funds to evaluate the suitable electricity market design for different smart charging strategies.

R8. R&D funds for studying the suitability of battery swapping in India from social, economic, and technical perspectives. Battery swapping stations will have more flexibility in the charging time and therefore, could incorporate smart charging strategies easily. Battery swapping is most suitable for 2-wheelers at first, while it could be implemented in the future for 3 and 4-wheelers.

R9. R&D funds to evaluate the possibility of EVs' provision of ancillary services to TSO and DSOs and participation in wholesale markets.

R10. Development of an affordable and interoperable AC charge point for light EVs with smart charging functionality.

### 5.1.6 Standardization

S1. Complete the standardization framework for the EV smart charging ecosystem. Gaps in international standards have been identified in this report for some areas such as e-mobility roaming services and back-end communication.

S.2. Regulate the standard connectors and front-end communication that may be used in private chargers to enable interoperability among different EV and charger models.

S.3. Regulate the standard back-end communication protocols that may be used for CS management, including the exchange of information with third-party operators (e.g., DSOs).

S.4. Regulate the standard communication protocols for roaming services in the e- mobility sector to ease market entry for eMSPs. As a result, EV users would benefit from a larger offer of smart charging services.

### 5.1.7 Revisiting protection schemes

In order to accommodate EV penetration in the distribution system while ensuring adequate protection and reliability, below proposed countermeasures can be adopted.

1. Adequate Forecast of EV growth: The distribution utilities can adequately forecast EV growth considering a 10–20-year time horizon. The EV growth forecast can help in identifying potential areas of high EV growth zones, thereby allowing to carefully analyse such critical regional network for potential protection related issues. Further, the utilities would also need to consider the expected load growth in their network due to charging events considering different charging behavior, such as uncoordinated charging, smart charging.

2. Protection equipment upgradation: Based on the predicted load growth in the area, the utility would need to upgrade the protection equipment's such as circuit breakers to handle the increased short circuit MVA. Moreover, reconfiguration of the relays based on the increase in the short circuit current and MVA level would be an important factor that needs to be carefully considered.

3. Redesign the protection strategies: With increasing focus on distributed generation, it is likely that future distribution network would need to accommodate a high number of distributed generation resources. Even EVs in future are likely to participate in bidirectional charging and feed power back to the grid. Thus, the utility would need to redesign the existing protection scheme taking into consideration future distributed generation proliferation.

4. Adaptive Protection Schemes: The analyses carried out under Chapter-2 has demonstrated that for EV only, particularly EV and distributed generation-based system, protection settings for the relays are likely to experience fault currents outside the thresholds designed for conventional distribution system. Therefore, to address such issues, adaptive protection schemes offer a promising option to avoid the mentioned protection related issues. Adaptive protection dynamically updates the protection settings while considering various factors, such as network topology, communication related constraints, unbalanced loading and other parameter variations.

## 5.2 Specific Recommendations for Smart charging Adoption in India

### 5.2.1. Smart charging using time-based tariffs

As mentioned in Section 2.3, there are different ways to implement smart charging. One of the simplest ways is to provide a time-based EV tariff, which can act as a passive smart charging. However, this would require a smart meter that would be able to log energy consumption with respect to the time of use. Here, the use cases will differ based on the type of users and the type of tariff structure.

**Private EV user**

Currently, ToD/ToU tariff has not yet been implemented for residential users in India. The customers pay a fixed energy price based on slabs as per their contracted demand. For a user with a private vehicle, a separate meter may be needed for the EV charger based on the tariff structure.

- If the tariff is structured such that ToU pricing is implemented for the household energy consumption, a separate meter would not be required as the smart energy meter of the household will record the total energy consumption. This can be further extended to include a smart energy management solution to optimize the household energy consumption based on the ToU prices.

- If the ToU tariff is specific for EVs, then installation of a separate smart meter would be required for the EV charger.

As discussed, enabling time-based tariffs such as ToU is bottlenecked by the smart meter proliferation in the country. Although the smart meter deployment has grown in the recent years, these smart meters have to be installed in private residential households in order to facilitate passive control over EV charging using time-based tariffs.

**Commercial EV user**

Different state electricity regulatory commissions have released tariffs in which they have included ToU/ToD pricing for commercial public chargers . For example,

- Andhra Pradesh Regulatory Commission has levied an addition charge of INR 1/kWh (1.1 cents/kWh) for usage during peak periods (6 am – 10 am and then 6 pm- 10 pm) and reduced the electricity price by INR 1/kWh (1.1 cents/kWh) for usage during off peak hours (10 pm – 6 am).

- Delhi Electricity Regulatory Commission has put a surcharge of 20% on the electricity price for usage during peak hours (2 pm – 5 pm and then 10 pm – 1 am) and a rebate of 20% on the electricity price for off peak periods (4 am – 10 am)

As the commercial players generally have larger budgets, these players generally pay for their own smart meters recommended by the respective DISCOMs.

### 5.2.2. Control signal based Smart Charging

In order to have coordinated smart charging based on command signals, there needs to be a smart grid infrastructure along with a charging management system, which may be either centralized or decentralized, to control the EV charging based on some grid parameter. The smart grid infrastructure is needed to provide complete observability at the transmission level and, more importantly, at the distribution level. The Ministry of Power (MoP) has initiated various Smart Grid Projects throughout the country. These projects can incorporate smart EV charging into their objectives as a demonstration of smart charging capability in the country. These projects can then be later studied and rolled out to the masses.

### 5.2.3. Regulations for smart charging

The development and installation of the required infrastructure alone is not sufficient to enable smart charging. The ministries and the grid operators would also need to frame regulations for smart charging. These regulations should be designed in such a way that they can solve various issues related to smart charging, such as,

- If multiple EVs respond to a command signal at exactly the same point, a sudden increase/decrease in load would occur in the network.

- How would the EVs respond if there is a sudden loss of communication with the central charge management system?

- Two different forms of data needs to be communicated between the EVSE and the CMS, the command signal and the actual EV response. What should be the frequency of transmission of these data?

- During extreme grid conditions, should DISCOMs have the authority to curtail EV charging?

The requirements for smart charging is summarized in Table 32.

Table 32. Requirements to enable smart charging.

| | | |
|---|---|---|
| **Technical requirements** | Hardware | Public and private smart charging points |
| | | Smart meters |
| | | Smart grid infrastructure for grid observability |
| | Software | Management software that runs the algorithm to implement smart charging by taking real time inputs from the EVs and the grid condition |
| | ICT | Interoperable communication protocols for communication across different charger types and entities |
| | | Interoperable standards for communications including hardware requirements |
| **Regulatory requirements** | Electricity Market | EVs through aggregators should be allowed to participate in the electricity market |
| | | Create revenue streams to incentivize smart charging |
| | Distribution System | Time based EV tariff needs to be created |
| **Stakeholders Roles** | State Institutions | Create sponsored projects to kickstart smart charging |
| | | Help in financing the projects |
| | e-mobility market | Incentivize customers to participate in smart charging programs through different schemes |
| | | Make smart chargers easily accessible to EV users |

### 5.2.4. Benefits and disadvantages of smart charging, ToU charging and uncontrolled charging

The different smart charging approaches have their own advantages and disadvantages as highlighted in Table 33.

Table 33. Benefits and disadvantages of various smart charging methodologies.

| | **Advantages** | **Disadvantages** |
|---|---|---|
| **Smart Charging using control signals** | The congestion and voltage of the feeder is maintained within system thresholds | If the feeder is already overloaded or the voltage is poor without EV integration, the EV user may have to refrain from charging which may cause discourage smart charging option in future. |
| | It helps the grid during contingency events | The EV may not have enough charge remaining to fulfil the users' travel requirements. This causes comfort reduction of the EV user. |
| | It may provide monetary incentives for the user by participating in grid support services | Complex to implement. ITC infrastructure and communication standards are necessary. |

| | | |
|---|---|---|
| **Smart Charging using control signals** | Defer the requirement of grid upgradation investments | |
| | Helps in integration of RE sources | |
| **Time based tariffs** | Reduces cost of charging by only charging when the electricity price is low | Integration of RE sources is limited |
| | Helps reduce congestion by only charging during off peak periods. Correlates energy price with grid congestion. | Relaying of price signals needs proper communication infrastructure, which increases the cost of implementation. |
| | Helps in load levelling by shifting load from the peak periods to the off-peak periods | Cannot provide grid support services apart from peak shaving and load shifting. |
| | Defer the requirement of grid upgradation investments | Might lead to negative impact due to increasing simultaneity in charging if not implemented carefully |
| **Uncontrolled Charging** | Low cost of implementation | May incur high price for charging |
| | No anxiety for the customer that vehicle will not have enough charge after end of charging period | May cause congestion, voltage issues in the distribution network |
| | | Cannot help in RE integration |

### 5.2.5. Congestion Management

Congestion in the distribution grids occur mostly during peak load conditions. Uncontrolled EV charging will further aggravate the issue of congestion of the distribution lines. In order to mitigate the congestion issue due to EV load, following potential measures would be required.

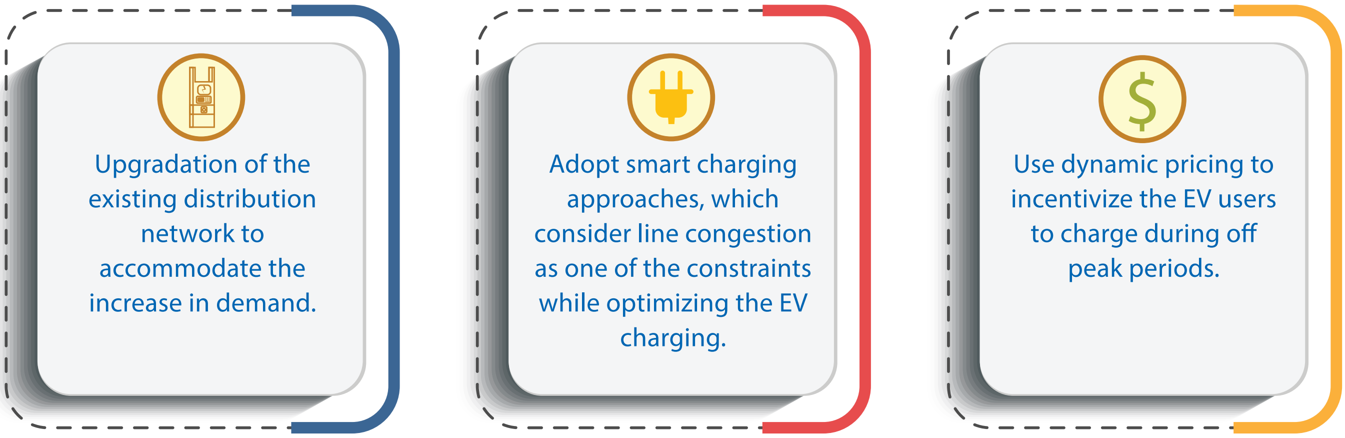


Figure 65. Potential measures to mitigate congestion issue

### 5.2.6. Infrastructure Upgradation

The obvious choice for mitigation of congestion in the distribution network is to upgrade the existing infrastructure with higher capacity transformers, transmission lines and other related distribution system assets such as fuses, circuit breakers, measurement devices etc. The added infrastructure will be system specific and will depend on the expected increase in load. In this context, the concerned DISCOM may need to perform individual assessments of their own network to check if their existing infrastructure will be able to cater to the expected increase in EV demand. Most DISCOMs in India are state-run and have a poor financial status, which may make it difficult for the DISCOMs to justify grid upgradation to cater to the EV load. In this respect, the DISCOMs can earn back the cost of grid upgradation in the following ways:

- Leveraging financial support from the government
- By levying higher demand charges to the specific set of customers with EVs and charge point operators under its jurisdiction. However, this would place a huge burden on the EV users and CPOs.
- Socializing the cost, i.e., by charging the entire customer base as per the net cost incurred. This can be reflected in the demand charge of the electricity bill.

The requirement of infrastructure can be reduced with the implementation of smart charging, as described in the section below.

### 5.2.7. Smart Charging for Congestion Management

In developing/designing an EV charging strategy, the maximum capacity of a feeder is taken as the constraint parameter for the EV charging. Considering feeder capability for charging optimization is crucial as feeder overloading can potentially result in feeder tripping, thereby leading to congestion in other lines. Because of this reason, EV charging is coordinated under consideration of the maximum feeder capacity. Feeder capacity constraint can be considered in two different ways while performing an optimization. The first option is by considering the thermal rating of the line. The second method of realizing the feeder constraint is by considering the amount of prespecified power flowing through the feeder, which can be calculated using load flow analysis .

Applying feeder capacity constraint is simple in a centralized method as all decisions are taken centrally by performing load flow analysis, and EV owners are not involved in charging decisions. The centralized mechanism is not very popular amongst customers as it does not facilitate the direct plug-and-charge mechanism. This reduces the customer's degree of satisfaction, and people are less interested in such charging strategies.

Contrary to this, applying feeder constraint in decentralized strategy is difficult because the EV owner takes the EV charging decision based on electricity price without considering any network constraints. Dynamic price variation by an aggregator cannot guarantee the optimal solution to maintain the feeder's capacity constraint. The aggregator decides the variation in price signal by taking the information of load flow and power requests by the customers. However, this indirect control alone is not sufficient as a failure in maintaining capacity constraint from this approach may lead to system instability. So, another local control is also used in addition to decentralized control for arresting capacity constraints.

### 5.2.8. Using Tariff

The third alternative to manage congestion in the grid is through utilization of Time of Use (ToU) tariffs in the form of dynamic pricing, Time of Day pricing etc. Using a variable electricity price, which reflects high electricity price during peak load periods and low electricity prices for off-peak periods incentivizes the EV users to shift their charging needs to off-peak periods which reduces the excess loads in the peak periods, thereby reducing congestion in the grid.

## 5.3 Prioritization of Recommendations and Roadmap

In the previous section, many general recommendations for the deployment of smart charging in India are presented. The results show that concrete and immediate actions must be taken to connect smart charging stations. However, there is a natural ordering of these measures from those that are more urgent to others in the medium term, which allow the full implementation of a smart EV load management system. A temporary classification of actions is proposed below.

In this section, the general recommendations are classified based on the priority of adoption. They are classified into short term (up to 2025), medium term (2030), and long term (2040). The priority of adoption for all recommendations is summarized in Table 34, and graphically presented in Figures 66-71.

Table 34. Summary of priority of adoption of general recommendations.

| | Short term (2023) | Medium term (2030) | Long term (2035) |
|---|---|---|---|
| Incentives | I1, I2, I8, I9, I10, I11, I12 | I2, I3, I4, I5, I6, I8, I9, | |
| I12 | I4, I5, I7 | | |
| Tariff design | T1, T3 | T2, T4 | T5 |
| Mandates | M1, M5 | M2, M3, M4 | M4 |
| Data management | D1, D2, D3, | D4 | |
| R&D | R2, R4, R5, R6, R8, R10 | R1, R2, R3, R7 R8, R9 | |
| Standardization | S1, S2 | S3, S4 | S4 |

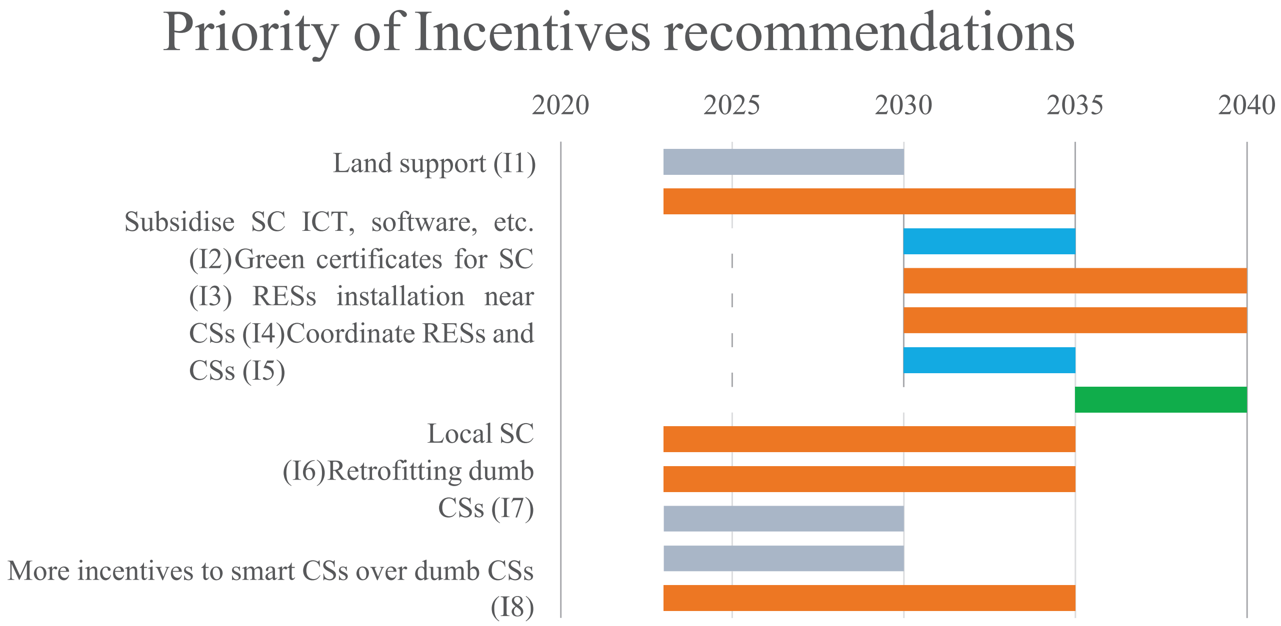


Figure 66. Priority of Incentives recommendations. (short term 2023, medium term 2030, and long term 2035). SC: smart charging, ICT: information and communication technology, CSs: charging stations, and RESs: renewable energy sources.

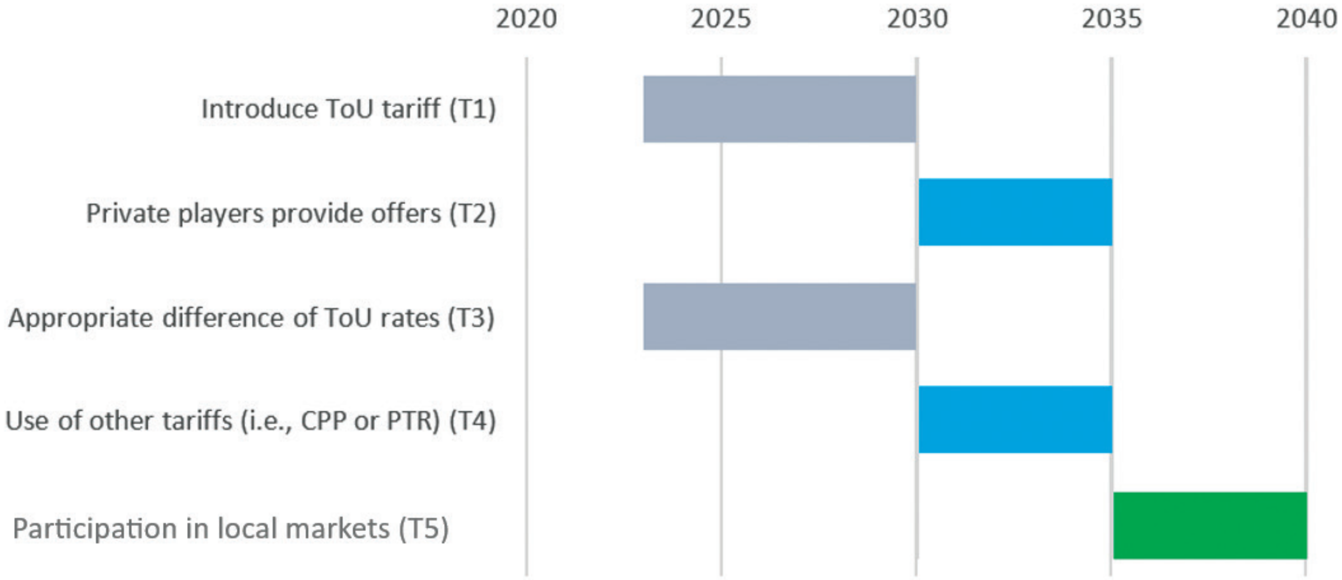


Figure 67: Priority of tariff design recommendations. (short term 2023, medium term 2030, and long term 2035). ToU: time of use, CPP: critical peak price, and PTR: peak time rebate.

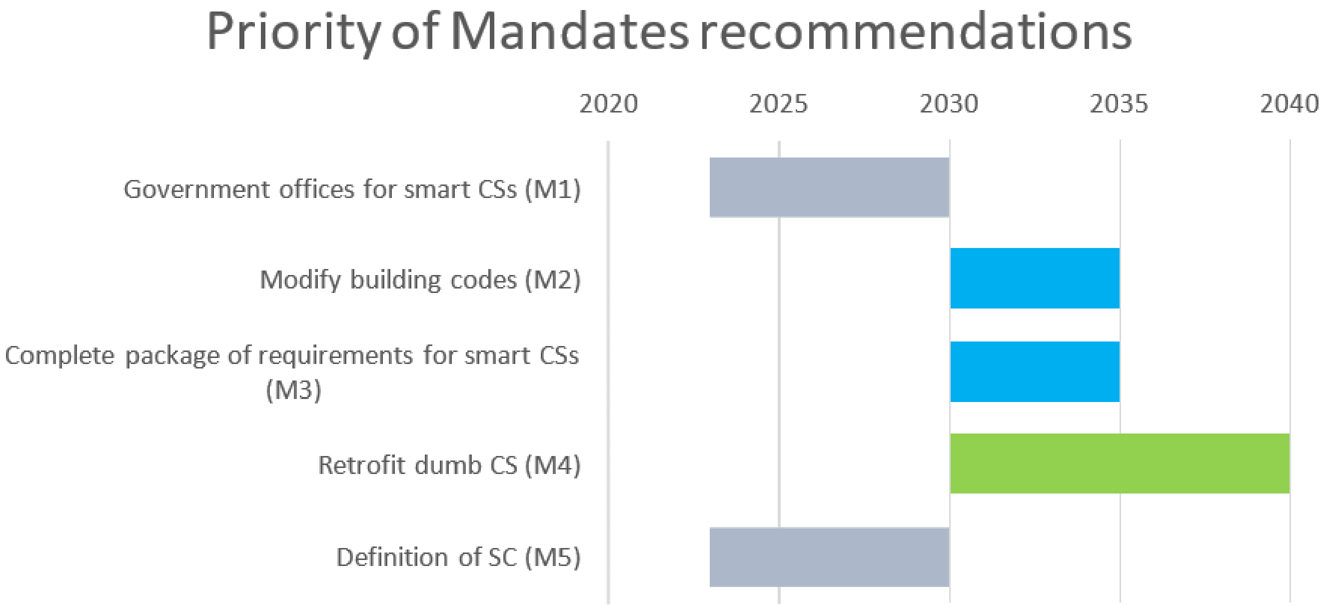


Figure 68. Priority of Mandates recommendations. (short term 2023, medium term 2030, and long term 2035). SC: smart charging and CSs: charging stations.

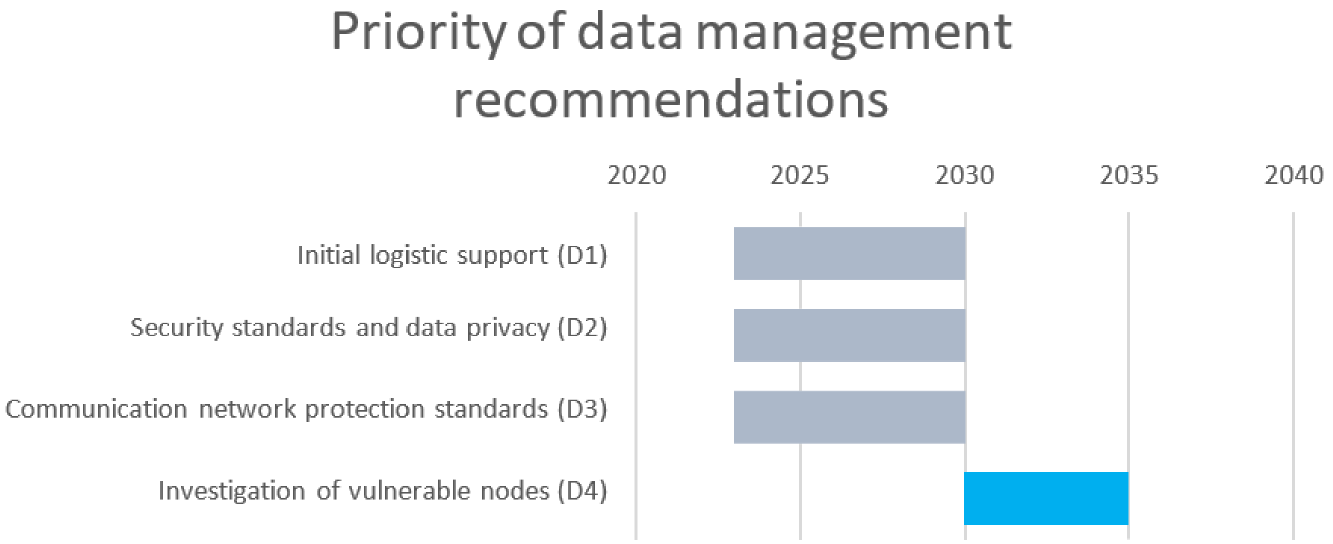


Figure 69. Priority of data management recommendations. (short term 2023, medium term 2030, and long term 2035).

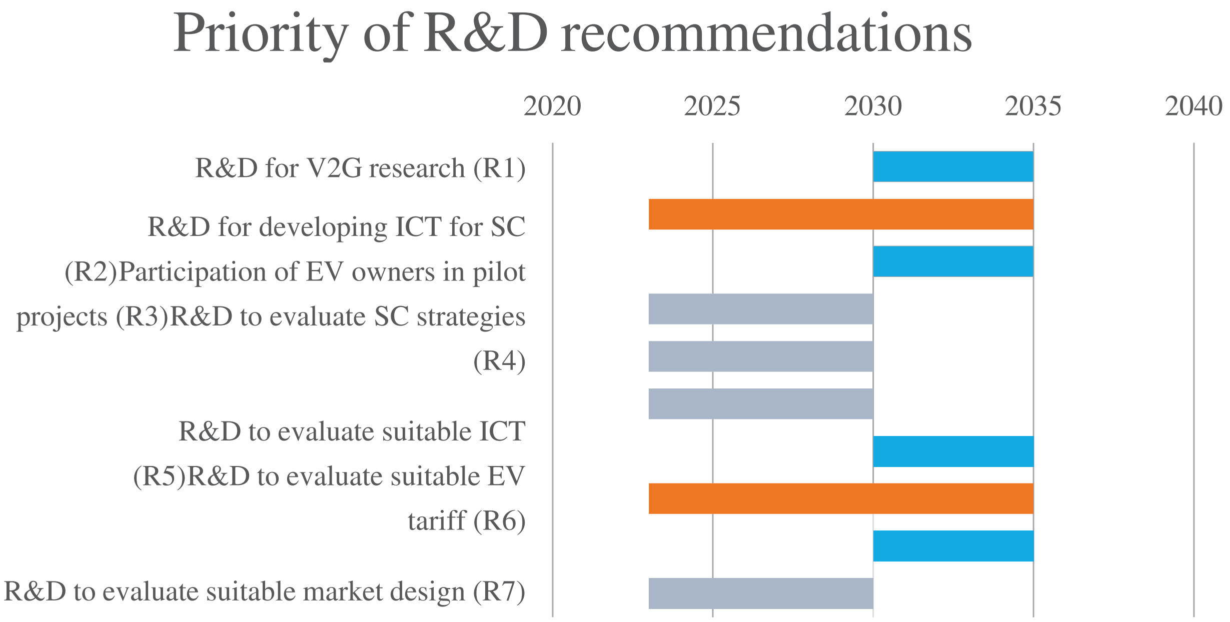


Figure 70. Priority of research and development recommendations. (short term 2023, medium term 2030, and long term 2035). R&D: research and development, V2G: vehicle to grid, SC: smart charging, ICT: information and communication technology, EV: electric vehicle.

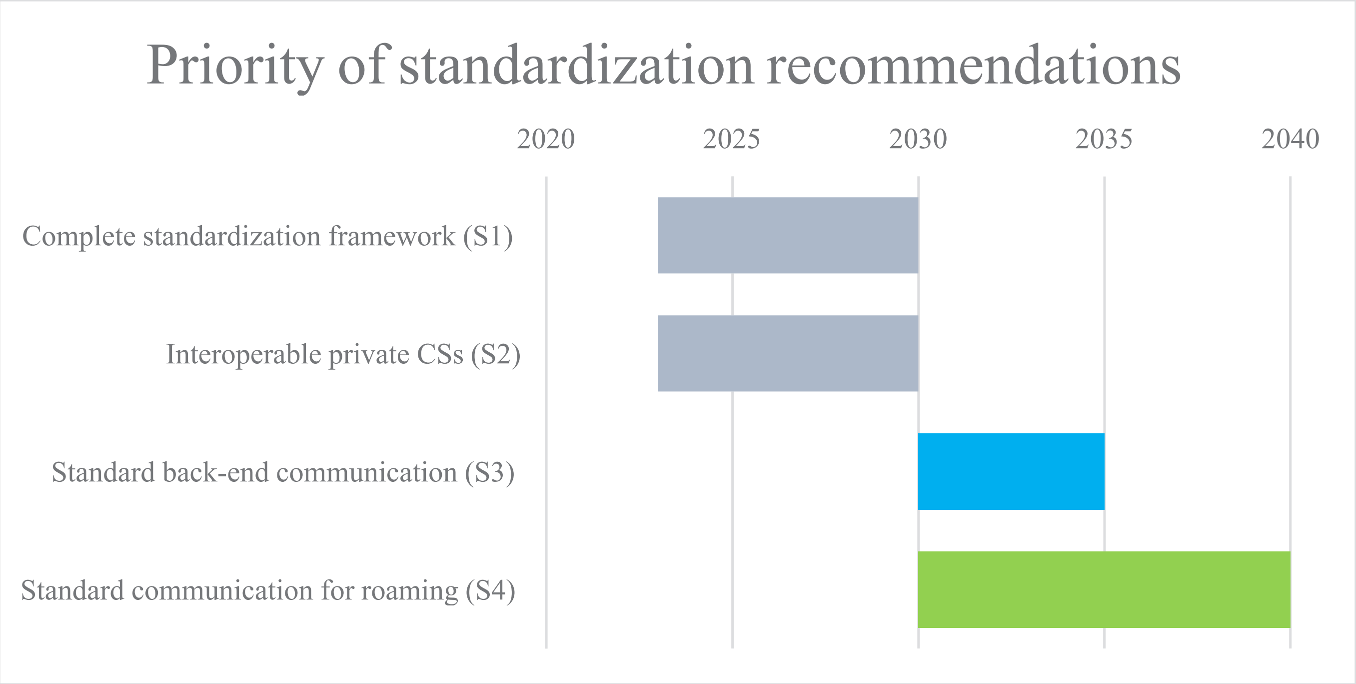


Figure 71. Priority of standardization recommendations. (short term 2023, medium term 2030, and long term 2035). CSs: charging stations.

## 5.4 Adoption of Protection System for secure integration of EVs

Protection strategies shall take into account the unique properties of the meshed network together with its new components as they function at a specific time. Based on how DERs are connected, which electric vehicles are charging, and how other loads are behaving, system topology and consequently, protection method, vary constantly. Given this, it is necessary to take into account the operational features of electric vehicles, distributed generation, and storage. Particularly, microgenerator dynamic performance and topology shifting are issues because of intermittent fault current changes in renewable energy sources[11]. Nonselectivity is a condition that occurs when more of the network is disconnected than is required to fix a specific defect. Apart from the inconvenience of the unserved loads, it is more challenging to locate the fault and consequently repair it. Resynchronization issues could happen in the case of islanding operation of the system, even in a short time. Protection systems are classified as active, passive, and hybrid by researchers[12] depending on their capacity to make judgments using measured data at nodes other than the ones to which they are connected or communicate. The brain of the system might be a centralised decision-making hub connected to each piece of protective gear.

### Protection Schemes

The operating scenarios of distributed networks are increasingly becoming more complex and irregular with increased adoption of EVs. Therefore, the protection conditions cannot be fulfilled by conventional protection, which generally considers the maximum and minimum fault current. A summary of protection schemes is listed under.

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[11] Brearley, Belwin J., and R. Raja Prabu. "A review on issues and approaches for microgrid protection." Renewable and Sustainable Energy Reviews 67 (2017): 988-997.

[12] Palizban, Omid, Kimmo Kauhaniemi, and Josep M. Guerrero. "Microgrids in active network management–part II: System operation, power quality and protection." Renewable and Sustainable Energy Reviews 36 (2014): 440-451.

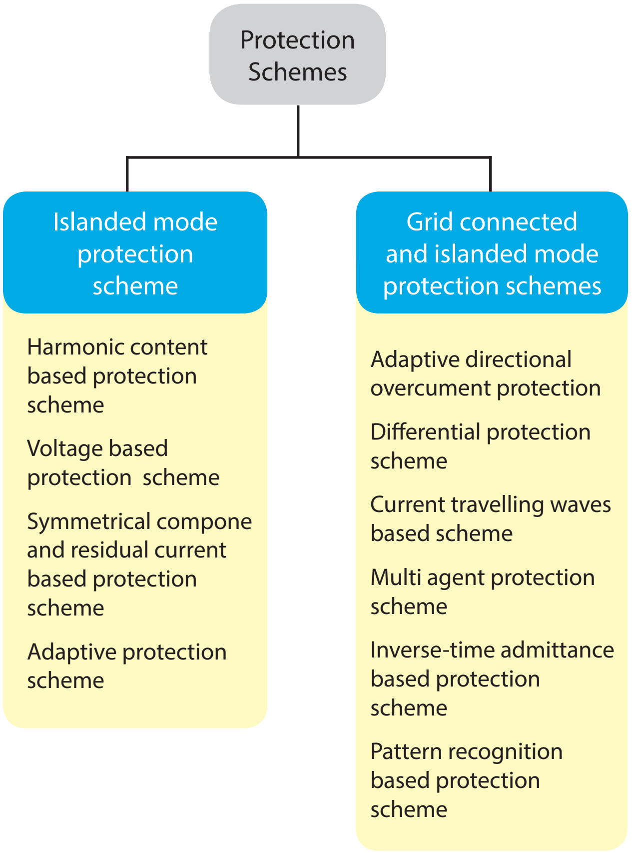

Figure 72. Protection schemes utilized for smart grids and electric vehicle integration.[13]

**Adaptive Protection System**

In general, adaptive protection is an online protection technique that aims to adapt protection configurations to any potential power system scenarios while maintaining adequate operation, regardless of system topology. When boundary operation conditions change, the protection system monitors the distribution network topology and applies new relay coordination. Both centralised and decentralized infrastructures often develop an adaptive protection system.[14-15]

The protection schemes currently used at the distribution level are distinguished in active, passive, and hybrid systems. Several approaches have been developed with the most widely used to be current limiters, centralized protection, distance protection, protection based on variables, differential protection, multi-agent protection schemes, and others, all based on relays and their coordination. An illustrative flowchart of adaptive protection scheme is provided in Figure 73.

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[13] Lazarou, Stavros, Vasiliki Vita, and Lambros Ekonomou. "Protection schemes of meshed distribution networks for smart grids and electric vehicles." Energies 11, no. 11 (2018): 3106.

[14] Ates, Yavuz, Mehmet Uzunoglu, Arif Karakas, Ali Rifat Boynuegri, Abdullah Nadar, and Bulent Dag. "Implementation of adaptive relay coordination in distribution systems including distributed generation." Journal of Cleaner Production 112 (2016): 2697-2705.

[15] Shih, Meng Yen, Arturo Conde, Zbigniew Leonowicz, and Luigi Martirano. "An adaptive overcurrent coordination scheme to improve relay sensitivity and overcome drawbacks due to distributed generation in smart grids." IEEE Transactions on industry applications 53, no. 6 (2017): 5217-5228.

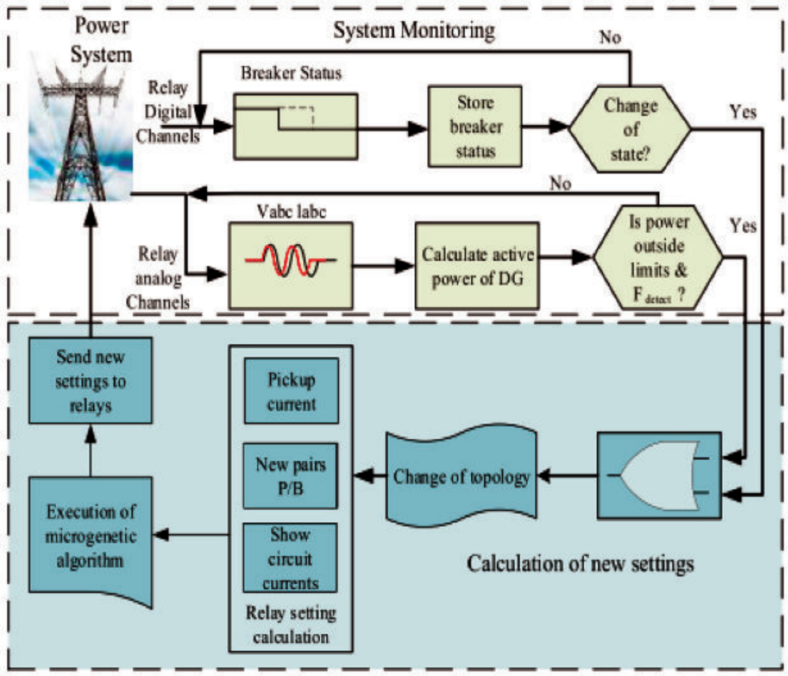

Figure 73. Flowchart of adaptive protection scheme.[16]

**Decentralised Framework**

A decentralised framework is made up of different autonomous control centres splitting the relays into portions or agents. Decentralized techniques are far more popular than centralised ones because of their endurance. Agent-based decentralised approaches are capable of self-checking and respond accordingly to prevailing operating conditions. In the framework described in, each and every protective relay is regarded as a smart agent. A relay agent (RA) is made up of sub-agents for connection, a sub-agent for operations, and sub-agents for measuring current transformers (CTs) and voltage transformers (VTs). Contact between distinct agents is carried out via the communication sub-agent. The operations sub-agent receives signals from the sub-agent calculation (VT and CT), which continuously checks the voltage and current at the relay site. The transmitted signals from all sub-agents, including the relay, DG, and PCC, to the operations sub-agent are used to determine the microgrid configuration. Each relay consequently gets aware of the remaining microgrid specifications for fault scenarios and any changes in the microgrid topology. Multiple pieces, including directional, memory, and computing parts, make up an operation sub-agent. The directional part detects the current direction that helps to distinguish microgrid faults.

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[16] Nsaif, Younis M., MS Hossain Lipu, Afida Ayob, Yushaizad Yusof, and Aini Hussain. "Fault Detection and Protection Schemes for Distributed Generation Integrated to Distribution Network: Challenges and Suggestions." IEEE Access 9 (2021): 142693-142717

[17] Daryani, Matin Jamaliyan, and Alireza Esmaeili Karkevandi. "Decentralized cooperative protection strategy for smart distribution grid using multi-agent system." In 2018 6th International Istanbul Smart Grids and Cities Congress and Fair (ICSG), pp. 134-138. IEEE, 2018.

# Annexure I

## A. Collated table with score

Table 35: Collated table outlining the scoring of all smart charging strategies

| Parameter | Priority factor | 1 | | 2 | | | 3 | 4 | | | 5 | | 6 | | 7 | 8 | 9 | | | | | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Practicability/ Technical feasibility (Convenient real-life implementation, Unconventional challenges to EV charging, Presence of non-standard EV infrastructure) | 5 | 5 | 5 | 2 | 6 | 6 | 4 | 6 | 5 | 4 | 9 | 8 | 6 | 5 | 2 | 2 | 3 | 7 | 3 | 6 | 3 | 5 | 5 |
| Grid friendliness/ improvement (Increased hosting capacity, Enabling Congestion management, Enabling tariff mechanism, Reduced curtailment of RE, Reliability and robustness) | 4 | 7 | 7 | 5 | 3 | 3 | 7 | 6 | 5 | 5 | 5 | 7 | 8 | 6 | 5 | 5 | 4 | 7 | 5 | 4 | 6 | 6 | 4 |
| Security | 4 | 4 | 4 | 4 | 5 | 5 | 6 | 4 | 3 | 3 | 8 | 7 | 3 | 6 | 4 | 4 | 4 | 5 | 4 | 6 | 5 | 6 | 6 |
| User acceptance | 4 | 6 | 6 | 3 | 5 | 5 | 4 | 4 | 4 | 3 | 7 | 5 | 5 | 9 | 4 | 4 | 4 | 6 | 5 | 7 | 3 | 6 | 5 |
| Efficiency | 4 | 6 | 6 | 4 | 5 | 5 | 4 | 7 | 5 | 3 | 5 | 7 | 3 | 8 | 3 | 3 | 5 | 6 | 6 | 6 | 4 | 5 | 5 |
| Requirement of Measuring instrument | 2 | 4 | 4 | 4 | 5 | 5 | 3 | 4 | 4 | 3 | 7 | 6 | 3 | 5 | 3 | 3 | 4 | 5 | 4 | 5 | 5 | 2 | 3 |

| Parameter | Priority factor | 1 |  | 2 |  |  | 3 | 4 |  |  | 5 |  | 6 |  | 7 | 8 | 9 |  |  |  |  | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ICT infrastructure (Enabling coordinated control) | 1 | 5 | 5 | 5 | 6 | 6 | 1 | 5 | 4 | 4 | 8 | 7 | 3 | 6 | 3 | 3 | 4 | 5 | 4 | 5 | 4 | 4 | 4 |
| **Total score** |  | **130** | **130** | **87** | **118** | **118** | **111** | **125** | **103** | **88** | **167** | **162** | **115** | **157** | **83** | **83** | **95** | **146** | **107** | **137** | **101** | **125** | **115** |

1: Centralized Control Based Strategy | 2: Decentralized Control Based Strategy | 3: Distributed Control Based Strategy | 4: Hierarchical Control Based Strategy | 5: Local Control Based Strategy | 6: Objective-Based Strategies | 7: Smart charging strategies based on optimization algorithms. | 8: Artificial Intelligence/Machine Learning-Based Charging Approach | 9: Price Based Coordination Methods | 10: Fleet Control | 11: Charging Station Coordination

## B. Rationale for priority factor

Rounds of consultation with the research team and DISCOM was conducted to arrive at a priority factor. The priority factor may change as per the case and grid conditions. The table below highlights considerations that were taken for the ranking of this study.

Table 36: Rationale for the priority factor ranking

| Priority factor | Remarks for Change in Priority Factor |
|---|---|
| Practicability (technical feasibility) | This parameter was ranked high considering the smart charging environment being in nascent stage in India. Hence, the need for strategy that could be implemented easily with minimal new additions to the system. |
| Grid-friendliness | Similar to practicability, it was agreed that smart charging strategy should be selected to avoid critical grid situations (avoiding congestions) and increasing the reliability of the power system. |
| Amount of necessary measurements | The priority factor can vary depending on whether enough measuring infrastructure has been deployed in the particular grid network considered.<br>The Discom considered for the study suggested that since there are already enough measuring instrument deployed in the network, this parameter could have mid-priority level. |
| Necessary additional ICT infrastructure | The priority factor can vary depending on the availability of ICT infrastructure deployed in the network.<br>The Discom considered for the study informed that the ICT infrastructure deployed at mass level i.e. 66kV is already automated, smart meter deployment, Distribution automation etc. Hence, the mid-priority ranking. |
| Security | Smart meters and AMI based on wireless technologies that are rolled out may be prone to communication failure. |
| User acceptance | The priority factor has mid-priority since for the easy role out of the strategies in a relatively new market the acceptance by user is important after initial technical feasibility assessment is conducted by the relevant stakeholders. |
| Efficiency | In this study, the efficiency implies strategy that can be implemented with little effort and in a relatively simple manner |

# Annexure II

## A. Feeder 1 results

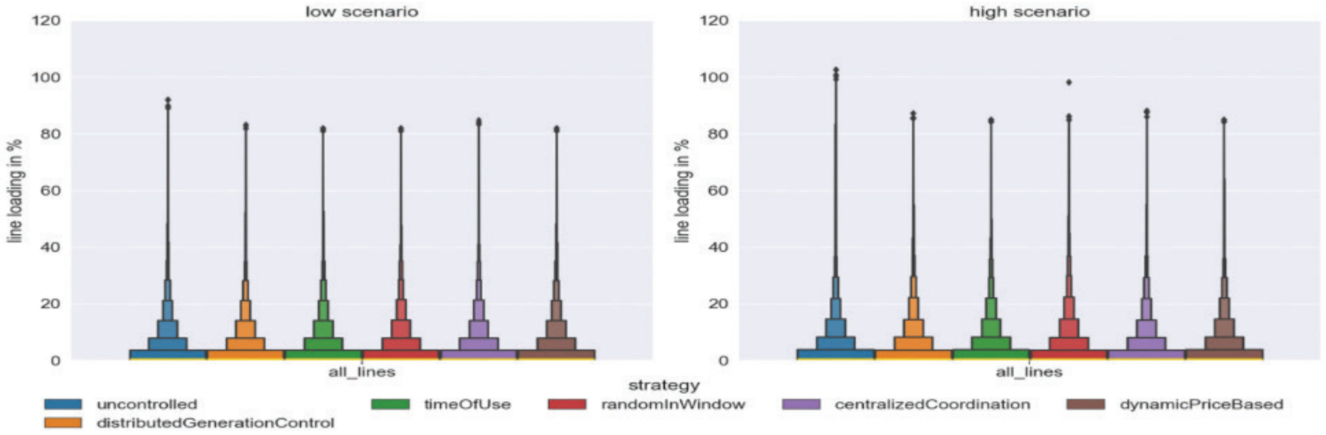

Figure 74: Strategy overview for two scenarios for one week containing a worst case (all lines)

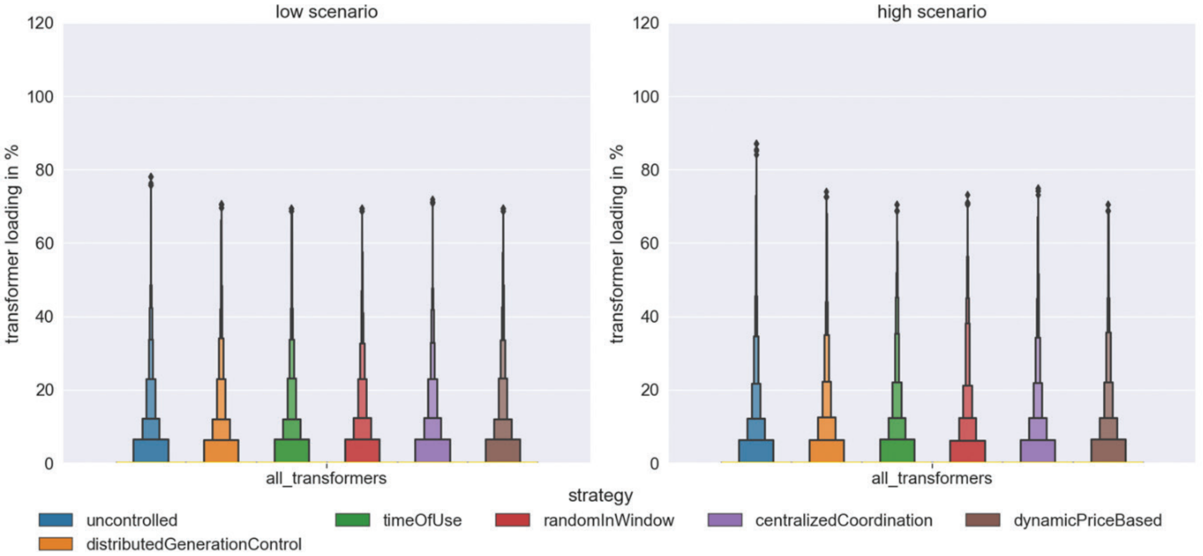

Figure 75:Strategy overview for two scenarios for one week containing a worst-case transformer loading (all lines)

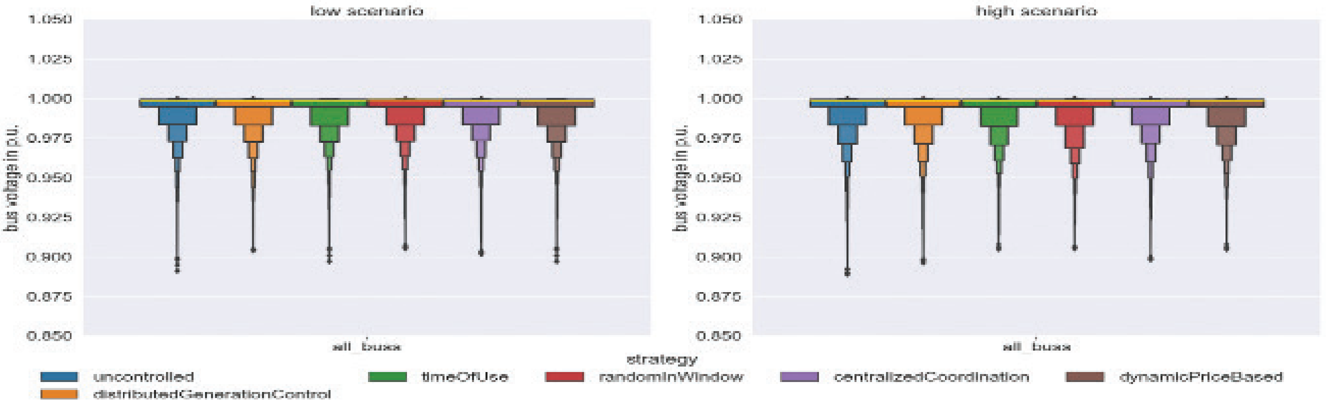

Figure 76:Strategy overview for two scenarios for one week containing a worst-case bus voltage (all lines)

## B. Feeder 2 results

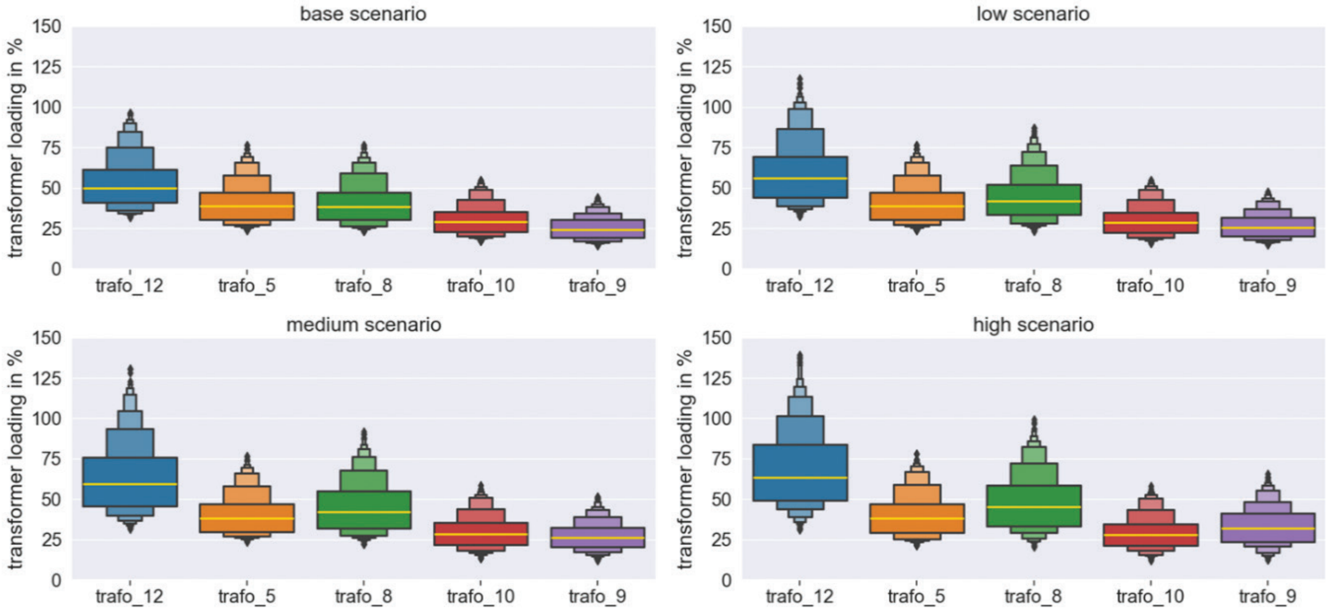

Figure 77: Transformer loadings for four scenarios (yearly uncontrolled simulations, five selected transformers)

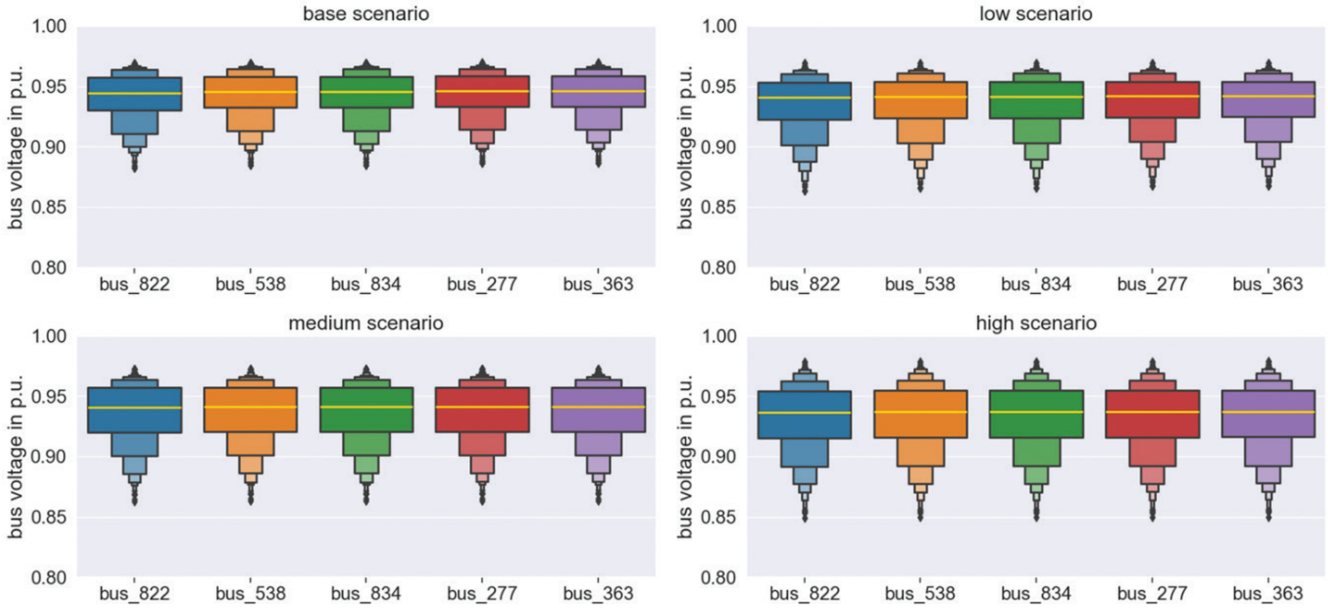

Figure 78: Bus voltages for four scenarios (yearly uncontrolled simulations, five selected buses)

## C. Feeder 3 results

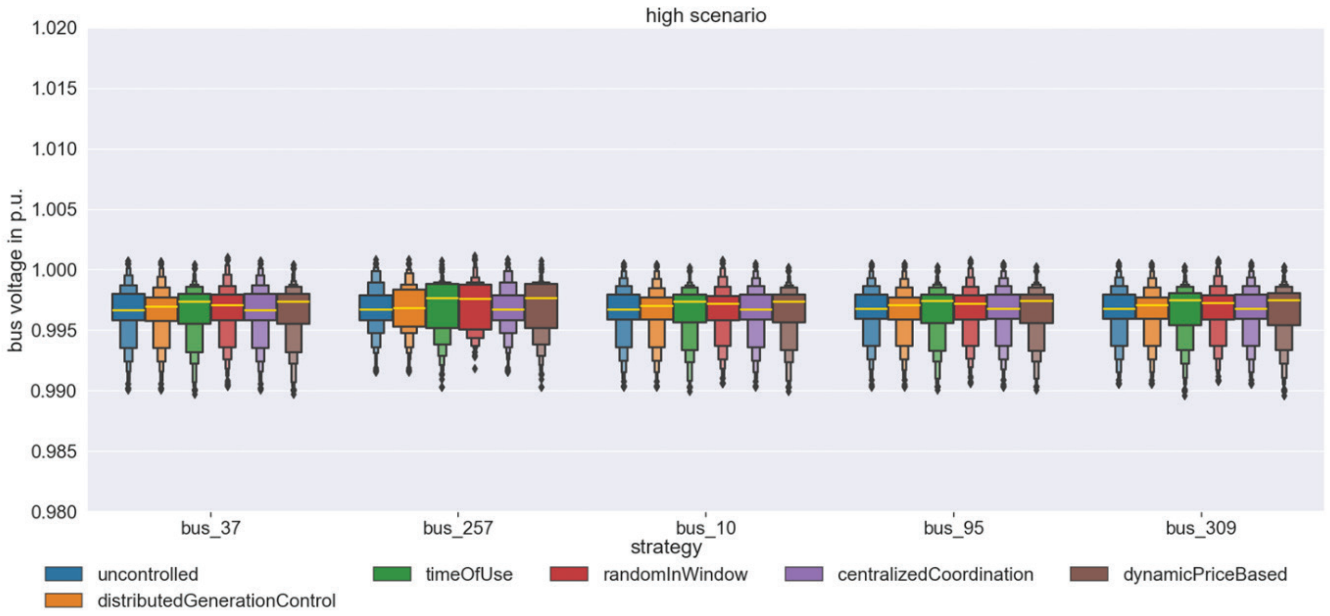

Figure 79: Strategy overview for one scenario for one week containing a worst case (selected buses)

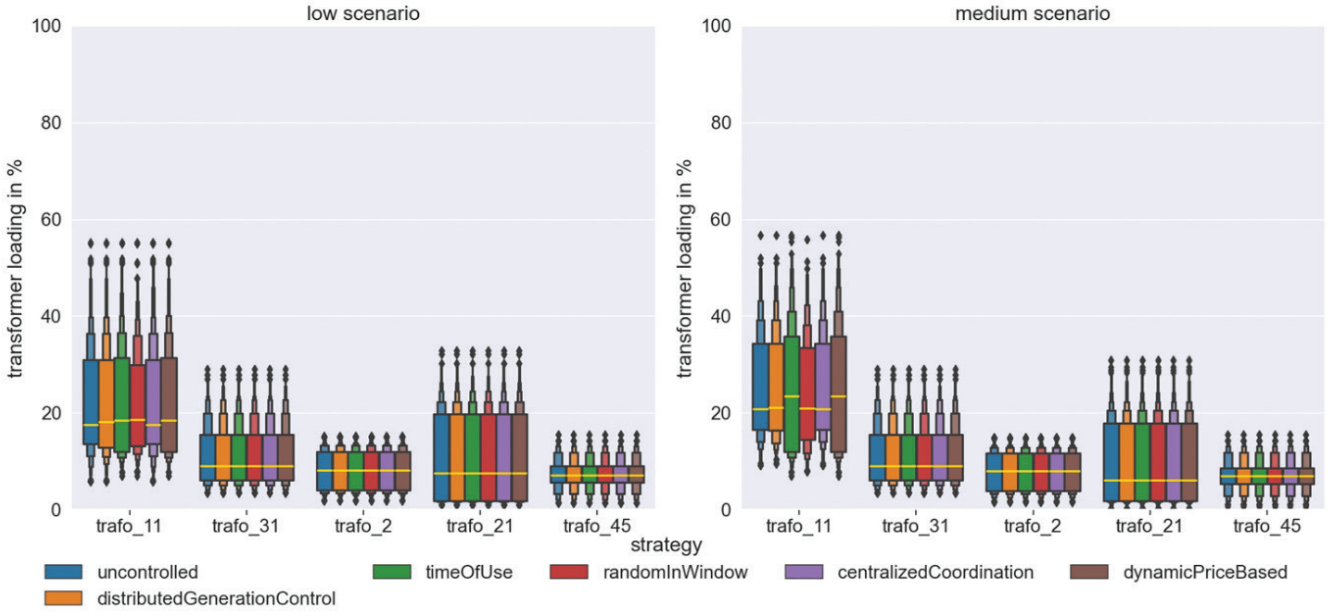

Figure 80: Strategy overview for two scenarios for one week (containing a worst case, five selected transformers)

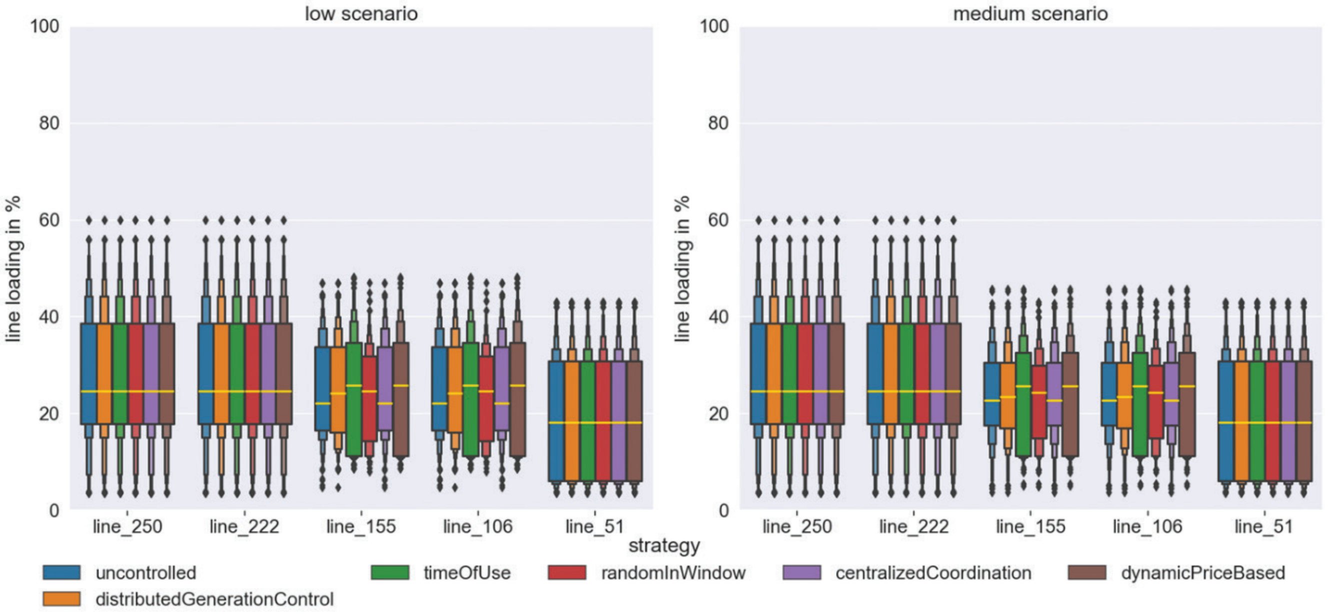

Figure 81: Strategy overview for two scenarios for one week (containing a worst case, five selected lines)

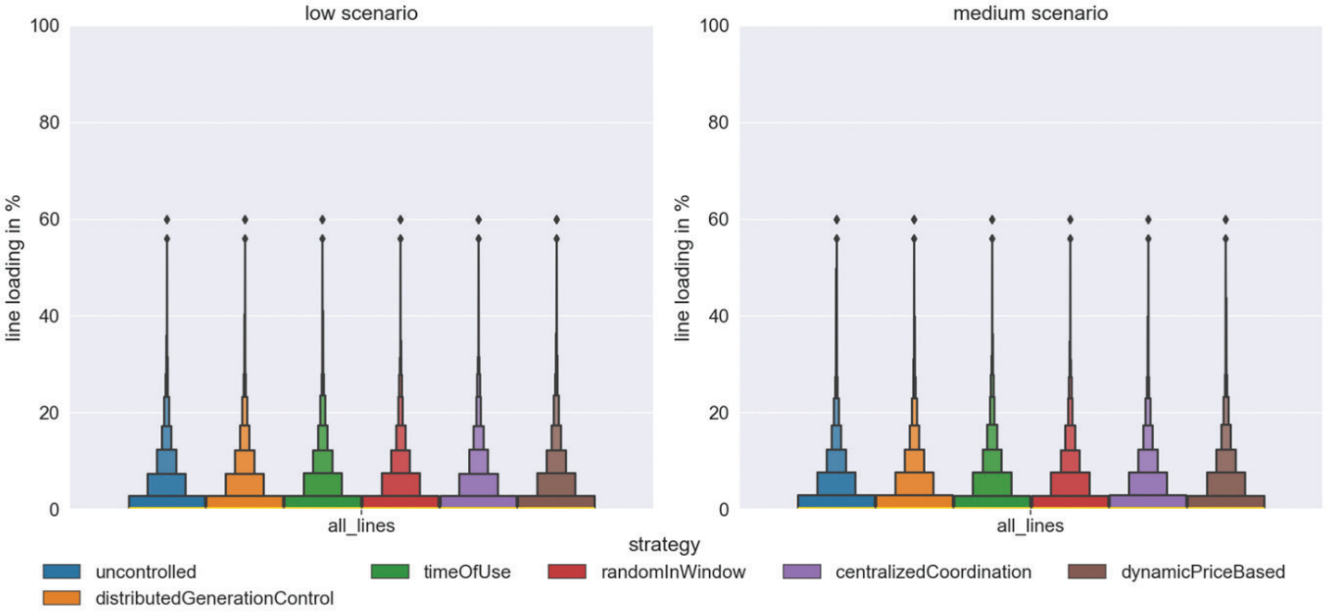

Figure 82: Strategy overview for two scenarios for one week (containing a worst case, all lines)

## D. Feeder 4 Results

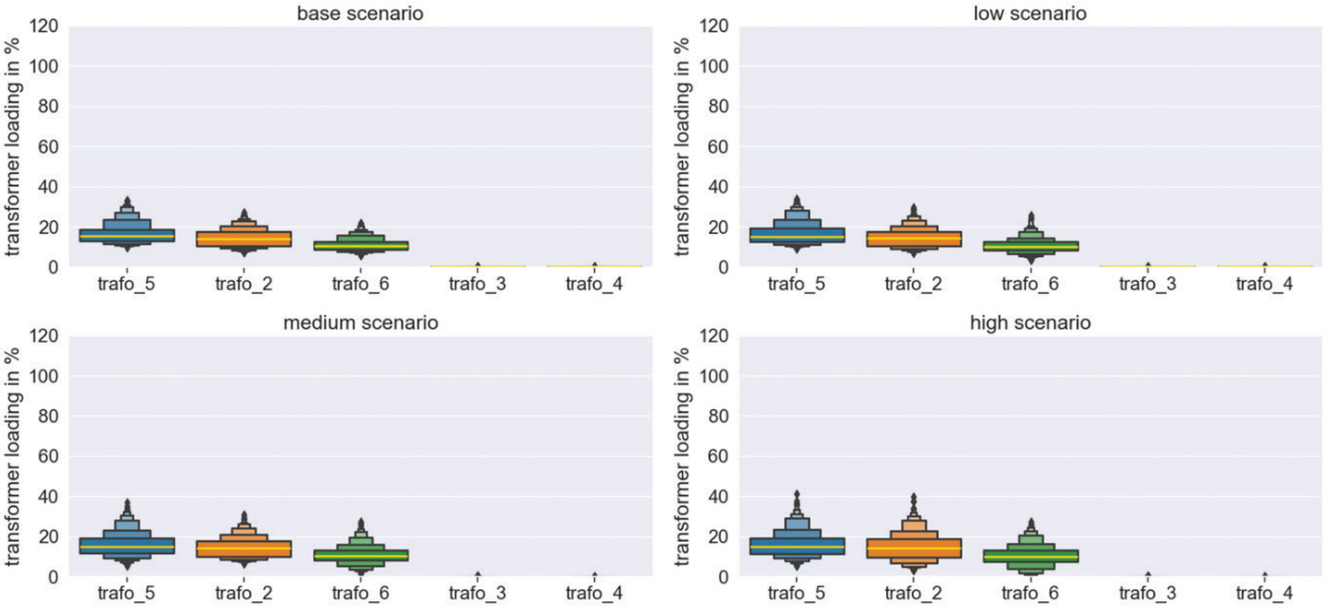

Figure 83: Transformer loadings for four scenarios (yearly uncontrolled simulations, five selected transformers)

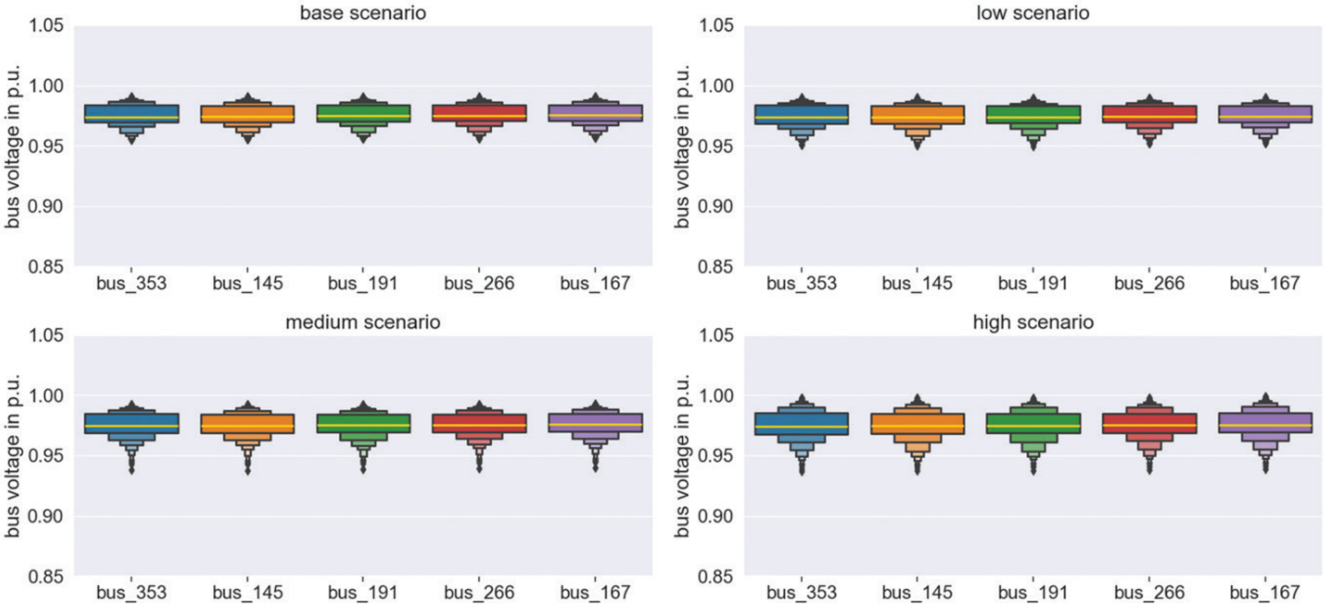

Figure 84: Bus voltages for four scenarios (yearly uncontrolled simulations, five selected buses)

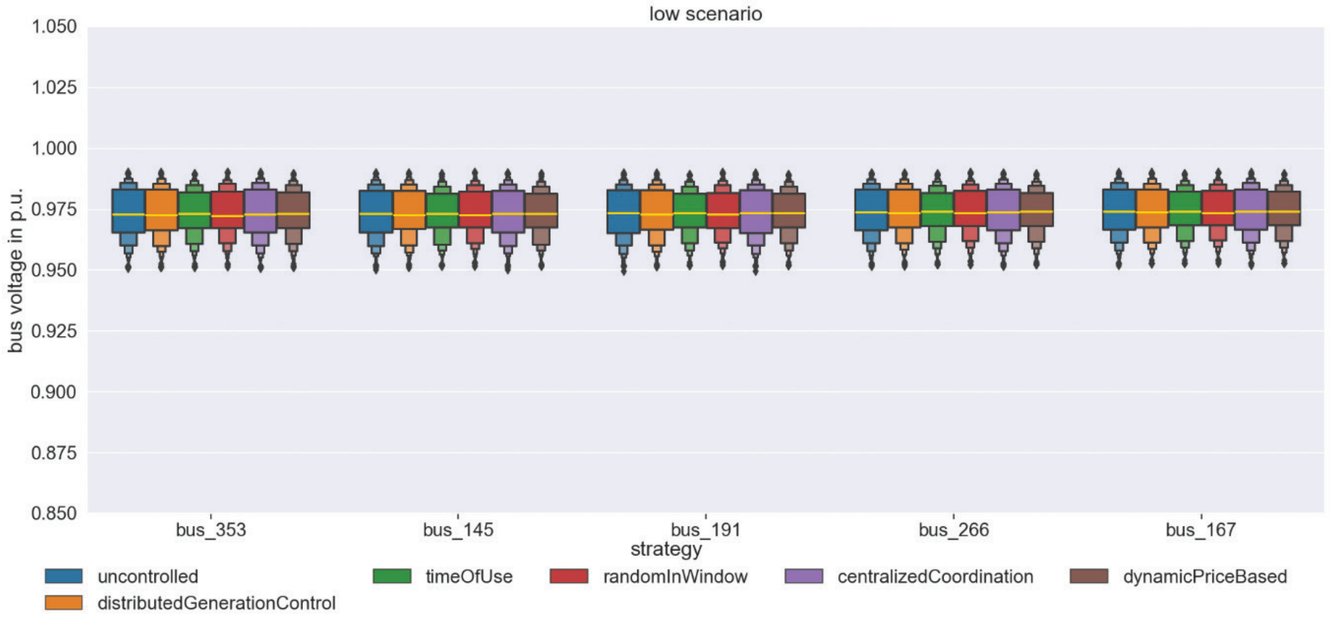

Figure 85: Strategy overview for one scenario for one week (containing a worst case, five selected buses)

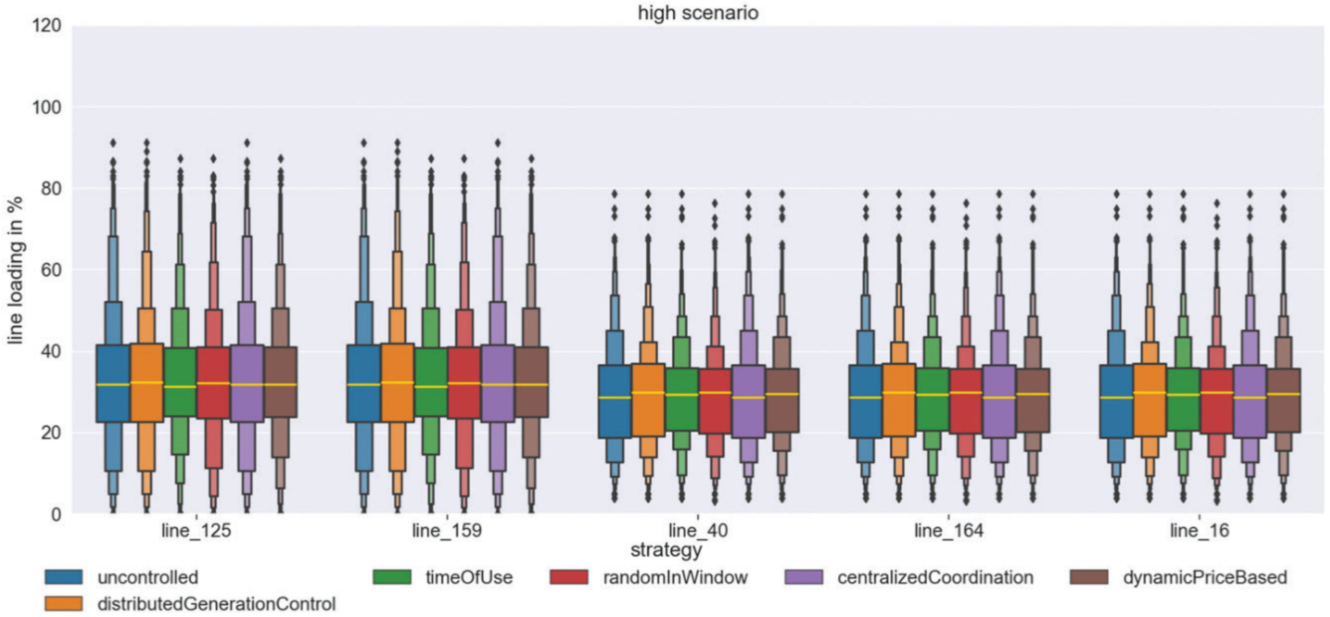

Figure 86: Strategy overview for one scenario for one week I (containing a worst case, five selected lines)

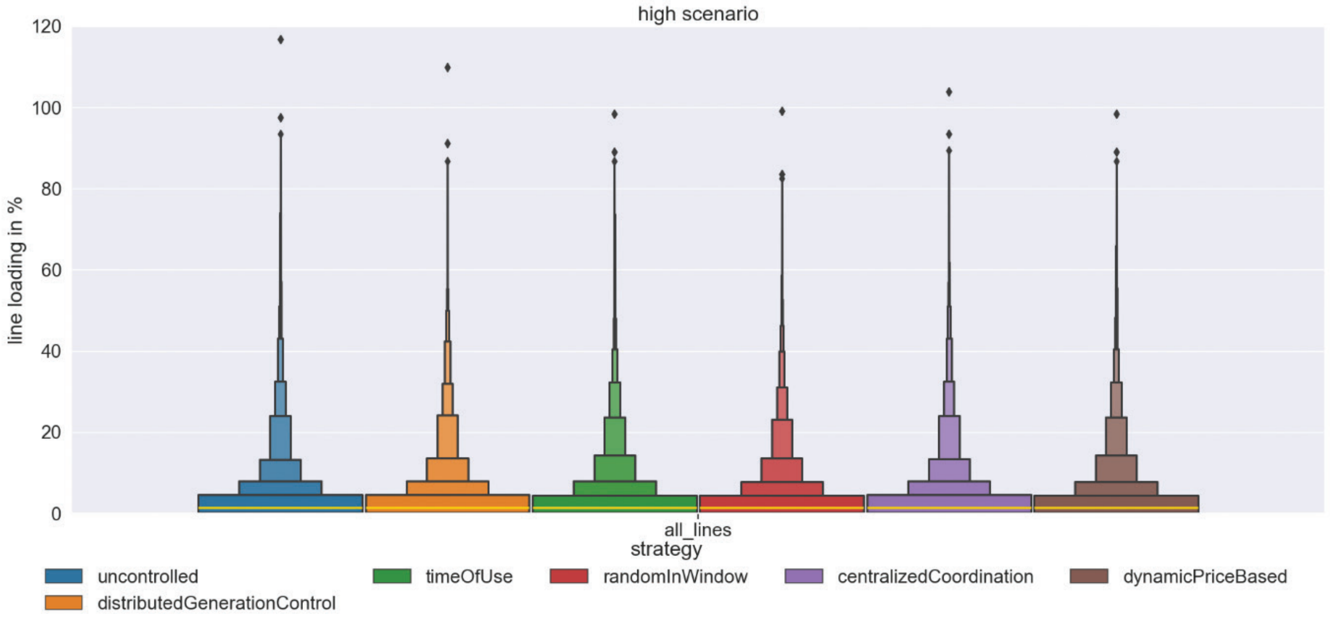

Figure 87: Strategy overview for one scenario for one week II (containing a worst case, all lines)

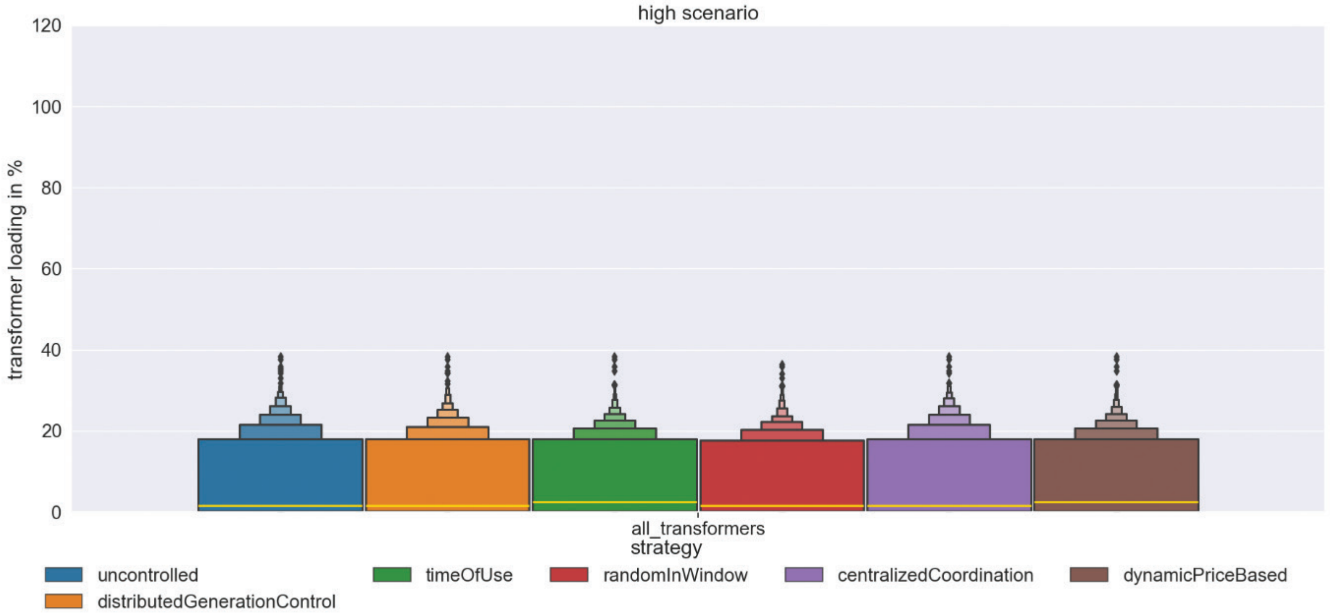

Figure 88: Strategy overview for one scenario for one week II (containing a worst case, all transformers)

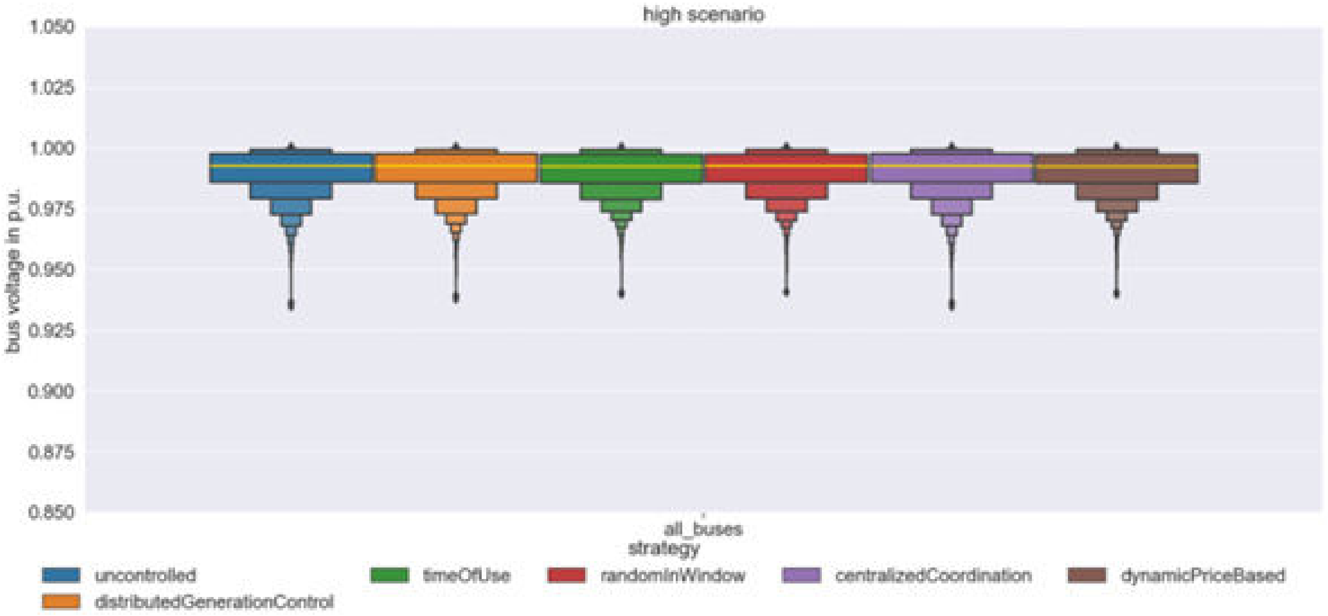

Figure 89: Strategy overview for one scenario for one week II (containing a worst case, all buses)

# Annexure III

## A. Pricing mechanism and Consumer behavior

Table 37: References used for the assessment of pricing mechanisms

| Ref. | Objective of the study | Price mechanism | Type of study | Place of study, data origin (if applicable) |
|---|---|---|---|---|
| Mohsenian, 2010 | Electricity cost minimization | RTP | S | USA |
| Ma, 2010 | Nash equilibirum: Social optimality filling the overnight demand valley | RTP | S | Indiana, USA (MISO DSO) |
| Deilami, 2011 | Reducing potential stresses, performance degradations, and overloads in distribution system. | RTP | S | Australia |
| Masoum, 2011 | Power loss minimization, peak shaving and voltage regulation | ToU | S | Australia |
| Cao, 2012 | Minimize charging cost and reduce peak and fill valley | ToU | S | Beijing, China |
| Taheri, 2013 | EV load scheduling | CAP | S | California, USA (PG&E baseline summer TOU rates) |
| Liang, 2013 | Optimized time based pricing schemes | TOU | S | Theoretical |
| Ghavami, 2013 | Minimize social costs of charging | RTP | S | USA (Theoretical) |
| Martinenas, 2014 | charging cost minimization | RTP | S | Denmark (NordPool) |
| Anderson, 2014 | charging cost minimization | TOU | S | USA |
| Ghavami, 2014 | Maximizing individual profit | RTP | S | USA, Benchmark data |
| Yin, 2015 | resolving peak on peak | CPP | S | China |
| Misra, 2015 | Cost optimization and reduction of extra load during peak hours | RTP | S | IIT Kharagpur, India (Microgrid) |
| Binetti, 2015 | Minimization of power losses, voltage deviation, load variance, operational cost, and emission control | TOU | S | California, USA (Southern California Edison rates) |
| Soltani, 2015 | Reducing load peaks | RTP | E | Northern California, USA (25 households) |
| Dubey, 2015 | Mitigating the impacts if EV load is on residential distribution circuit. | ToU | S | Texas, USA (theoretical) |
| Yang, 2015 | EV route optimization | ToU | S | Benchmark data |
| Soares, 2015 | Reducing distribution transformer overloading, voltage irregularities | UDP | S | Zaragoza, Spain |

| Ref. | Objective of the study | Price mechanism | Type of study | Place of study, data origin (if applicable) |
|---|---|---|---|---|
| Hajforoosh, 2016 | Reducing unwanted peaks, transformer over-loading | TOU | S | Theoretical |
| Xiong | Minimize charging costs | RTP | S | Singapore |
| Wen, 2016 | Studying the willingness to pay for a faster/peak charging sessions | CPP | E | USA, Survey |
| Maigha, 2017 | Load factor improvement, electricity cost reduction, mitigating line overloading | ToU | S | California, USA |
| Chen, 2017 | Solution of power congestion, under voltage, and grid instability | ToU | S | China |
| Xu, 2017 | Reducing imbalance usage and long charging delays at charging stations | RTP | S | Beijing, China |
| Chen, 2017 | Electricity cost minimization and flattening peak power demand curve | RTP | S | USA |
| De, 2017 | Reducing peak load demand and transformer overloading | RTP | S | Búzios, Rio de Janeiro, Brazil |
| Korolko, 2017 | Reducing distribution transformer overloading, voltage irregularities, and uncontrolled charging effect | RTP | S | Theoretical |
| Yang, 2017 | Resolving large and unpredictable peaks | RTP | S | PJM, East Coast, USA |
| Latinopoulos, 2017 | EV load scheduling | RTP | E | UK |
| Zang, 2017 | Minimize the peak–valley and economical improvements | ToU | S | Beijing, China |
| Moon, 2017 | Balanced charging | ToU | S | Benchmark data |
| Zang, 2017 | Provides benefits to electricity supplier, charging station, EV user | RTP | S | Beijing, China |
| Xu,2018 | Reduce waiting time at charging stations | RTP | E | Beijing, China |
| Southern California Edison, 2018 | TOU in California | TOU | RW | California, USA |
| Limmer, 2019 | Maximizing the stations' operator profit and reducing the peak | RTP | S | Germany (Intraday market, EPEX SPOT SE) |
| Xu, 2020 | Peak shaving | TOU | S | China |
| Synapse Energy Economics, 2020 | Comparison of mechanisms | All | RW | USA |

Type of study: S= Simulation, E=Experiment, RW=Real-world experience.

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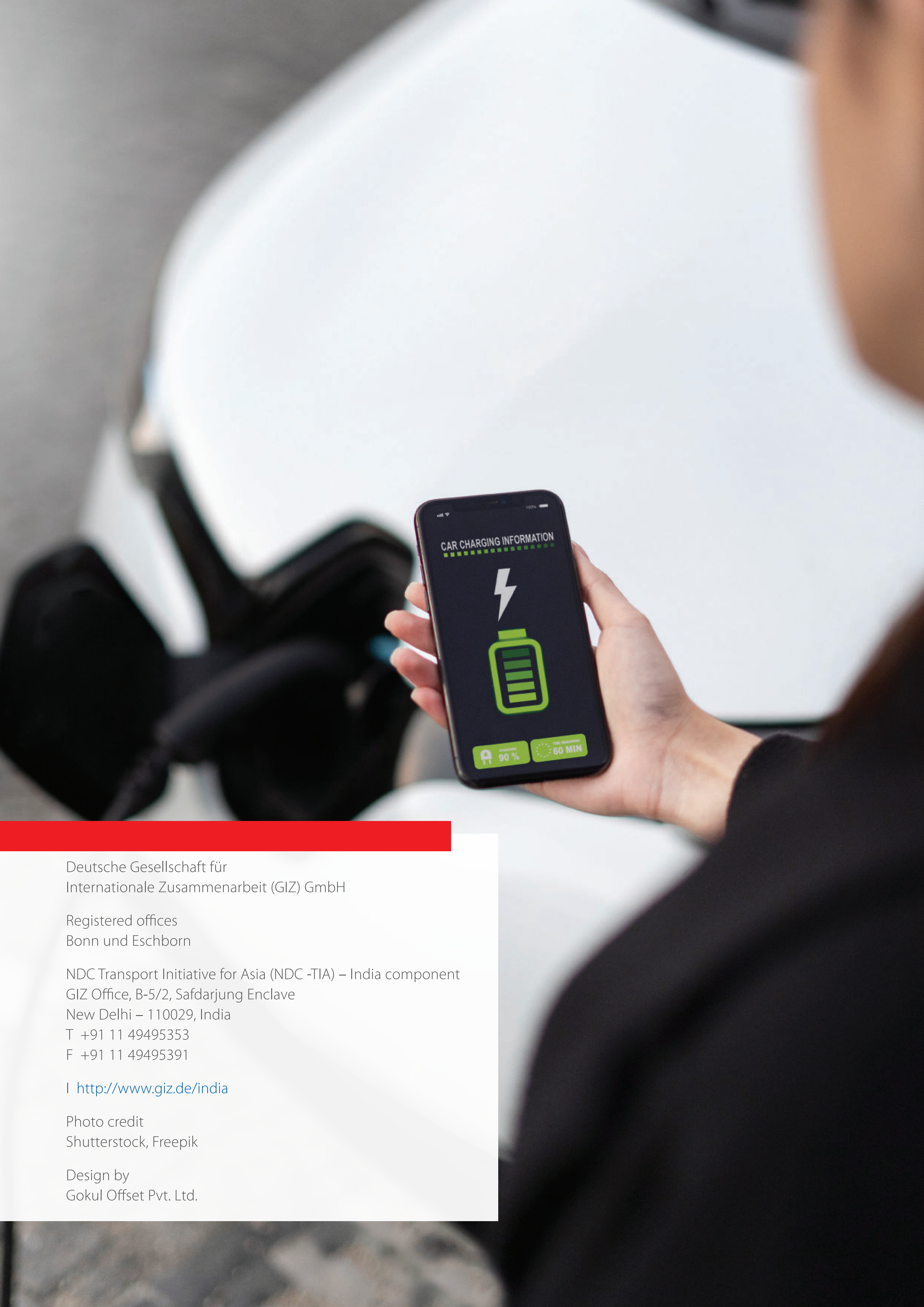

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