Mitigating the Impacts of the Electric Vehicle Charging Infrastructure on Residential Grids

Next Generation Grid Operations Knowledge Framework

Waleed Nasr

TUDelft

Mitigating the Impacts of the Electric Vehicle Charging Infrastructure on Residential Grids

Next Generation Grid Operations Knowledge Framework

by

Waleed Nasr

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on the 19th of August, 2021.

Student number:	5121019	
Project duration:	November 30, 2020 – August 19, 2021	
Thesis committee:	Dr. P. Vergara,	TU Delft (supervisor)
	Ir. B. Kruimer,	DNV (supervisor)
	Dr. ir. J.L Torres ,	TU Delft
	Dr. T. Alskaif,	Wageningen University & Research

Preface

I want to take this moment to thank my supervisors, Dr.Pedro Vergara & Ir.Bas Kruimer, and my co-advisors, Ir.Coen Berenschot & Ir.Lino Prka, for their continuous support and unwavering efforts. All of you have played a major role in nurturing my technical, interpersonal, and professional skills that will surely be of major importance in my future career. I extend my gratitude to DNV for allowing me to engage with experts in the energy field while I was completing my thesis. Finally, these are very harsh times for everyone and this would have not been possible without the support of my family, friends, and colleagues…

Waleed Nasr
Delft, August 2021

Abstract

With the advancements in technology and the enforcement of governmental regulations and incentives, the share of electric vehicles (EVs) in the mobility sector is on the rise. Although this aids the transition into a greener future with net-zero carbon emissions, the increase in EV penetration rates can have immense impacts on the grid and its operations. Coordinated charging strategies can help relieve grid stress by adhering to grid codes and requirements while carrying-out EV charging routines. Coordinated charging strategies can be of three types: centralized, decentralized, and price-oriented. The aim of this thesis is to investigate and mitigate the impacts of EV charging on Dutch residential grids, namely the impacts of voltage magnitude regulation and distribution transformer loading. This thesis proposes a decentralized coordinated charging strategy with local voltage control at its essence. The proposed charging strategy effectively allocates the charging power by prioritizing users based on their preferences, which are communicated to the charge controller through an IoT platform. Furthermore, in order to investigate whether users would be inclined to enroll into a coordinated charging routine, the impact on the user is also taken into account in this thesis by comparing to what extent can a user charge their EV battery with a coordinated charging strategy when compared with an uncoordinated one. Finally, all relevant and practical results from this thesis will be integrated into DNV's Next Generation Grid Operation Knowledge Framework to aid DNV employees in the future.

Contents

1

Introduction

1.1. Current Mobility Sector & Future Projections

The mobility sector, which comprises of 57% of the global oil demand, has been responsible for a large portion of greenhouse gas emissions in the last decades [17]. Between 2018 and 2020, passenger vehicles, alone, accounted for approximately 10.8 Giga Tons (Gt) of Carbon Dioxide (CO_2) emissions with an average of 3.6 Gt of CO_2 per year [17]. On the other hand, 2.1 million Electric Vehicles (EVs) were deployed in 2019, accounting for 2.6% of global car sales and setting a record increase of 40% from the previous year [18]. The reason for this staggering increase in EV deployment may be owed to the governments' efforts in increasing public awareness, issuing subsidies, and also the rules and regulations set to electrify the mobility sector [15]. With respect to the Paris Agreement, "the EU has been at the forefront of international efforts to fight climate change" and the Netherlands, in specific, has developed its own plan to accelerate the energy transition [13].

To increase the electrification of the transport sector, the Dutch government is fully committed to prolong its position as the "European leader in electric driving" and have set clear goals and initiatives in the so-called Mission Zero [4]. This commitment includes the selling of only zero-emission vehicles from the year 2030 and onward. As a result, projections estimate an average of 400,000 EVs to be deployed every year. Furthermore, market and governmental parties are currently exploring the charging infrastructure requirements that will need to handle the expected large electrical fleet. In 2018, the total number of EV chargers in the Netherlands summed up to 37,707. On the contrary, predictions show the need for an enormous amount of 1.8 million EV chargers, whether public or private, for the year 2030. As part of the "roll-out strategy", the Netherlands aims to install a maximum of 8,000 fast-charging points in strategic locations by the year 2025 [4].

1.2. Research Focus and Objectives

The high penetration of EVs in the coming years will trigger higher, unpredictable loads at random locations in the grid and thus causing grid operations to be highly volatile [14]. Additionally, the impact of EV charging on the grid is not only affected by the number of EVs charging per bus/grid section, but also by the speed of charging [5]. The aim of this research is to investigate the impact of EV charging on a residential distribution grid with regards to voltage magnitude regulation and distribution transformer loading using real data (consumption, load profile, etc.) from a Dutch residential grid. These impacts will be mitigated by developing a local control algorithm that would also set user priorities for charging. Finally, the relevant findings would be integrated into DNV's Next Generation Grid Operations (NextGen GridOps) Knowledge Framework.

1.3. Thesis Outline

In the following chapter, the literature will be discussed. Furthermore, the control algorithm along with all factors that aided in its development are dissected in detail in Chapter 3. Additionally, Chapter 4 presents the case of study along with the results of the three scenarios used to evaluate the control algorithm. Lastly, Chapter 5 introduces DNV's NextGen GridOps Knowledge Framework along with the relevant findings that have been integrated from this research and into the framework. Moreover, Chapter 6 encompasses the conclusion and recommendations for future work.

2

EV Charging Impacts and Mitigation Techniques

2.1. Introduction

In this chapter, the common impacts of the EV charging infrastructure on the residential, distribution grid will be discussed in Section 2.2 including the the two impacts of focus in this research: voltage magnitude regulation, and distribution transformer loading. Additionally, relevant mitigation techniques available in the technical literature are summarized and compared in Section 2.3. Finally, the chapter concludes in Section 2.4.

2.2. EV Charging Impact on Residential Grids

The technological advancements in EVs and batteries, along with governmental incentives and regulations, have increased the share of EVs in today's mobility market [14] [25]. As a result, the classic residential load will be altered due to the presence of an extra EV load which is considered random in nature. The impact on the residential, distribution grid is even more severe when the heavy EV load is unscheduled and demanded during peak hours of consumption [26]. Unfortunately, since the deployment of commercial chargers is yet in its initial stages, EV users typically charge in the evenings and late night using residential charging stations [15]. This, therefore, arises the need for coordinating charging among EV users. It is estimated that the current distribution grid capacity can withstand a considerably low EV penetration rate with uncoordinated charging mechanisms. Additionally, fast chargers (or high power rating chargers) can also escalate the severity of the impacts on distribution grid [5].

A study in [6] presents the possibility of finding a system with violations as a function of the charging power and EV penetration rate. Assuming a 20% EV penetration scenario, nearly half of the systems are estimated to include violations when charged at a low power of up to 3.3 kW. Given the same scenario but with a charging power of 11 kW, violations became more prominent and the percentage of systems with violations nearly doubled. Therefore, identifying which factors cause the most violations is of major importance in order to coordinate charging and mitigate impacts as much as possible. Among the most common impacts of EV charging include poor voltage magnitude regulation, line congestion, transformer overloading, and voltage unbalance [6]. Other impacts include harmonic distortion and poor power quality [15].

An EV load consumes a tremendous amount of power at once when compared to the classical household consumption. This huge consumption of power often translates into lower voltage magnitudes at the charging node. As a result, under-voltage is proven to be a predominant violation factor when compared to any other type of violations [6]. From a regulatory perspective, the grid requirements in Europe are defined in EN 50160, which requires the operating voltage to be between 90% to 110% of the nominal voltage at all times [16]. In other words, any operating voltage that is less than 0.9 p.u. or greater than 1.1 p.u. is considered a voltage magnitude violation. In distribution systems, voltage magnitudes can be controlled using on-load tap changers (OLTCs) in overhead transformers or using voltage regulators such as static var compensators

(SVCs) [10]. Each tap-change operation in the OLTCs method causes an increase in the total amount of reactive power available in the whole distribution network and therefore increases the voltage magnitude across all the nodes. The OLTCs method is used as a means of centralized control with less control over a specific bus or feeder. On the contrary, SVCs operate on a local level and inject reactive power into the distribution network (through a specific node) which, in turn, causes the voltage magnitude in a specific bus or feeder to increase [14]. As a result, the injection of reactive power from both methods reduces the power factor, reduces the power quality, increase the harmonic distortion, and increases energy losses. Additionally, injecting reactive power using the OLTCs method may cause generators to reach their maximum VAR rating which could possibly result in a voltage collapse [21].

Furthermore, another common impact from the EV loads may be observed in the overhead, distribution transformer supplying the low voltage (LV) network. A distribution transformer is often considered overloaded if the power supplied to the network exceeds the transformer's power rating [11]. Overloading a distribution transformer can rapidly increase the amount of energy losses and the amount of heat generated in the transformer. Consequently, this damages the internal components in the transformer and reduces the transformer life-time. Transformer aging, alone, is responsible for 70% of transformer failures in the European Union (EU) [8]. A typical control mechanism in distribution networks would be to shed the load at a local level by curtailing the active power (drawn by the loads) at the most severely congested lines and also busses with the most voltage drop (i.e where most power is being drawn). Curtailing the active power that the EV draws will not only reduce line congestion and increase voltage magnitudes, but also reduce the loading on the distribution transformer and therefore prolong the transformer's lifespan [5].

2.3. Mitigation

Traditionally, an auctioneer agent that operates in the day-ahead electricity market would be employed to mitigate impacts on the grid [25]. The principle of operation in day-ahead markets is that all user charging schedules are obtained one day before consumption in addition to the scheduled generation. Then, these demand and supply curves are plotted to obtain the equilibrium market price of electricity consumption for that specific day (as demand and supply will vary from day-to-day activities). As of now, such action is coordinated by a Balance Responsible Party and no user input takes place. Such method guarantees consumers to charge at a low cost (usually overnight in off-peak hours); however, once EVs penetrate at a higher rate, the impacts on the grid will be severe due to the absence of any coordination with respect to the grid condition [12].

EV charging can be coordinated using centralized methods, decentralized methods, and market-based approaches. Centralized methods are more prominent; however, apart from being very expensive, these methods are very complex due to the interaction of many measurement instruments and communication infrastructures [9]. On the contrary, decentralized methods asses the problem on a local level and take-action accordingly. Decentralized methods often provide a control strategy that not only takes into account the constraints set by the Distribution System Operator (DSO), but also adapts to the current circumstance of the distribution grid in order to effectively schedule and dispatch EV charging autonomously [25]. In addition, they are easier to implement and are more economically attractive when compared to centralized methods. What is common between centralized and decentralized control is that both methods solely operate on minimizing and distributing load from a DSO's perspective rather than just relying on minimum charging costs. The minimum load method assumes the presence of incentive regulations, as in the case of many European countries, in order to minimize the EV charging load when the corresponding house consumption is high and vice-versa [26]. The resulting load curve is an effective shift in the EV charging load to off-peak hours while respecting the grid capacity limits. In this way, the grid assets would be utilized to its maximum potential and would result in lower costs with regards to grid upgrades. Furthermore, the issue of utilizing the grid as much as possible is of major concern to a country such as the Netherlands. The distribution network is formulated of mainly underground medium voltage (MV) and LV cables [27]. Consequently, upgrading the existing grid capacity is avoided as much as possible giving room for innovative solutions to underlying problems. The third approach to controlling EV charging routines, however, is to use price-oriented methods to alter the EV users' charging behavior by giving monetary incentives. Control strategies that follow this approach generally determine a physical factor that would set the charging price in a specific time-period. Consequently, the customers are expected to change their consumption patterns in response to the time-dependent prices.

Market Based Approaches

In [14], a demand response strategy has been developed in order to reduce grid overload during peak hours of consumption. The goal of this demand response strategy is to encourage users to change their standard consumption patterns in response to changing electricity prices. In this way, users will be encouraged to shift their EV charging routines to off-peak hours and therefore reduce the pressure on the distribution transformer during peak hours of consumption. On the contrary, [26] argued that scheduling charging according to the Time-Of-Use (TOU) is only effective up to a certain extent and can often result in a second load peak during off-peak hours of consumption.

To avoid a second load peak in off-peak hours, [8] proposed a price-oriented approach that is directly influenced by the current loading on the distribution transformer. The amount of loading on the distribution transformer, in addition to the transformer temperature at a specific instant, are translated into a monetary value and then added to the current EV charging cost to result in a total charging cost for the user at that specific instant. As a result, during peak hours of consumption, users who do not require charging will find it economically attractive to charge later in the day when the total charging cost is low (i.e. the loading on the transformer is low). Since the charging cost is directly influenced by the level of heating and loading on the distribution transformer and not only the hour of consumption, the presence of a second load peak during off-peak hours is non-existent and impacts are mitigated at a higher scale.

Centralized Control

A smart charging solution has been proposed in [15] in which EV charging is only allocated in a 12-hour window that takes place between 6 pm and 6 am. The aim of this solution is to optimally allocate the best charging time for each EV at a specific node by minimizing voltage magnitude variations, at a local level, while taking into account user satisfaction (preferred time-window of charging, lowest cost of charging, etc.). However, this algorithm greatly relies on the EV users' input from the previous day, in addition to the day-ahead household load forecast, in order to optimally dispatch EV charging at either full power, half power, or zero power during the allocated charging period.

Since centralized control methods usually require a huge amount of information before the charging routine is dispatched, [12] suggests employing an EV aggregator to coordinate EV charging. An EV aggregator not only handles EV charging routines in a specific region, but also aims to support the DSO and comply with the network's operational limits. Furthermore, the proposed control strategy in [12] defines a set of charging powers, each with a different price range for the users. Users can charge at any power between 0 - 7.2 kW depending on their time flexibility (i.e. time of departure). In that way, users who are departing soon will charge at the maximum power, given the distribution grid is not overloaded, and will pay more for this service than a user who is very flexible and can wait to charge overnight. The fairness in this approach remains a major concern indeed; therefore, the idea of employing an EV aggregator has been extended in [7], where the EVs and aggregator directly contact each other to schedule the charging routines. In this approach, EV users would initially set the required charging powers and then the aggregator would calculate the estimated voltage magnitudes on the respective nodes and give its feedback to the EV accordingly. Communication between the EV and the aggregator will keep iterating up until convergence is achieved and the system is stable. The EV aggregator in this case effectively and fairly allocates power at a global level while still preventing under-voltages.

Decentralized (local) Control

An approach to detect and mitigate line congestion and under voltages at a local level has been proposed in [24] and [9]. The reasoning behind these approaches is the ability to detect the severity of a congested line by the amount of voltage drop at a specific node. As a result, the charging power/current is adjusted according to the condition of the charging node in order to relieve the stress on the grid. Furthermore, [19] supports this approach but also takes into account transformer overloading in order to effectively disperse the EV load and mitigate impacts. In addition, [9] and [19] both aim to achieve fairness among EV charging users while also complying with the distribution network's operational limits. An obvious drawback to the above approaches, however, has been proven in [20] where continuously adjusting the charging power in response to the distribution network's condition will affect the EV battery's State-Of-Health (SOH) in the long-term.

Additionally, EV users who have a high SOC percentage and remain idle for long periods of time can damage their batteries' SOH too [2]. Therefore, [29] and [28] suggest employing an approach that relies on the Vehicle-to-Grid technique (V2G) where EV users can participate in supporting the distribution network while getting rewarded. The technical principle of operation of the V2G technique is to supply power from the EV battery to the respective charging node. As a result, the voltage magnitude at that specific charging node increases. Therefore, EV users who remain idle for long periods of time can support a severely impacted region of the network and, at the same time, generate a considerable amount of money. Although V2G has proven to be effective for peak load shedding, the round-trip efficiency (of charging and discharging an EV battery) and the impact on the EV battery's SOH both remain ambiguous and under investigation [2].

2.4. Conclusion

To sum up, EV loads are of random nature and need to be coordinated in order to not overload the distribution grid and delay transformer aging. Other impacts such as line congestion and voltage magnitude violations can also be avoided. Consequently, a higher penetration of EVs coupled with faster EV chargers can be accommodated using the current grid capacity. Furthermore, a coordination method with an objective to minimize peak load has proven to greatly mitigate EV charging impacts when compared to the traditional price-oriented methods. Price-oriented charging methods usually produce a second load peak during the first few hours of the off-peak period while minimum load methods utilize the off-peak hours effectively and aim to spread-out the load during that time. Finally, in order to be implemented on a large-scale, user satisfaction is vital for any smart charging mechanism to be commercialized as compensations have to be made from the EV users' side as well as that of the DSO's. The increase in fairness and flexibility between the DSO and EV users will ultimately provide the best EV charging solution.

3

Control Algorithm Development

3.1. Introduction

In this chapter, the development of a decentralized control algorithm will be discussed. The control algorithm endorses the following assumptions:

1. An interactive platform between the user and DSO is already developed and operational. This platform will be used to communicate users' preferences to the charge controller.
2. Each household has a charging point with a charge controller installed. The charge controller should be able to communicate with the user in order to determine the dispatched charging power autonomously.

The proposed control algorithm aims to enhance user satisfaction by setting priorities for charging while also adhering to the constraints of the distribution system. Section 3.2 explains how voltage magnitudes are controlled locally in order to dispatch charging. Furthermore, Section 3.3 demonstrates how the Internet of Things (IoT) platform can be employed to set user-priorities for charging while Section 3.4 presents how the dispatched charging power is dependent on the EV's current State-of-Charge (SOC). Finally, how all parts of the control algorithm fit together is summarized and concluded in Section 3.5.

3.2. Local Voltage Control

The essence of the proposed control algorithm lies in its ability to dispatch EV charging for a specific user based on the current voltage magnitude measurement of the household connection. Assuming the distribution transformer is able to provide the charging power decided upon by the charge controller, the charging power is set as a function of the household voltage magnitude. Consequently, the lower the household voltage magnitude, the lower the charging power that would be dispatched and vice-versa. This not only aims to prevent voltage magnitude violations, but also aims to reduce line congestion and transformer loading.

Six key abbreviations need to be defined before diving deep into the local voltage control:

1. $V_{\mathbf{i,t}}$: represents the household voltage for user, i, at time-step, t.
2. $\hat{V}_{\mathbf{i,t}}{}^{\mathbf{min}}$: represents the cumulative moving average of the household voltage magnitude. This is calculated by taking the average of the household voltage for user, i, of all previous time-steps. The household voltage magnitude reflects on both, the user's day-to-day consumption and the user's EV charging routine. Practically, this would be considered as the minimum household voltage magnitude at time-step, t.
3. $V_{\mathbf{th}}$: represents the voltage threshold.
4. $P_{\mathbf{min}}$: represents the minimum limit for charging power dispatch.
5. $P_{\mathbf{max}}$: represents the maximum limit for charging power dispatch.
6. $P_{\mathbf{i,t}}{}^{\mathbf{char}}$: represents the dispatched charging power for user, i, at time-step, t.

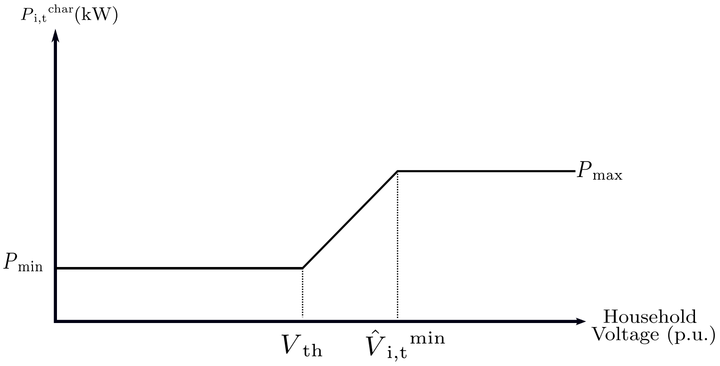


Figure 3.1: The EV charging power dispatched at time-step, t, directly depends on the voltage magnitude of the respective household user.

Figure 3.1 presents the standard EV charging dispatch curve that will be used throughout this thesis. This dispatch curve essentially has three main regions:

1. **If $V_{\mathbf{i,t}} \geq \hat{V}_{\mathbf{i,t}}{}^{\mathbf{min}}$, then $P_{\mathbf{i,t}}{}^{\mathbf{char}} = P_{\mathbf{max}}$.**

   This usually indicates that the household is not heavily loaded (i.e. the voltage magnitude is high) and the EV can charge at the maximum power.

2. **If $V_{\mathbf{th}} \leq V_{\mathbf{i,t}} < \hat{V}_{\mathbf{i,t}}{}^{\mathbf{min}}$, then $P_{\mathbf{i,t}}{}^{\mathbf{char}}$ is curtailed**.

   This means

   $$P_{\mathrm{i,t}}{}^{\mathrm{char}} = (V_{\mathrm{i,t}} * m) + c,$$

   where m and c are the line's slope and y-intercept, respectively, and calculated as follows:

   $$m = \frac{P_{\mathrm{max}} - P_{\mathrm{min}}}{\hat{V}_{\mathrm{i,t}}{}^{\mathrm{min}} - V_{\mathrm{th}}}$$

   $$c = P_{\mathrm{max}} - (\hat{V}_{\mathrm{i,t}}{}^{\mathrm{min}} * m)$$

   The purpose of this region is to gradually decrease $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ as the household voltage magnitude drops and gradually increase $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ as the household voltage magnitude increases.

3. **If $V_{\mathbf{i,t}} < V_{\mathbf{th}}$, then $P_{\mathbf{i,t}}{}^{\mathbf{char}} = P_{\mathbf{min}}$.**

   This usually indicates that the household is heavily loaded (i.e. the voltage magnitude is low) and the EV can charge at only the minimum power.

What is interesting to note is that regardless of how low the household voltage magnitude is, EV charging resumes but at a lower $P_{\mathrm{i,t}}{}^{\mathrm{char}}$. Therefore, in order to prevent any voltage magbitude violations as per the rules and regulations of EN 50160, V_{th} has to be chosen carefully (more emphasis on that in Chapter 4). Additionally, every household user will have a unique charging power dispatched at every time-step (where charging occurs) depending on which of the three aforementioned regions the household corresponds to. Therefore, the household voltage magnitude does not only reflect the dispatched charging power, but also reflects the respective household consumption. This local voltage control algorithm has been summarized in the flowchart in Figure 3.2.

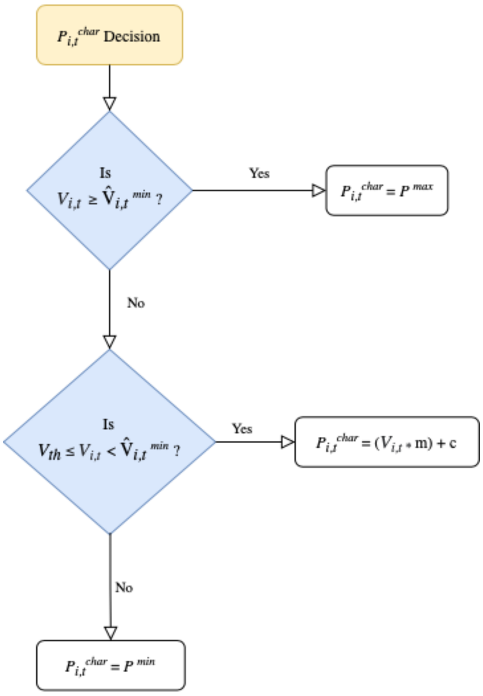


Figure 3.2: The flowchart describes the process in which the charge controller decides on the charging power to dispatch for user, i, at time-step, t. At any given time-step, a user may fall into one of the three regions depending on the EV and household load collectively.

3.3. Priority-Based Charging Strategy

To further enhance user satisfaction, three different charging strategies are proposed in which users can qualify for priority based on their SOC percentage, Time-of-Departure (ToD), or both. The fourth proposed charging strategy, however, qualifies users for priority based on the current loading on the distribution transformer supplying the LV network. Within each charging strategy lies three levels: high, moderate, or low priority level. As a result, users who qualify for a high priority level, for example, are allocated more charging power than that of the users with a moderate or low priority level. Consequently, instead of overloading the distribution network by all users charging at once, $P_{\mathrm{i,t}}^{\mathrm{char}}$ is effectively allocated to users who urgently require charging. The implementation of user priorities inherently assumes an interactive IOT platform has been developed and deployed. The purpose of this platform is for users to communicate their preferences to the charge controller which will then autonomously set a priority level to the respective user. EV charging would then be scheduled and dispatched as long as the distribution grid constraints are respected.

In Figure 3.3, the three distinct priority levels that will be used by the four proposed charging strategies are defined as follows :

1. **High priority level:** Users who qualify for high priority will charge with an adjusted minimum power, P'_{min}, that is higher than the original minimum charge power, P_{min}. As a result, the charge controller allocates the highest charging power to high priority users and charging is restricted between two, high charging powers.

2. **Moderate priority level:** Users who qualify for moderate priority will charge with an adjusted maximum power, P'_{max}, that is lower than the original maximum charge power, P_{max}. As a result, when compared to high priority users, the charge controller allocates less charging power to moderate priority users and charging is restricted between a moderate-to-low charging power.

3. **Low priority level:** Users who qualify for low priority will charge with a furtherly adjusted maximum power, P''_{max}, that is lower than both, the original maximum charge power, P_{max}, and the previously adjusted maximum charge power, P'_{max} (in moderate priority). As a result, the charge controller allocates the least amount of power to low priority users and charging is restricted between two, low charging powers.

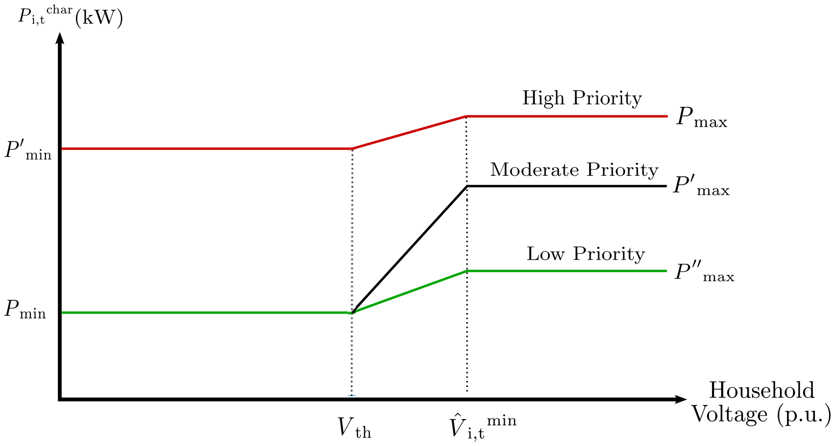


Figure 3.3: An extension to the basic EV charging dispatch shown in Figure 3.1. Once a user has been given a certain priority level, the P_{max} and P_{min} limits are set and $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ can be dispatched according to the user's household voltage magnitude.

Strategy I: Priority assigned based on SOC percentage

As the name suggests, this strategy sets user priority depending on the initial SOC percentage, $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}}$. Users with a low $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}}$ percentage will be given higher priority than users with a high $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}}$ percentage. The three priority levels are defined as follows:

1. A user qualifies for **high priority** if the user's $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}} \leq 40\%$.
2. A user qualifies for **moderate priority** if the user's $40\% < SOC_{\mathrm{i,t}}{}^{\mathrm{initial}} \leq 70\%$.
3. A user qualifies for **low priority** if the user's $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}} > 70\%$.

Strategy II: Priority assigned based on Time-of-Departure (ToD)

The second charging strategy sets user priority depending on the time a user intends to leave. The earlier the ToD is, the higher the priority level and vice-versa. The three priority levels are defined as follows:

1. A user qualifies for **high priority** if the user's ToD is within one hour.
2. A user qualifies for **moderate priority** if the user's ToD is more than one hour but within two hours.
3. A user qualifies for **low priority** if the user's ToD is more than two hours.

Since residential EV chargers are employed in this research, the power rating of these chargers is considerably lower than that of the commercially available, fast and ultra fast chargers; consequently, EVs connected to residential chargers need longer periods of time to charge. Therefore, it makes sense that the high and moderate priority levels for this charging strategy is set on the basis of one-hour intervals rather than few minutes. In that way, users who qualify for high or moderate priority under this control strategy, can benefit from a considerable amount of added SOC percentage towards the end of their charging period (i.e. just before the EV's ToD).

Strategy III: Priority assigned based on SOC percentage & ToD

To further extend the idea of priority-based charging, this charging strategy sets priority levels based on both, the $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}}$ percentage as well as the ToD of the respective EV. Accordingly, EV users with a low SOC percentage and earlier ToD are allocated more charging power than EV users with a higher SOC percentage or later ToD. The three priority levels are defined as follows:

1. A user qualifies for **high priority** if the user's $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}} \leq 40\%$ **and** the user is leaving within two hours.
2. A user qualifies for **moderate priority** if the user's $40\% < SOC_{\mathrm{i,t}}{}^{\mathrm{initial}} \leq 60\%$ **and** the user is leaving within two hours.

3. Else, a user qualifies for **low priority**. That essentially means the user is either leaving in more than two hours or leaving in the coming two hours but with an $SOC_{\mathrm{i,t}}^{\mathrm{initial}} > 60\%$.

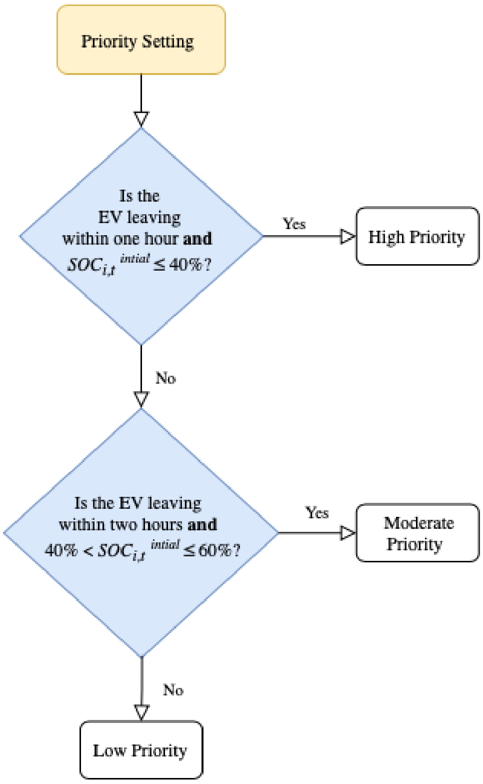


Figure 3.4: The flowchart summarizes how priority levels are set when employing a charging strategy that depends on both, the EV user's SOC percentage and ToD. EV users are checked for which priority level they qualify for at the start of every time-step where charging occurs.

Strategy IV: Priority assigned based on Distribution Transformer Loading

In the previous charging strategies, setting priority levels is directly related to the users' preferences. This means users were provided with the maximum and minimum charging power limits as a result of their EVs' SOC and/or ToD. In this charging strategy, however, the minimum and maximum charging power limits are defined and set based on the current loading on the distribution transformer regardless of the EV's SOC and ToD. Yet again, the three priority levels employed in the aforementioned charging strategies are used here and are defined as follows:

1. All users qualify for **high priority** if the current loading on the transformer is less than or equal to 80%. This threshold represents the normal operational limits of a typical distribution transformer and therefore users can charge at high power rates [11].
2. All users qualify for **moderate priority** if the current loading on the transformer is greater than 80% but less than or equal to a 100%. Users at this priority level can charge at a considerably lower charging power than that of the high priority level as the transformer is heavily loaded in this region of operation.
3. All users qualify for **low priority** if the current loading on the transformer exceeds 100% and therefore indicates the transformer is overloaded.

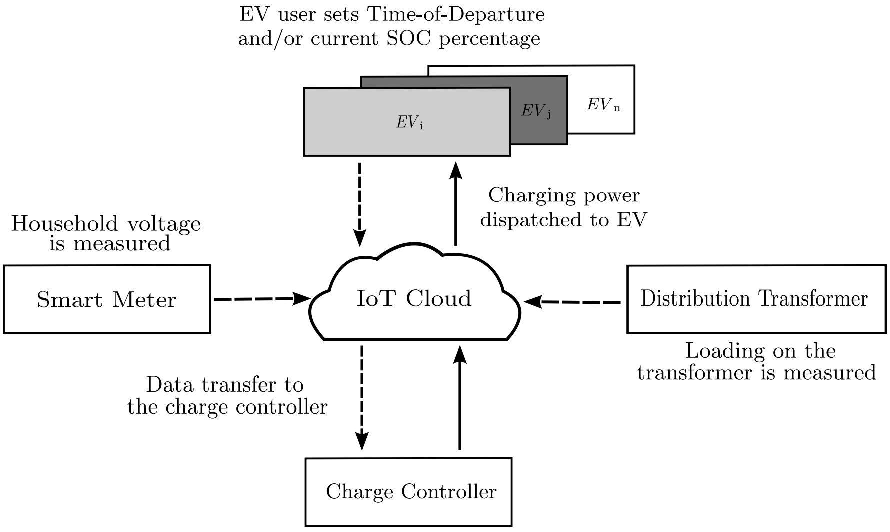


Figure 3.5: Three of the four proposed charging strategies dispatch power by setting priority levels depending on the user's preference. Depending on the charging strategy employed, the user is asked to set their Time-of-Departure and/or current SOC percentage once the user connects to the charging point. The charge controller then sets the minimum and maximum charging power limits and dispatches the charging power with respect to the voltage magnitude of the household connection. The fourth charging strategy sets the maximum and minimum charging power limits (priority level) with respect to the current loading on the distribution transformer. The charge controller then dispatches the charging power with respect to the voltage magnitude of the household connection. All information and decisions are exchanged through the IoT cloud as depicted in the figure.

3.4. Charging Power Decay

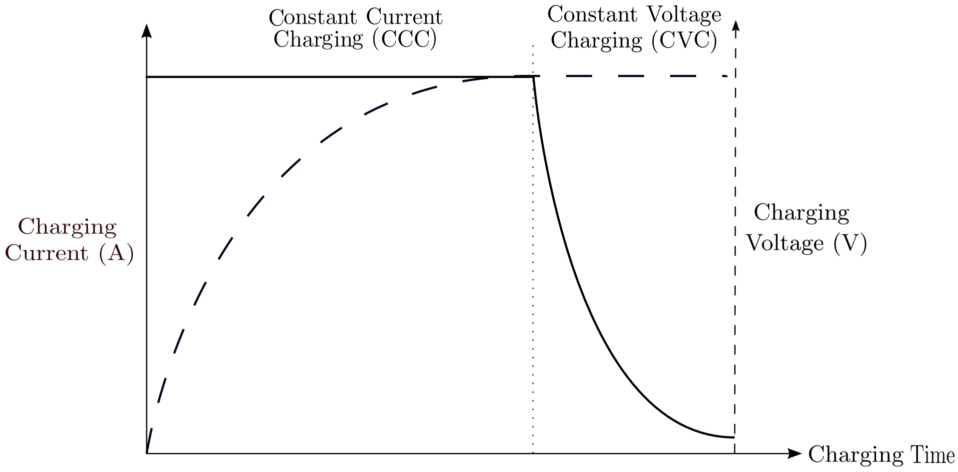


Figure 3.6: This curve shows the charging process of a typical Li-ion battery. The charging process relevant to EV charging is divided into a constant-current charging phase and constant-voltage charging phase.

The charging process of Lithium-ion (Li-ion) batteries usually takes place in three phases; of which the second and third phases are most prominently related to EV charging as shown in Figure 3.6 [22]. In the second phase (also known as constant-current charging), the charging current is constant while the voltage rises and consequently increases the charging power. Once a certain voltage level has been reached (usually towards the final, few percentages of the battery's SOC), the charging process enters into its third phase (also known as constant-voltage charging). In the third phase, the charging current decays exponentially, and therefore extremely decreases the charging power rate.

Therefore, before ${P_{\mathrm{i,t}}}^{\mathrm{char}}$ is finally dispatched by the local control algorithm, ${SOC_{\mathrm{i,t}}}^{\mathrm{initial}}$ is checked. If ${SOC_{\mathrm{i,t}}}^{\mathrm{initial}}$ is less than **93%**, ${P_{\mathrm{i,t}}}^{\mathrm{char}}$ would be dispatched as is (more emphasis on the choice of an SOC threshold of 93% is available in Appendix A.2). However, if ${SOC_{\mathrm{i,t}}}^{\mathrm{initial}}$ is greater than or equal to **93%**, ${P_{\mathrm{i,t}}}^{\mathrm{char}}$ would be multiplied by a decay factor of $(1 - {SOC_{\mathrm{i,t}}}^{\mathrm{initial}})$. This decay factor complies with the third phase of EV charging and also prevents batteries from being overcharged to more than 100% SOC . Figure 3.7 demonstrates this control check before $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ is finally dispatched.

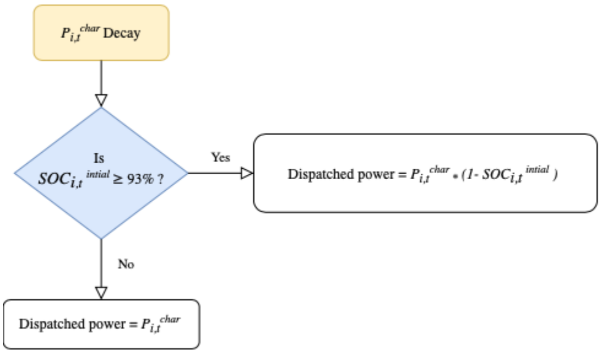


Figure 3.7: The flowchart shows how the charge controller decides whether or not to decay the charging power. This control check depends on the EV's initial SOC percentage before the charging power is dispatched at the given time-step.

3.5. Conclusion

In this chapter, the reasoning behind the control algorithm's distinct parts have been discussed and presented separately. This control algorithm aims to dispatch EV charging using a decentralised method with local voltage control at its essence. In addition, user experience and satisfaction has been enhanced by using an IoT platform that sets charging priority levels depending on the user's preference. Furthermore, to sum up how all the distinct parts of the control algorithm fit together:

1. The EV's $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}}$ is read.
2. The user's $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}}$ and ToD are processed by the charge controller to determine which priority level the user qualifies for.
3. Once the user qualifies for a certain priority level and the corresponding P_{min} and P_{max} limits have been defined, the charge controller will determine which $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ can be dispatched depending on the voltage magnitude of the user's household.
4. Before finally dispatching $P_{\mathrm{i,t}}{}^{\mathrm{char}}$, the charge controller will check the EV's $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}}$ to decide whether to decay $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ or not.

The whole charging strategy for the SOC & ToD Combined priority control is summarized in Figure 3.8.

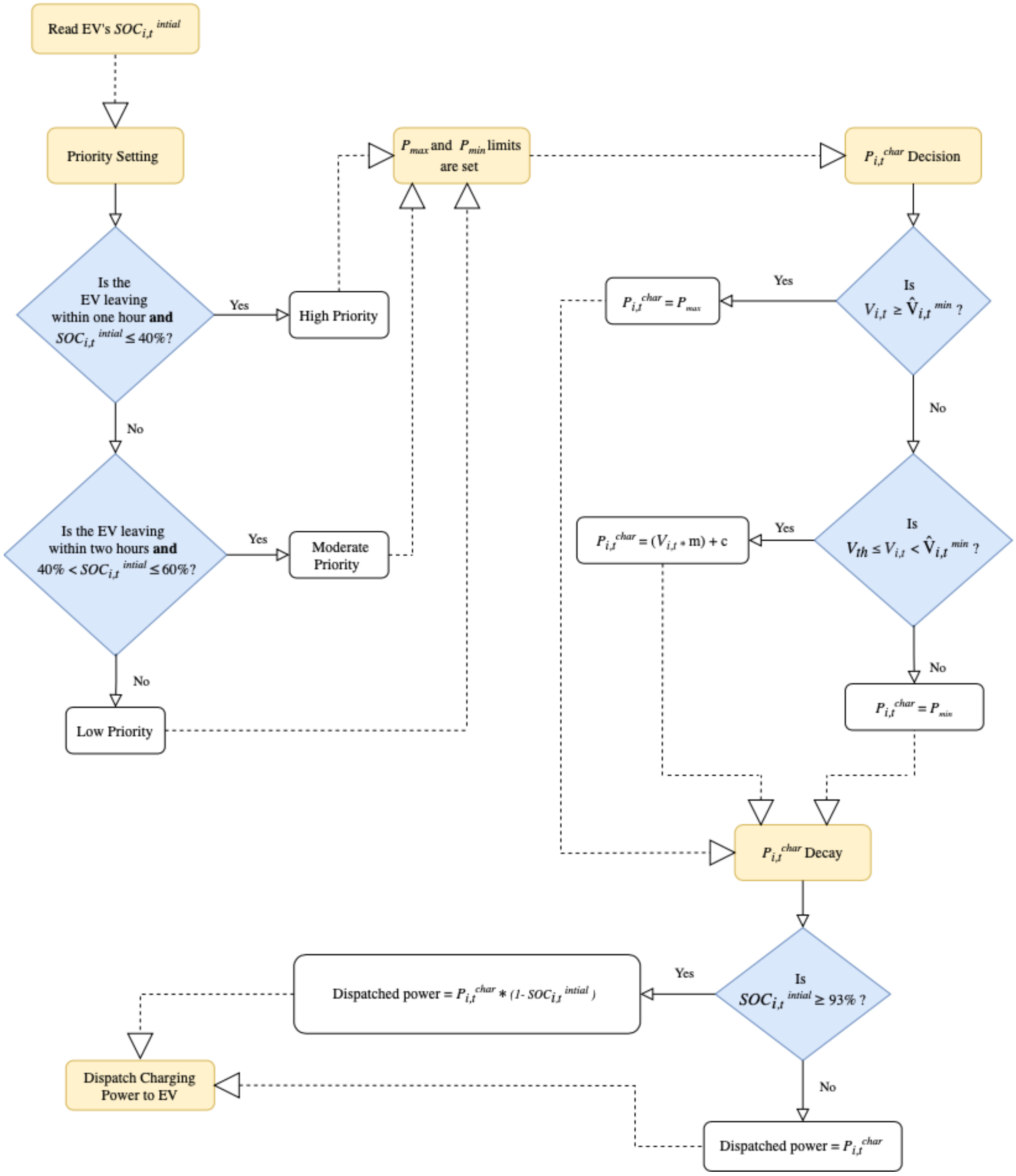


Figure 3.8: The flowchart presents the complete control algorithm overview with the "SOC & ToD Combined Priority Control" charging strategy. The EV's SOC is initially read at the beginning of time-step, t, and a priority level will then be set depending on the user's SOC and ToD. After the P_{min} and P_{max} limits are set, the charge controller checks the household's voltage magnitude to decide what charging power can be dispatched. Before the decided charging power is finally dispatched, the charge controller will check if it should be decayed or not, depending on which charging phase the EV is at (which is also directly related to the EV's current SOC percentage).

4

Scenarios & Results

4.1. Introduction

In order to test the performance of the proposed charging strategies developed in Chapter 3, a series of scenarios were adopted. The scenarios offer a variety of charging power limits and include the "Base" scenario, the "Netherlands Enterprise Agency (RVO)" scenario, and the "Future" scenario which will be discussed in detail along with their corresponding results in Section 4.3, 4.4, and 4.5, respectively. Furthermore, a sensitivity analysis for the threshold voltage parameter, V_{th}, and the minimum household voltage, $\hat{V}_{\text{i,t}}{}^{\text{min}}$, will be presented in Section 4.6 followed by a conclusion in Section 4.7.

Important simulation settings to take into account before indulging into the results:

1. For every scenario, the simulation ran for the same time-period of 672 time-steps which translates to one week of operation (every time-step equals 15 minutes).
2. The control parameter, V_{th}, was set at 0.95 p.u. for all scenarios (more reasoning to that choice is discussed in Section 4.6).
3. Unless stated otherwise, the EV penetration rate is set to 100% and each household has one EV.
4. The number of voltage magnitude violations associated with every control strategy is a global variable and indicates the total number of voltage magnitude violations in the whole residential grid and not only in the voltage profile of the presented user (if applicable).
5. In the EV's SOC curve, an SOC of 0% indicates the EV is disconnected from the charging point.

4.2. Case of Study

A typical distribution grid in the Netherlands usually starts from the HV/MV transformer station, through the MV/LV transformer station, and ends at the individual household connections. Power is transmitted in the MV and LV cables which are mostly underground. Conventionally, around 10 MV/LV transformers are connected to one MV cable and around 80 households are connected to one MV/LV transformer [27].

4.2.1. Residential Grid Topology and Load Profile

The residential grid under investigation endorses a topology that is similar to that of a conventional Dutch, distribution grid. In addition, the residential grid employed represents a real LV distribution grid and is provided by a Dutch DSO at a certain location in the Netherlands. The grid serves 86 households using a single, distribution transformer with a voltage rating of 11 kV/400 V and a nominal power rating of 150 kVA. The voltage magnitude of the reference bus/swing bus is set at 1.0 p.u. Not all feeders are identical as every feeder contains a different number of households and each household is connected to one-phase or three-phase. This residential grid is shown in Figure 4.1.

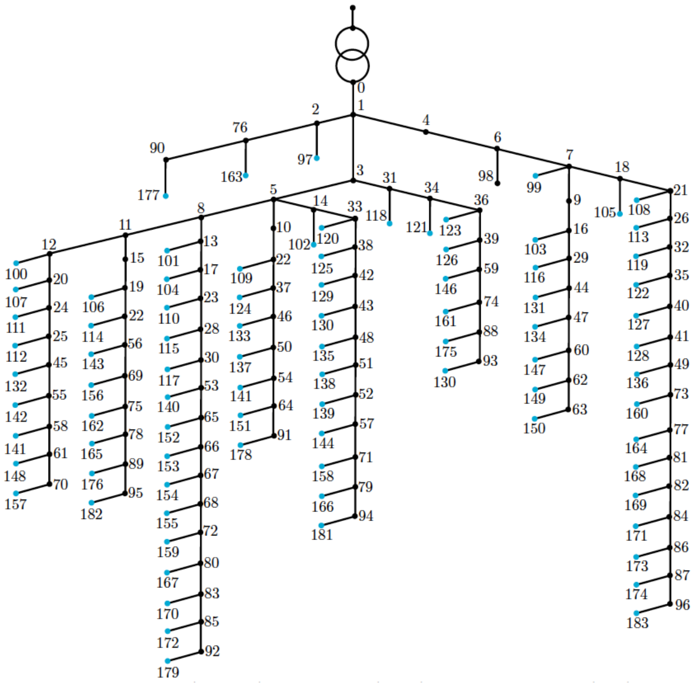


Figure 4.1: Residential grid with one MV/LV transformer serving 86 households. Each blue dot represents a household user and their corresponding user number.

The load profile of each household is obtained from real, smart meter measurements for one year. The measurements are arranged into 15-min time slots. The load profile for the total power demanded by all 86 households throughout the first week of the year is plotted in Figure 4.2. A typical Dutch household consumes the most amount of power during the evening hours of every day as shown in the seven peaks depicted in the figure.

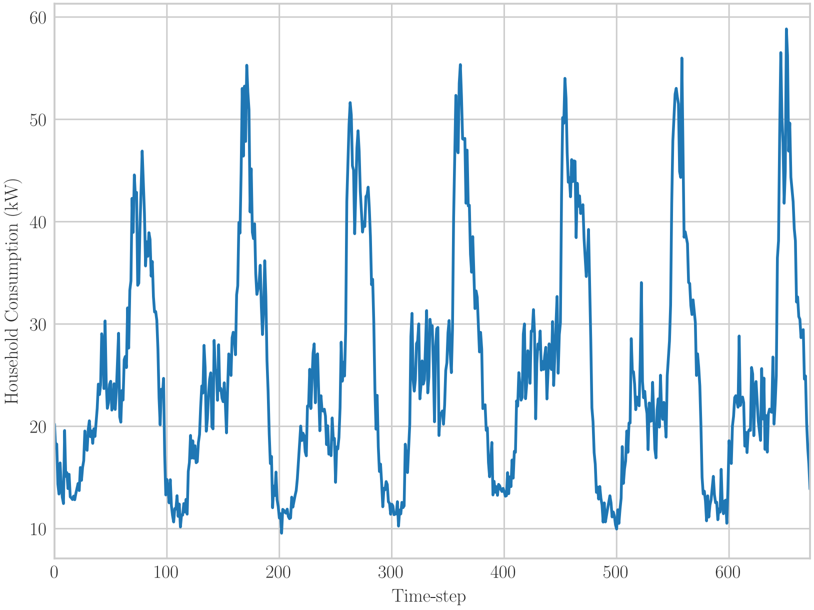


Figure 4.2: The total household consumption of 86 users for one week. The peaks in the household consumption curve show that the highest consumption occurs during the evening of everyday.

4.2.2. EV Load Profile and Battery Pack

The EV load profile has been obtained from the U.S. Department of Energy and includes 348 EVs corresponding to 200 households in the Midwest region [23]. The data set is formulated of 10-min time-slots for one year. For the purpose of this research, only 86 EVs were considered randomly from the pool of 348 EVs in the aforementioned data set. Each EV corresponds to one household and has the same number label as that of the household user. Since a different set of scenarios with various charging powers will be considered, this data set is of major importance as it provides the time-of-arrival and time-of-departure (i.e. consumption patterns) for each EV User and therefore the charging powers can be set by the charge controller accordingly.

Additionally, the battery pack considered in this research is that of a Nissan Leaf. The battery pack capacity is 40 kWh with an average real-range of 220 km depending on the ambient temperature of the corresponding geographical location. This battery has a Type 2 charging port with a typical charging power of 3.6 kW AC, but can also accommodate a maximum charging power of 46 kW DC (provided by fast chargers) [1]. Furthermore, the standard Type 2 charge ports are appointed by the European Commission and EVs employing Type 2 ports usually have a maximum charging power of approximately 22 kW [3].

4.3. Scenario I: Base

The most prominent residential chargers in the Netherlands adopt the so-called "Mode 2" charging technique [3]. Mode 2 chargers can normally provide a maximum charging power between 2.3 kW and 3.7 kW using a one-phase connection as per the RVO guidelines [3]. As a result, the "Base" scenario is developed on the basis of providing the most likely scenario to occur in today's world. The parameters of interest for this scenario are summarized in Table 4.1.

Table 4.1: Base scenario parameters.

Parameter	Power Rating (kW)	Priority
P_{max}	3.7	High
P'_{max}	2.5	Moderate
P''_{max}	1.7	Low
P'_{min}	3.0	High
P_{min}	1.2	Moderate & Low

4.3.1. Voltage Magnitude Regulation

Initially, User 182 was chosen due to its presence at the end of one of the feeders (which means the voltage magnitude is considerably lower than that of the users on top of the feeder) and also due to its extensive EV charging profile as opposed to the other users located at the end of the other feeders. Although these qualities make User 182 a good candidate; however, User 182, in specific, has not shown any voltage magnitude violations for this scenario. Therefore, to prove voltage magnitude violations occur in this scenario, the residential grid has been simulated with uncontrolled EV charging at a maximum charging power of 3.7 kW and the voltage profile of User 179, which is also at the end of one of the feeders but has a much less EV charging profile, has been plotted in Figure 4.3.

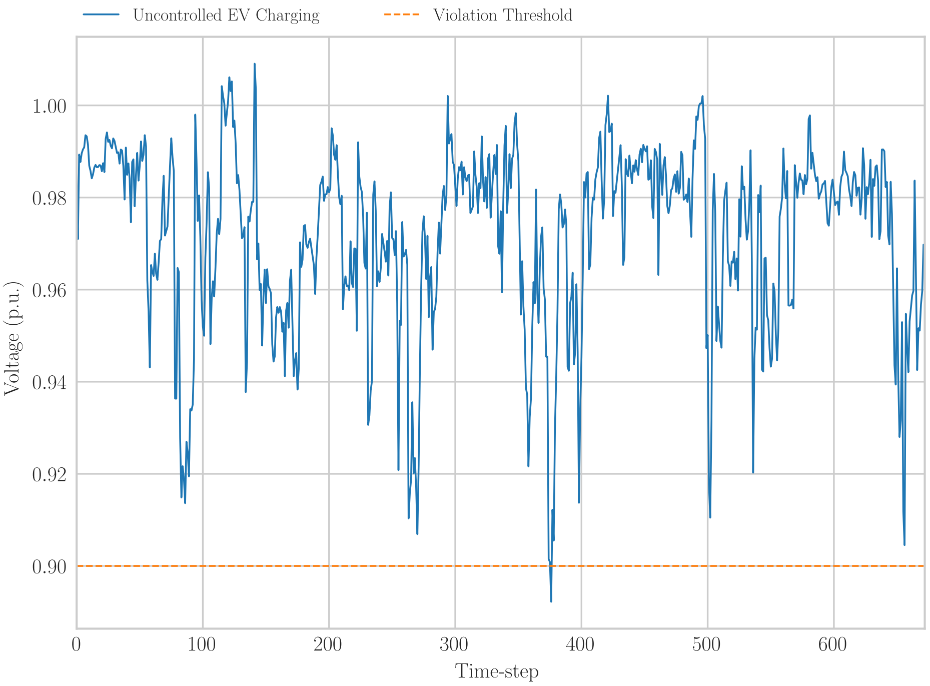


Figure 4.3: Voltage profile of User 179 with uncontrolled EV charging in the base scenario. The violation threshold has been crossed once in approximately time-step 375.

For User 179, a voltage magnitude violation has been recorded on one occasion during the one-week simulation period. In addition, the total number of voltage magnitude violations across the residential grid has summed up to 112 violations with uncontrolled EV charging during that same week of operation. Furthermore, to compare the performance of the charging strategies developed in Section 3.3, the residential grid has been simulated under six strategies:

1. Household consumption without EVs.
2. Uncontrolled EV charging.
3. Controlled EV charging with SOC-based priority.
4. Controlled EV charging with ToD-based priority.
5. Controlled EV charging with SOC-based and ToD-based (combined) priority.
6. Controlled EV charging with priority based on the distribution transformer loading.

Household consumption without EVs resulted in 0 voltage magnitude violations and a voltage profile between approximately 0.97 p.u. and 1.0 p.u which reflects the normal day-to-day consumption. Since 112 voltage magnitude violations have resulted due to the absence of coordinated charging, one would expect the charging strategies to mitigate the impacts of under-voltage. Consequently, SOC-based priority control, ToD-based priority control, Transformer Loading priority control, and SOC & ToD Combined priority control resulted in 8, 14, 12, and 0 voltage magnitude violations, respectively. It is evident from these results that formulating a control strategy based on only one factor will not fully mitigate the resulting impacts. If the SOC-based charging strategy is considered, EVs are prioritized in terms of their SOC percentages without taking into account when their respective ToD is scheduled. As a result, if two EV users had the same SOC percentage, both would be assigned the same level of priority even if one of the users is leaving in one hour and the other user is leaving in eight hours, for example. On the contrary, the ToD-based charging strategy would set priorities solely depending on the EV's ToD without taking into account the EV's SOC percentage. Consequently, if two users are leaving at the same time, they would be prioritized at the same level even though one user could have a very low SOC percentage while the other has a high SOC percentage. Additionally, the transformer loading priority control defines the same priority level and charging power limits across all users while taking into account the current loading on the distribution transformer. This, therefore, does not take into account any user preference and adds extra stress on the distribution network as some users may not require charging immediately. However, SOC & ToD Combined priority control has eliminated all voltage magnitude violations and also provided a better voltage profile than that of the other control strategies. This is because users who do not urgently require charging are prioritized at a lower level than that of users who severely require charging; therefore, relieving the grid from any extra stress. The aforementioned results are plotted in Figure 4.4 and tabulated in Table 4.2.

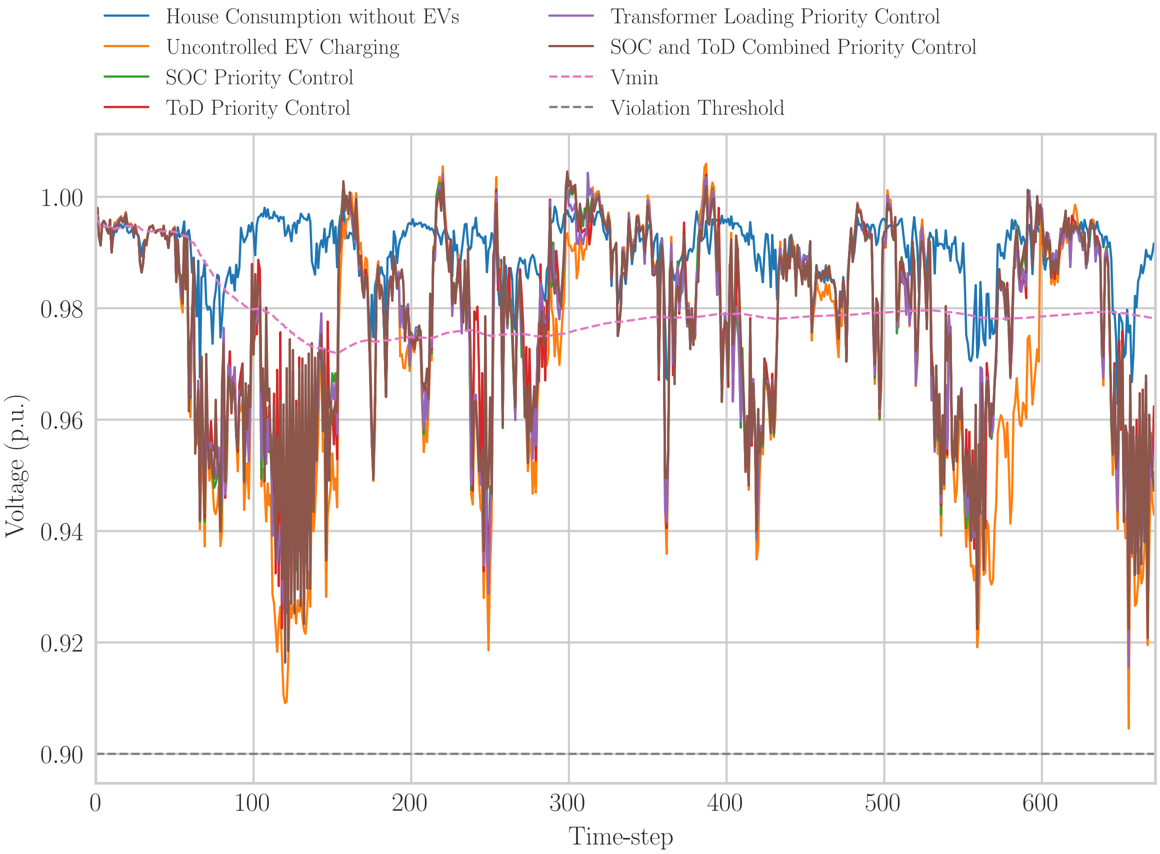


Figure 4.4: Voltage profile of User 182 under six strategies in the Base scenario. The voltage profiles have been improved under the four charging strategies, specifically when employing SOC & ToD Combined priority control.

Table 4.2: Voltage magnitude violations per strategy used in the Base scenario .

Strategy	**Number of Voltage Violations**
House consumption without EVs	0
Uncontrolled EV charging	112
SOC priority control	8
ToD priority control	14
Transformer Loading priority control	12
SOC & ToD Combined priority control	0

4.3.2. Distribution Transformer Loading

The three, distinct regions of interest for transformer loading are shown in Figure 4.5. Any transformer loading percentage less than or equal to 80% is considered as normal load. The normal load region is the most desirable region of operation as it provides an appropriate reserve of power while preserving the transformer life due to lower thermal heating and lower energy losses. Furthermore, any transformer loading percentage higher than 80% but less than 100% is considered as heavy load. Finally, any transformer loading percentage greater than 100% indicates the transformer is overloaded and the load must be curtailed immediately to avoid any damage to the distribution transformer.

Under normal household consumption in this scenario, the transformer loading barely exceeds 40% and is plotted in a dashed-blue line in Figure 4.5. It also proves that the highest transformer loading occurs during the peak hours of consumption towards the end of every day. Additionally, this figure proves that most of the loading on the distribution transformer is owed to EV charging which indicates the importance of employing a coordinated charging strategy especially at high charging power rates. For this scenario, however, the uncontrolled charging strategy has not resulted in an overload in the distribution transformer, but has heavily loaded the distribution transformer to approximately 90% of its power rating during the peak hours of consumption of the third day of operation. Furthermore, all charging strategies have successfully brought down the loading percentage from the heavy load region to the normal load region as the power drawn by the EVs is curtailed to adhere to the minimum voltage magnitude threshold of every household connection. In spite of that, whenever charging occurred during peak hours of consumption, the Transformer Loading priority control has shown a higher transformer loading percentage than that of the the other charging strategies as all EV users are prioritized at a high priority level as long as the distribution transformer loading is less than 80%. On the contrary, the other coordinated charging strategies rely on user-oriented factors (such as SOC & ToD) to set a priority level; therefore, users will not qualify for a priority level up until the requirements of the respective charging strategy are met regardless of the transformer loading. Finally, the resultant impacts on the distribution transformer loading in this scenario suggests no upgrades are needed with regards to the transformer capacity.

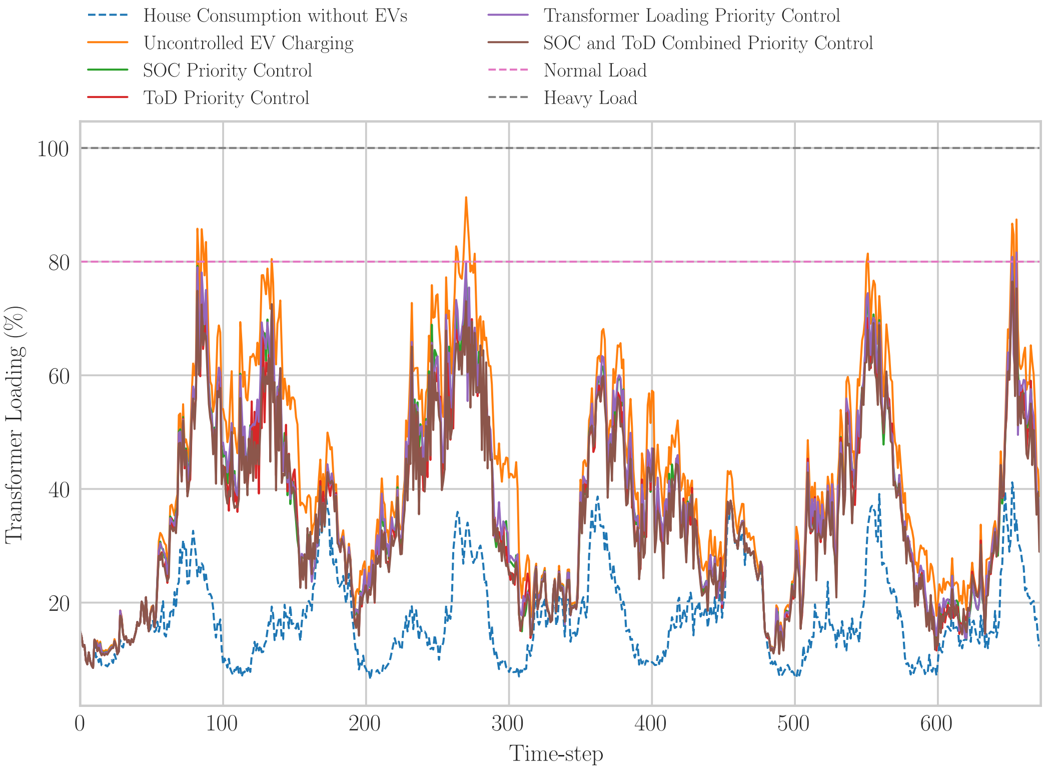


Figure 4.5: This plot shows the transformer loading percentage per strategy in the Base scenario. The plot emphasizes that the loading on the distribution transformer is mostly owed to EV charging rather than household consumption. Uncontrolled EV charging heavily loads the distribution transformer while the control strategies aim to mitigate and decrease the loading on the distribution transformer.

4.3.3. Impact on the User

The promising results of this scenario suggest that the current grid capacity can handle an EV penetration rate of 100% without causing any voltage violations (given the SOC & ToD Combined priority control is employed). However, an investigation to what extent the EVs' SOC percentages are being charged with respect to uncoordinated charging and all four charging strategies is of utter importance in order to know if EV users would be inclined to enroll in a coordinated charging program and support the DSO. To do so, the SOC of EV 182 (corresponding to household User 182) resulting from different charging strategies is plotted in Figure 4.6. Furthermore, the SOC resulting from each charging strategy is compared with the SOC resulting from the uncontrolled strategy in order to calculate the difference during every charging period. The SOC deviation from the uncontrolled charging strategy is plotted in Figure 4.7.

Since uncontrolled EV charging simply applies the maximum charging power continuously, one would expect this strategy to charge the EVs faster than the other coordinated charging strategies. As a result, the difference in SOC between the coordinated charging strategies and the uncontrolled charging strategy is high when the charging period is short. This can be seen in the charging period that shortly started after time-step 100 in Figure 4.6. The SOC deviation at the end of this charging period is shown in figure 4.7 where the exact difference in SOC between the coordinated and uncoordinated charging strategies is between 10% to 23% (depending on the charging strategy employed). This is because the coordinated charging strategies cannot always apply the maximum charging power as the dispatched charging power is heavily dependent on the voltage magnitude of the household connection regardless of what priority control the respective charging strategy is adopting. However, it can be concluded that the longer the charging period, the lower the SOC difference between the uncontrolled and controlled strategies. This can be observed in Figure 4.6 at exactly time-step 600, when EV 182 disconnected from the charging point after being connected for approximately 50 continuous time-steps (equivalent to 12.5 hours). To put this into perspective, let's consider the ToD priority control strategy for this 12.5 hour charging period. At the beginning of the charging period, EV 182 will be prioritized at a low level regardless of the SOC percentage and therefore more power will be allocated to other users who are leaving shortly. As the EV approaches its ToD, the priority level will be increased (i.e the charging power rate is increased) in order to charge the EV as much as possible before its ToD. This is why the SOC deviation from that of the uncontrolled strategy is nearly 9% at the beginning of the charging period but diminishes to less than 2.5% at the end of the charging period. Additionally, all the other coordinated charging strategies showed nearly similar SOC deviations from that of the uncontrolled strategy which proves that approximately the same SOC percentage can be achieved at the end of a given charging period suggesting that EV users may be highly inclined to participate in a coordinated charging program.

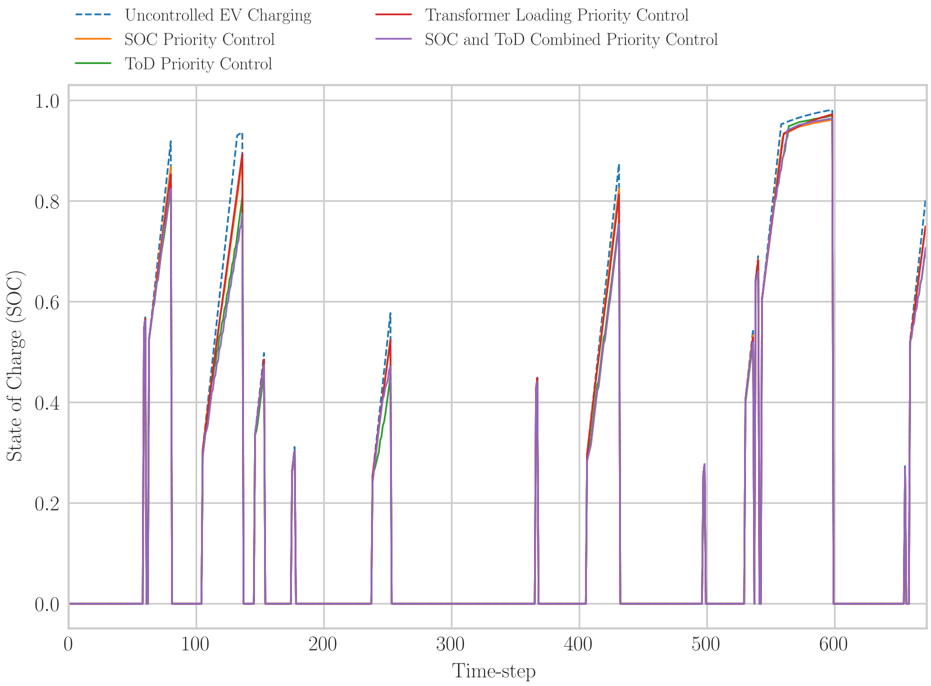


Figure 4.6: The resulting SOC for EV 182 using the uncontrolled and controlled charging strategies for the Base scenario is plotted in this figure. The highest SOC percentage has been reached under the uncontrolled strategy while the controlled strategies aimed to reach the same SOC percentage while taking into account the local voltage magnitudes of the household connections.

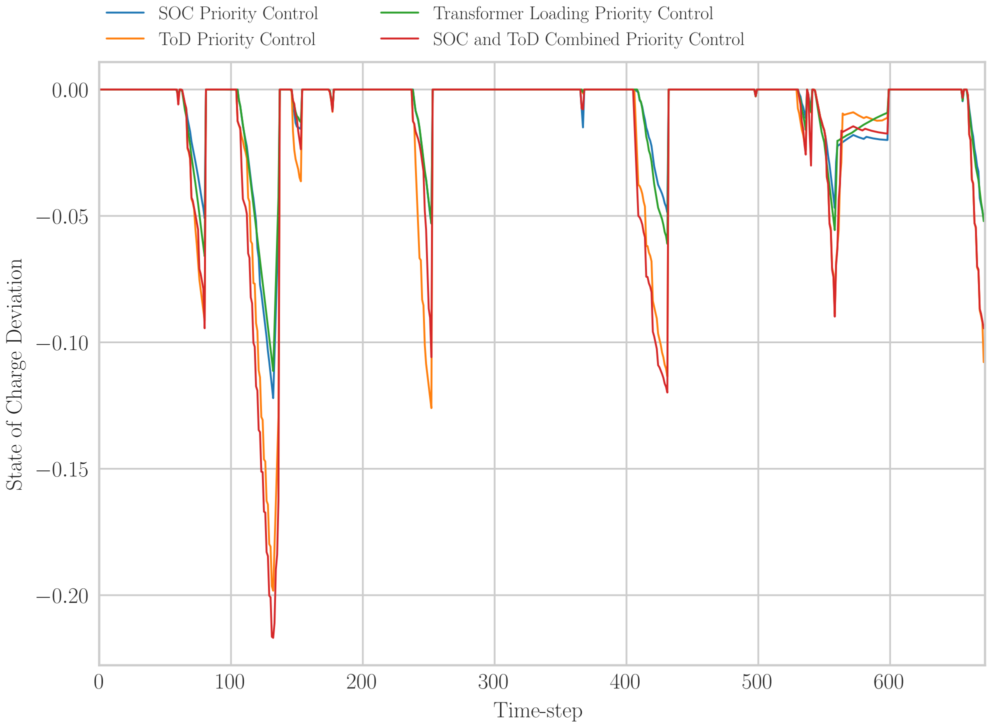


Figure 4.7: This plot shows the difference in SOC between all charging strategies compared to the uncontrolled strategy in the Base scenario. It is evident that at shorter charging periods, the SOC deviation between a controlled charging strategy and the uncontrolled one is high; however, if the EV is connected for a long period of time, the deviation in SOC between the uncontrolled and controlled charging strategies is minimized to less than 2.5% SOC.

4.3.4. Evaluation at Different EV Penetration Rates

The aforementioned results evaluated the uncoordinated charging strategy and coordinated charging strategies at an EV penetration rate of 100%. This means every household user has one EV, summing up to a total of 86 EVs in the whole distribution network. In order to further extend these results, the distribution network is evaluated at these additional EV penetration rates:

1. At **0%**, meaning the only load in the distribution network is from the 86 household users.
2. At **26.7%**, which translates to 23 EV users in the distribution network.
3. At **50%**, which translates to 43 EV users in the distribution network.
4. At **74.4%**, which translates to 64 EV users in the distribution network.

At every penetration rate, the total number of voltage and transformer violations are recorded in order to have an understanding to what extent the current grid capacity can handle a certain number of EVs. Recall, a voltage magnitude violation is recorded when the voltage magnitude of a single household connection drops below 0.9 p.u at a given time-step. However, a transformer violation is recorded whenever the transformer exceeds its power rating (i.e the transformer is overloaded and is operating at more than 100% of its capacity).

Under all charging strategies (whether coordinated or uncoordinated) in this scenario, the current grid capacity can handle an EV penetration rate of 100% without showing any transformer violations as shown in Figure 4.5 previously. On the contrary, with exception to the SOC & ToD Combined priority control, voltage magnitude violations are present in all other charging strategies with an EV penetration rate of 50%, 74.4%, and 100%; yet, no voltage magnitude violations were recorded across all strategies with an EV penetration rate of 26.7%, which indicates the extent to which the current grid capacity can handle uncontrolled EV charging in this scenario. Finally, no voltage magnitude violations are recorded with an EV penetration rate of 0% as the only load present in the distribution network comes from the day-to-day household consumption. The resultant voltage violations per charging strategy per EV penetration rate are tabulated in Table 4.3 and plotted in Figure 4.8.

Table 4.3: Resulting voltage magnitude violations per charging strategy per EV penetration rate in the Base scenario.

Strategy	**0%**	**26.7%**	**50%**	**74.4%**	**100%**
Uncontrolled charging	0	0	12	62	112
SOC priority control	0	0	1	3	8
ToD priority control	0	0	3	4	14
Transformer Loading priority control	0	0	5	9	12
SOC & ToD Combined priority control	0	0	0	0	0

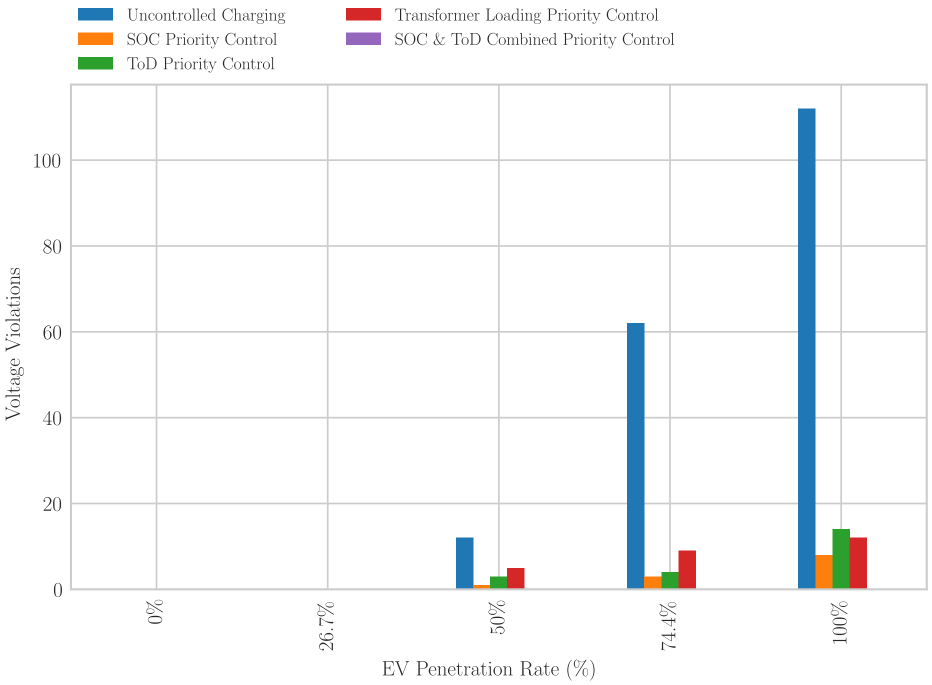


Figure 4.8: This bar chart shows the number of voltage magnitude violations per charging strategy per EV penetration rate in the Base scenario. As the number of EV users increases, the impact on the grid gradually increases as evident in the uncontrolled charging strategy. The coordinated charging strategies aim to reduce voltage magnitude violations as much as possible, but only the SOC & ToD Combined priority control fully mitigated the resulting impact on the distribution network.

4.4. Scenario II: Netherlands Enterprise Agency (RVO)

Although Mode 2, residential chargers in the Netherlands are generally rated between 2.4-3.7 kW, they can be rated up to a maximum of 7.4 kW for a one-phase connection; given EV charging is controlled by an In-Cable-Control-Box (ICCB) and the supply current is rated at 32 Ampere (A) [3]. This therefore provides a faster charging capability for the EV users to enjoy by dropping down charge time by approximately 2-3 times. Although customer satisfaction is vital for the electrification of the mobility sector, such scenario needs to be investigated from the DSO's perspective in order to have a clear idea of the challenges coming forth. Therefore, the "RVO" Scenario is developed to investigate how enhancing EV users' leisure can affect the current distribution grid. The parameters of interest for this scenario are summarized in Table 4.4.

Table 4.4: RVO scenario parameters.

Parameter	Power Rating (kW)	Priority
P_{max}	7.4	High
P'_{max}	5	Moderate
P''_{max}	4	Low
P'_{min}	6.5	High
P_{min}	3.7	Moderate & Low

4.4.1. Voltage Magnitude Regulation

To remain consistent with the results presented in the first scenario, User 182 has been employed in this scenario too. In addition, the residential grid has been simulated under the same six strategies that were used in the first scenario. Given that P_{max} has been doubled in this scenario in comparison to that of the first one, one would expect to observe more voltage magnitude violations. The resulting impact on voltage magnitude regulation is plotted and tabulated in Figure 4.9 and Table 4.5, respectively.

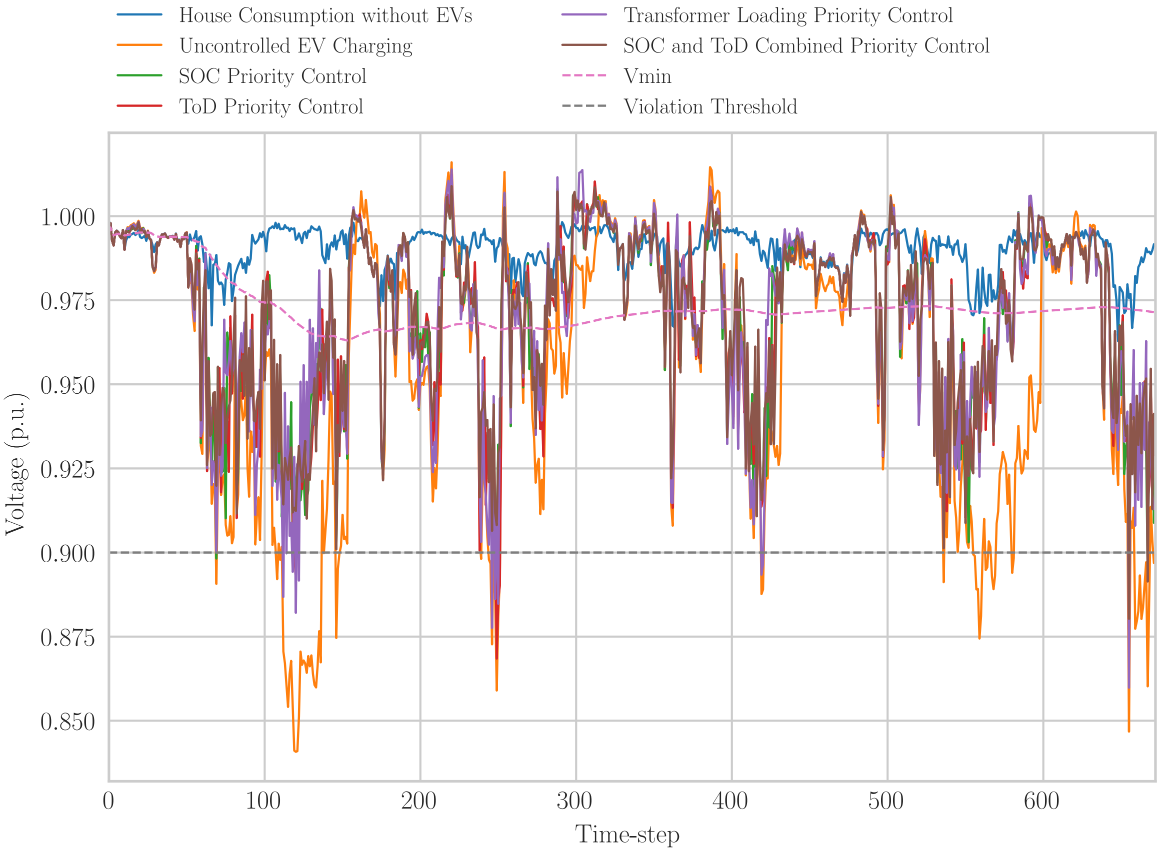


Figure 4.9: Voltage profile of User 182 under six, different strategies in the RVO scenario. Uncoordinated charging with a 7.4 kW power rating causes severe voltage impacts with voltage magnitudes reaching as low as 0.85 p.u. Additionally, coordinated charging strategies have provided a better voltage profile and mitigated voltage magnitude violations in most of the time periods.

Table 4.5: Voltage magnitude violations per strategy used in the RVO scenario.

Startegy	**Number of Voltage Violations**
House consumption without EVs	0
Uncontrolled EV charging	3,107
SOC priority control	725
ToD priority control	1,087
Transformer Loading priority control	1,327
SOC & ToD Combined priority control	580

As suggested by [3], Mode 2 charging can provide high charge rates given that charging is controlled. Consequently, uncoordinated charging with such high power rates has shown a severe impact on the residential grid voltage with voltage magnitudes reaching as low as 0.85 p.u. in User 182 and a total of 3,107 voltage magnitude violations for just one week of operation. Coordinated charging strategies have decreased the impact by approximately 3 times using ToD-based and transformer loading priority controls, by 6 times using SOC-based priority control, and by 7 times using the SOC & ToD Combined priority control. Yet again, the SOC & ToD Combined priority control has mitigated the under-voltage impact on the residential grid at a higher scale than that of the other control strategies. Additionally, comparing the voltage magnitudes at nearly every time-step, the voltage level was the highest with combined priority control than with any other strategy. As a result, apart from decreasing the number of voltage magnitude violations, it provides a larger margin for users to consume more power in their day-to-day household consumption.

4.4.2. Distribution Transformer Loading

Since the resulting voltage magnitude violations were not fully mitigated in this scenario, one would expect the transformer loading to exceed its operational capacity especially with the uncontrolled strategy. In Figure 4.10, employing the uncontrolled strategy generally overloaded the distribution transformer on many occasions with loading percentages reaching as high as 140%. On the other hand, the controlled charging strategies have brought down the transformer loading to the heavy load and normal load regions during most instances of the one-week period of operation. Such results are expected as each controlled charging strategy aims to curtail the charging power when the voltage magnitudes suddenly drop at charging nodes. Curtailing the power drawn by the loads not only increase the nodal voltage magnitudes, but also decreases the loading on the transformer. This is vital for preserving the distribution transformer's life span as overloading the transformer for extended periods of time often generates a large amount of heat that consequently damages its internal components. Since the distribution transformer has been overloaded at very few occasions when employing any of the controlled charging strategies, these results suggest that an upgrade to the transformer capacity is not urgently required; however, considering a minor upgrade is highly suggested since the loading on the transformer would further decrease and therefore less thermal heat would be produced and less damage to the transformer's internal components would be observed.

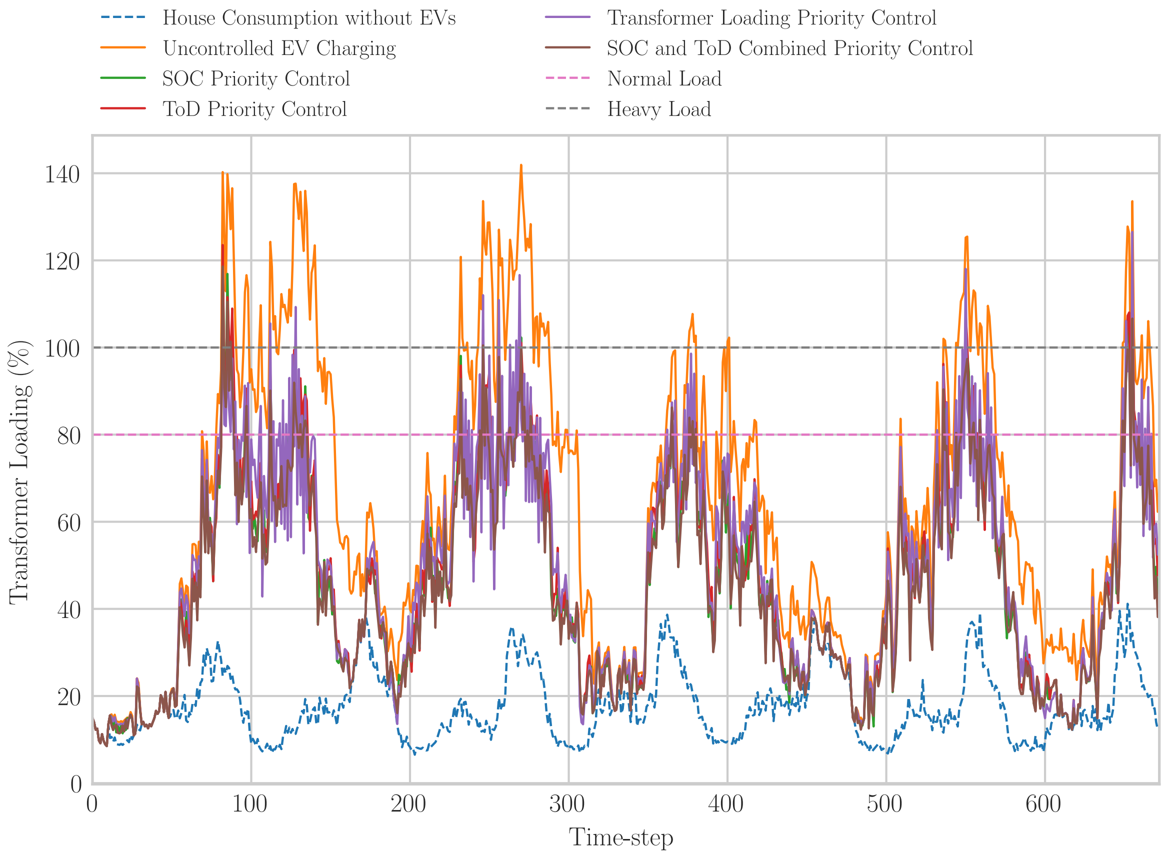


Figure 4.10: This plot shows the transformer loading percentage per strategy in the RVO scenario. Most of the transformer overloading is observed in the uncontrolled charging strategy with few occasions observed in the controlled charging strategies. The coordinated strategies always aim to improve the voltage profile at a local level which reflects on the lower loading percentage on the distribution transformer when compared to the uncontrolled strategy.

4.4.3. Impact on the User

In the previous scenario, neither the uncontrolled charging strategy nor the coordinated ones have fully charged EV 182 during the one-week period. In this scenario, however, the SOC percentage has reached 100% using the uncontrolled charging strategy at time-step 600 in Figure 4.11. This scenario also showed considerably higher SOC percentages across all charging periods when compared to that of the previous scenario. This result is expected given that the maximum charging power rate has been doubled in this scenario. Additionally, doubling the maximum charging power means the SOC deviation (plotted in Figure 4.12) between the uncoordinated and coordinated charging strategies should be higher than that of the first scenario during short charging periods. This can be seen at time-step 250 where the maximum SOC deviation is 12.5% in the Base scenario and 32.5% in the RVO scenario. Although the SOC deviation has increased during short charging periods, the SOC deviation has decreased during long charging periods in this scenario too. This can be observed at time-step 600 where the SOC deviation at the end of the 12.5-hour charging period is less than 2.5% in the Base scenario and less than 1% in the RVO scenario. Nevertheless, the faster charging and decreased SOC deviations in this scenario came at the expense of causing more voltage magnitude violations and higher loading on the distribution transformer during many instances of the week.

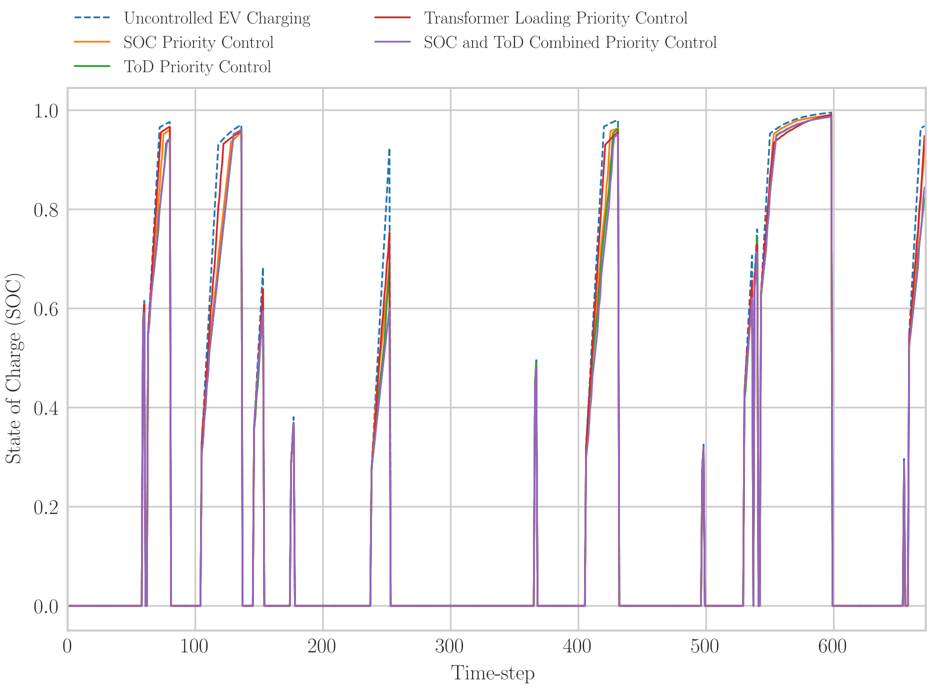


Figure 4.11: The resulting SOC for EV 182 using the uncontrolled and controlled charging strategies for the RVO scenario is plotted in this figure. The highest SOC percentage has been achieved under the uncontrolled strategy as expected. Additionally, the SOC percentages across all charging periods have increased when compared to the Base scenario.

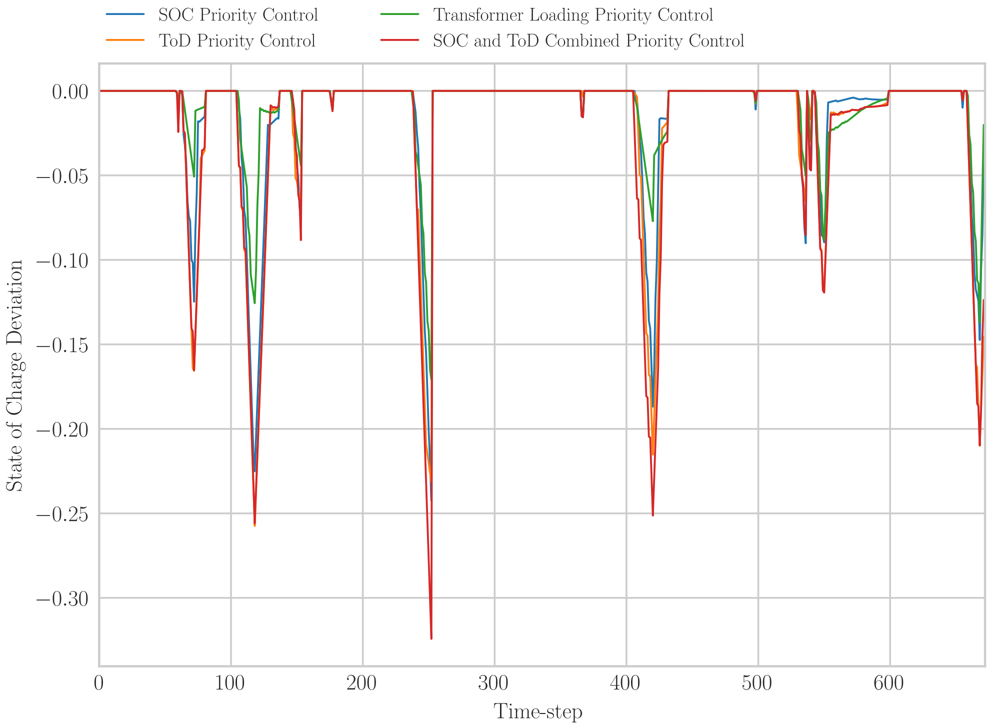


Figure 4.12: This plot shows the difference in SOC between all charging strategies compared to the uncontrolled strategy in the RVO scenario. Compared to the Base scenario, the higher charging powers in this scenario have increased the SOC deviation during short charging periods and further decreased the SOC deviation during the long charging periods.

4.4.4. Evaluation at Different EV Penetration Rates

In this scenario, the current grid capacity cannot handle any of the EV penetration rates (used for evaluation) as voltage magnitude violations were recorded with penetration rates as low as 26.7%. This result is expected given that the maximum charging power has doubled when compared to that of the Base scenario. Nonetheless, coordinating charging at an EV penetration rate of 26.7% and 50% has not resulted in any transformer violations while these violations were more prominent at EV penetration rates of 74.4% and 100%. Uncontrolled charging, in specific, has resulted in transformer violations that are ten times more than that of any other coordinated strategy which also explains why the voltage magnitude violations in the uncontrolled strategy summed up to 3,107 violations. Yet again, the SOC & ToD Combined priority control has shown the least number of both, voltage magnitude and transformer violations at every EV penetration rate. However, voltage magnitude violations are not fully mitigated under this charging strategy which suggests the current grid capacity requires an upgrade. The resultant voltage magnitude violations per charging strategy per EV penetration rate are tabulated in Table 4.6 and plotted in Figure 4.13. Finally, the resultant transformer violations per charging strategy per EV penetration rate are tabulated in Table 4.7 and plotted in Figure 4.14.

Table 4.6: Resulting voltage magnitude violations per charging strategy per EV penetration rate in the RVO scenario.

Strategy	**0%**	**26.7%**	**50%**	**74.4%**	**100%**
Uncontrolled charging	0	209	768	2,037	3,107
SOC priority control	0	26	181	453	725
ToD priority control	0	41	311	695	1,087
Transformer Loading priority control	0	65	459	971	1,327
SOC & ToD Combined priority control	0	21	148	367	580

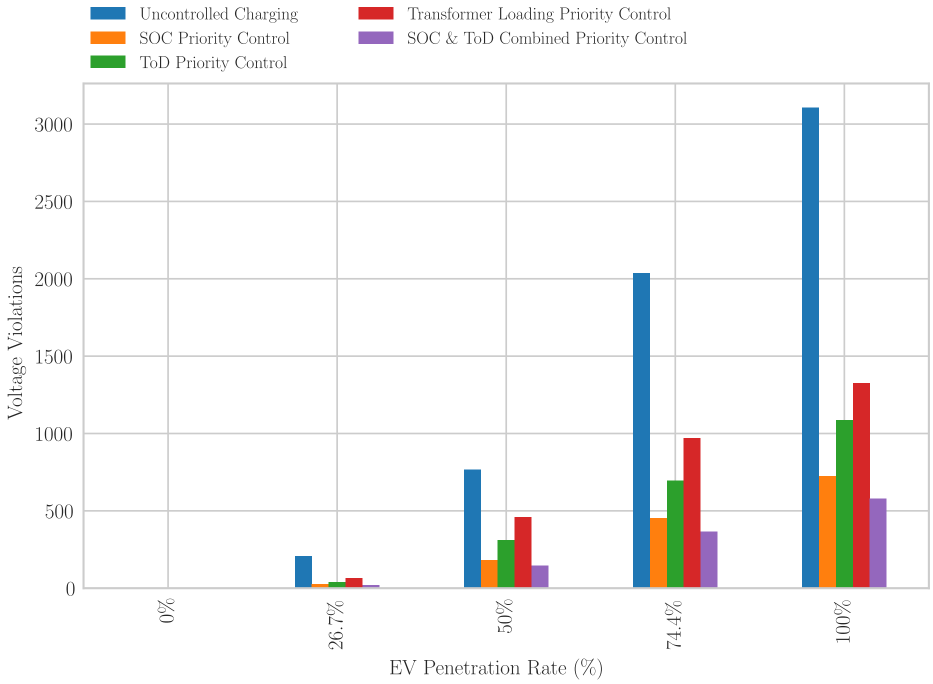


Figure 4.13: This bar chart shows the number of voltage magnitude violations per charging strategy per EV penetration rate in the RVO scenario. With a 100% EV penetration rate, the uncontrolled charging strategy resulted in voltage magnitude violations that are 15 times more than that of an EV penetration rate of 26.7%. Additionally, the SOC & ToD Combined priority control has mitigated most of the voltage magnitude violations under all EV penetration rates but has failed to fully mitigate them.

Table 4.7: Resulting transformer violations per charging strategy per EV penetration rate in the RVO scenario.

Strategy	**0%**	**26.7%**	**50%**	**74.4%**	**100%**
Uncontrolled charging	0	0	1	25	122
SOC priority control	0	0	0	0	8
ToD priority control	0	0	0	1	12
Transformer Loading priority control	0	0	0	3	11
SOC & ToD Combined priority control	0	0	0	0	7

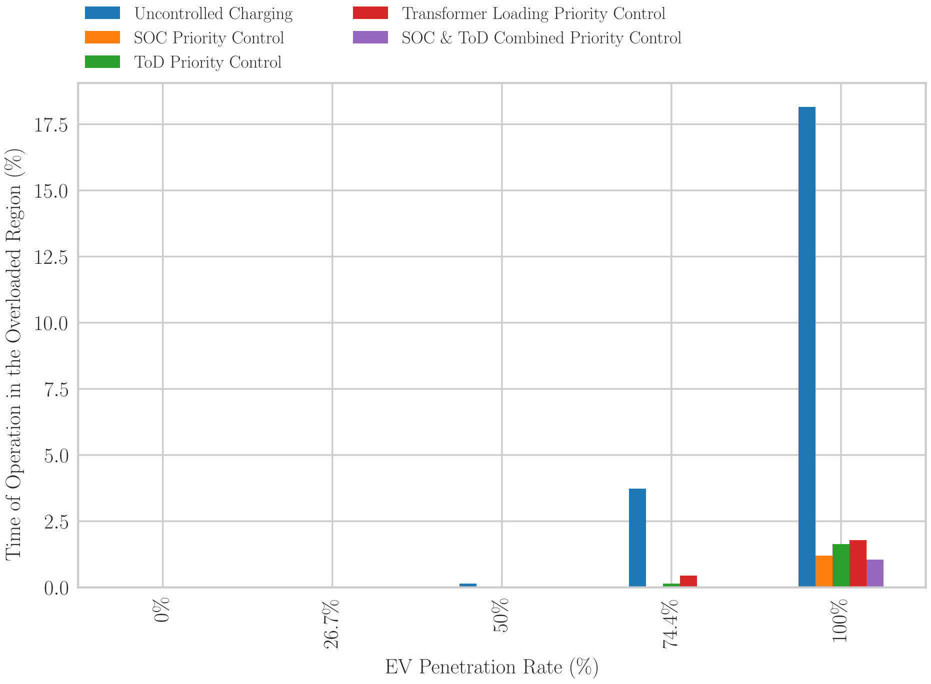


Figure 4.14: This bar chart shows the percentage of time the transformer operated in the overloaded region during the one-week period in the RVO scenario. Since the charging power rates in this scenario have resulted in a notably larger number of voltage magnitude violations than that of the Base scenario, it is expected that the loading on the transformer will consequently increase and cause transformer violations.

4.5. Scenario III: Future

Future projections suggest that residential chargers will also become fast chargers that further enhance user satisfaction and aid in the electrification of the mobility sector by attracting more customers. The so-called "Mode 3", three-phase chargers can charge EVs with powers as high as 11 kW, 22 kW, or 43 kW [3]. Furthermore, the required charging capacity will be allocated based on communication between the EV and the charging point [3]. To put this into perspective, assume a charge power of 11 kW without any interruption, a Nissan Leaf would need less than 4 hours to charge fully when compared to requiring nearly 11 hours and 5.5 hours to charge fully under the first and second scenario, respectively (assuming $P_{\max}$ is applied continuously without interruption). Now that the user's perspective has been identified, the "Future" Scenario has been designed to further investigate the impacts that have been previously evaluated in the two, preceding scenarios. The household and charging point connections, however, have been adjusted to three-phase to accommodate the 11 kW EV chargers. The parameters of interest for this scenario are summarized in Table 4.8.

Table 4.8: Future scenario parameters.

Parameter	Power Rating (kW)	Priority
P_{max}	11	High Priority
P'_{max}	9	Moderate Priority
P''_{max}	5	Low Priority
P'_{min}	10	High Priority
P_{min}	3.7	Moderate & Low Priority

4.5.1. Voltage Magnitude Regulation

User 182 has been used again for this scenario and the corresponding voltage magnitude violations occurring from different strategies have been plotted in Figure 4.15. and tabulated in Table 4.9. Since the power rating of the EV chargers has been increased to 11 kW, the largest amount of voltage magnitude violations is expected to correspond in this scenario. Consequently, the highest amount of mitigated violations is expected in this scenario too.

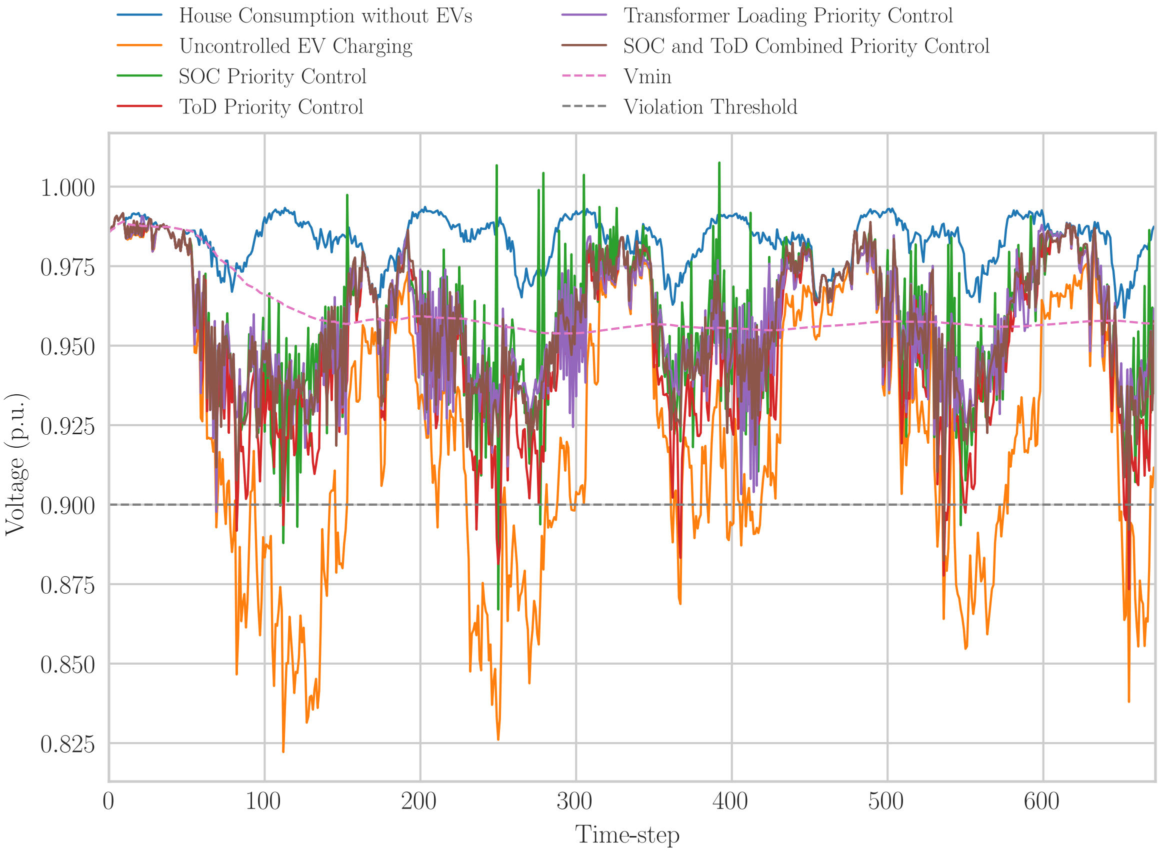


Figure 4.15: Voltage profile of User 182 under six, different strategies in the Future scenario. The impacts of uncoordinated charging are even more severe at higher power ratings. Coordinated charging strategies aim to keep the voltage level above the violation threshold but fail in certain time-periods due to the high charging power rates in this scenario.

Table 4.9: Voltage magnitude violations in the Future scenario.

Strategy	**Number of Voltage Violations**
House consumption without EVs	0
Uncontrolled EV charging	14,017
SOC priority control	540
ToD priority control	1,569
Transformer Loading priority control	310
SOC & ToD Combined priority control	290

Uncontrolled charging in this scenario has yielded even more severe impacts on the grid when compared to the previous scenario as voltage magnitudes diminished to approximately 0.825 p.u. at certain instants of the week; in addition to the total number of voltage magnitude violations, which has nearly quadrupled when compared to the RVO scenario. Overall, the four types of control strategies kept the voltage above the violation threshold except at certain time periods where it is evident that ToD-based priority control yielded results that are similar and as severe as that of the uncontrolled charging strategy. Furthermore, the SOC & ToD Combined priority control has again yielded the best results by mitigating the impact to approximately 49 times less than the uncontrolled strategy and with approximately 20, 250, and 1,300 lesser voltage magnitude violations than transformer loading priority control, SOC-based priority control, and ToD-based priority control, respectively. Nevertheless, voltage magnitude violations have also been recorded using the SOC & ToD Combined priority control. This may be owed to the current residential grid capacity which is not able to withstand the sudden, 11 kW load even when the voltage magnitude of a household connection is high enough to apply it. Therefore, once a voltage magnitude violation is recorded, the charge controller adjusts/curtails the charging power and brings the voltage magnitude back to operational limits. This can be seen in approximately time-step 540 and again in time-step 660. Even though the maximum charging power has increased by 3.6 kW when compared to the RVO scenario, the resulting voltage magnitude violations while using the SOC priority control, transformer loading priority control, and SOC & ToD Combined priority control were considerably less than that of the RVO scenario. Therefore, the resultant voltage magnitude violations in this scenario suggest that a high charging power rate, along with three-phase household and charging point connections, can pose very severe impacts on the distribution grid when an uncontrolled charging strategy is adopted; however, controlled charging strategies can mitigate impacts and result in lesser voltage magnitude violations than that of the RVO scenario (which comprises of one-phase connections and a noticeably lower maximum charging power of 7.4 kW).

4.5.2. Distribution Transformer Loading

Since each household has a three-phase connection in this scenario as opposed to a one-phase connection in the previous scenarios, the household consumption, alone, accounted for more than half of the distribution transformer's maximum loading capacity during the peak hours of consumption of everyday. Additionally, household consumption peaked on the seventh day of the week which accounted for a distribution transformer loading of 82% as depicted in Figure 4.16 (i.e. the distribution transformer is operating in the heavy load region). Furthermore, when compared to the RVO scenario, the maximum loading percentage on the distribution transformer with the uncontrolled charging strategy has increased from 140% to 350% in this scenario. In addition, the charging strategies have considerably decreased the loading on the distribution transformer; however, the distribution transformer operated in the overloaded region during most instances of the one-week period. As a result, solely coordinating charging is not enough to fully mitigate the impacts on the distribution transformer and a capacity upgrade is urgently required.

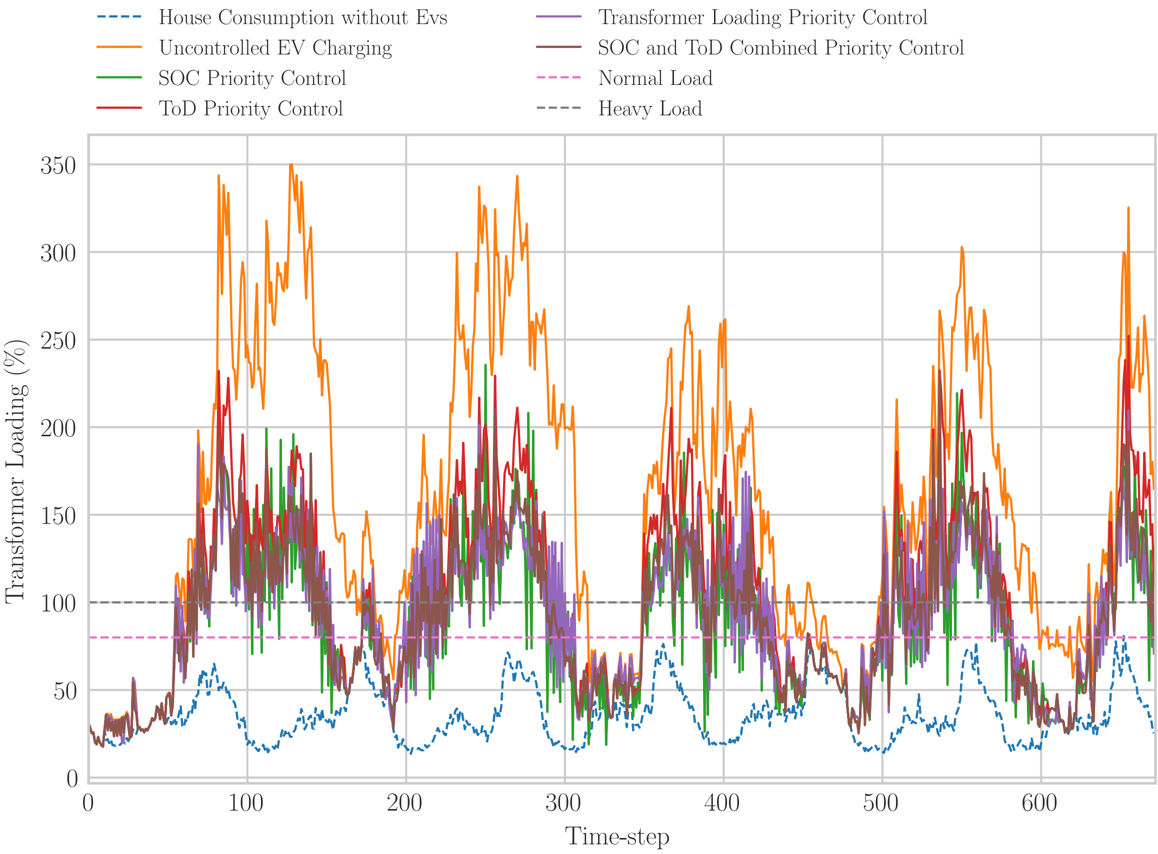


Figure 4.16: This plot shows the transformer loading percentage per strategy in the Future scenario. The impact on the distribution transformer using the uncontrolled charging strategy has reached a staggering loading percentage of 350%. Additionally, the transformer was overloaded during most of the week even with controlled charging strategies which suggests the distribution transformer urgently requires a capacity upgrade.

4.5.3. Impact on the User

For the mass population to start adopting EVs as soon as possible and aid the governments' goal for a greener and cleaner future, EV users are concerned to what extent the EV's battery can be a charged in a given period of time. As a result, the adoption of fast chargers can be a major factor in convincing non-EV users to invest in an EV. With respect to Figure 4.17, the fast chargers adopted in this scenario fully charged EV 182's battery on six different occasions during the week as opposed to only one occasion in both of the preceding scenarios combined. Yet again, the SOC deviation has further increased in this scenario with regard to short charging periods as shown in Figure 4.18. The the SOC deviation at time-step 250 has reached 50% which increased by 37.5% and 17.5% from that of the Base and RVO scenario, respectively. The SOC deviations in longer charging periods is nearly negligible with deviations reaching less than 0.5% SOC at the end of the charging period at time-step 600 compared to less than 2.5% and 1% in the Base and RVO scenarios, respectively.

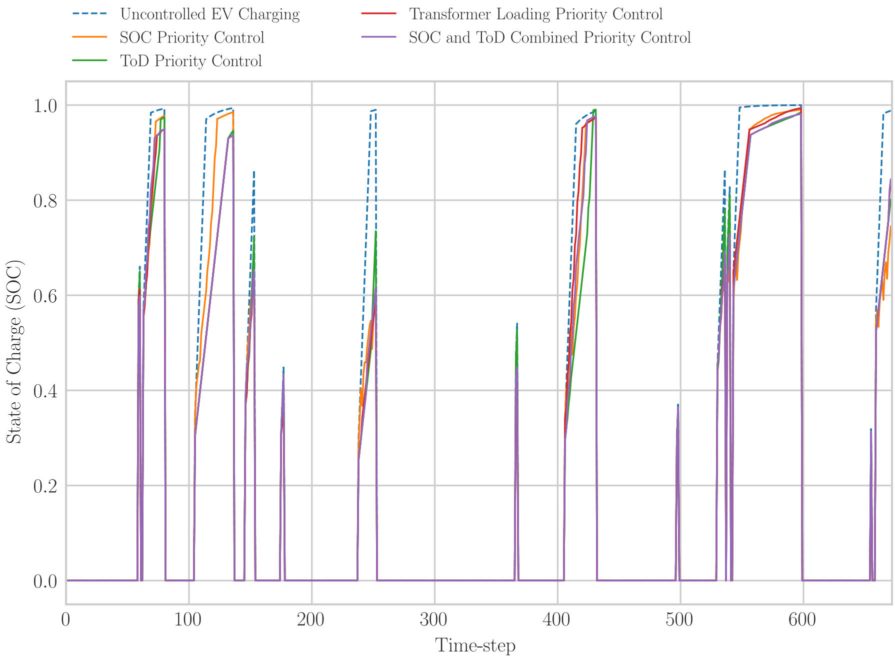


Figure 4.17: The resulting SOC for EV 182 using the uncontrolled and controlled charging strategies for the Future scenario is plotted in this figure. SOC percentages across all charging periods has considerably increased since the maximum charging power in this scenario is nearly 1.5 and 3 times more than that of the RVO and Base scenarios, respectively. Whenever the EV has been connected to the charging point for a considerable amount of time, the battery was either fully charged or very close to being fully charged.

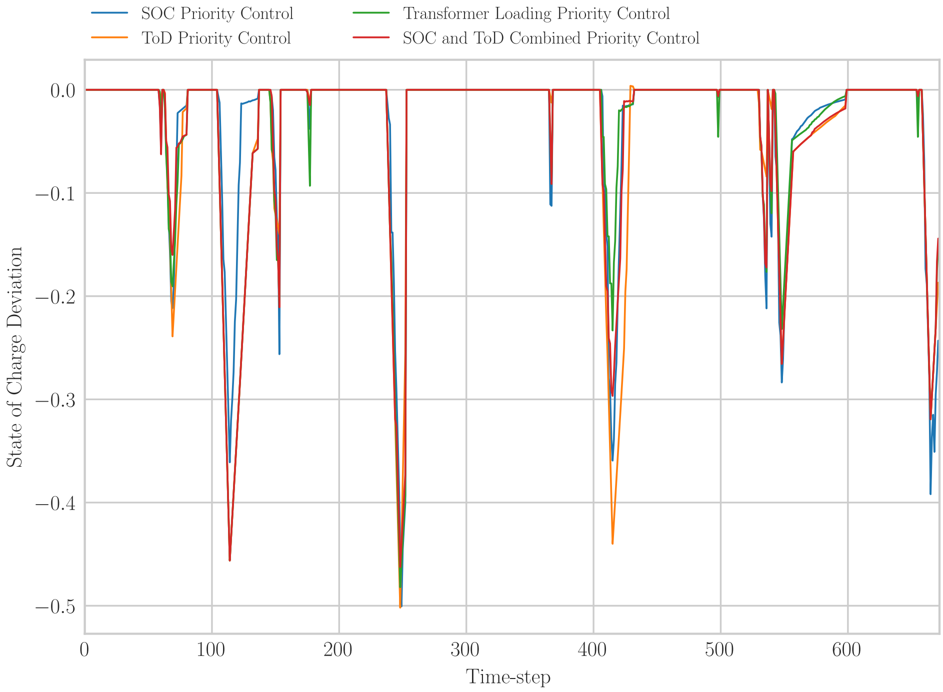


Figure 4.18: This plot shows the difference in SOC between all charging strategies compared to the uncontrolled strategy in the Future scenario. Compared to the preceding two scenarios, the extremely higher charging powers in this scenario have increased the SOC deviation during short charging periods to a maximum of 50% in of the instances during the one-week operation period.

4.5.4. Evaluation at Different EV Penetration Rates

As the charging power rates further increased in this scenario when compared to that of the previous two scenarios, the intensity of voltage magnitude and transformer violations can be observed at EV penetration rates as low as 26.7% and 50%. Furthermore, uncontrolled charging at a 100% EV penetration rate overloaded the transformer for 464 time-steps out of the 672 time-steps in the one-week operation period and has resulted in a total of 14,017 voltage magnitude violations. SOC priority control, Transformer Loading priority control, and SOC & ToD Combined priority control have significantly reduced the number of voltage magnitude violations by 25 to 47 times more than that of the uncontrolled case and also decreased transformer violations by about 50%. Regardless, the transformer was overloaded in approximately 33% and 50% of the one-week operation period for an EV penetration rate of 74.4% and 100%, respectively; additionally, voltage magnitude violations were not fully mitigated. As a result, similar to the RVO scenario, the current grid capacity cannot handle such high charging power rates. The resultant voltage magnitude violations per charging strategy per EV penetration rate are tabulated in Table 4.10 and plotted in Figure 4.19. Finally, the resultant transformer violations per charging strategy per EV penetration rate are tabulated in Table 4.11 and plotted in Figure 4.20.

Table 4.10: Resulting voltage magnitude violations per charging strategy per EV penetration rate in the Future scenario.

Strategy	**0%**	**26.7%**	**50%**	**74.4%**	**100%**
Uncontrolled charging	0	160	1,071	6,284	14,017
SOC priority control	0	6	57	195	540
ToD priority control	0	8	175	651	1,569
Transformer Loading priority control	0	8	69	225	310
SOC & ToD Combined priority control	0	5	45	152	290

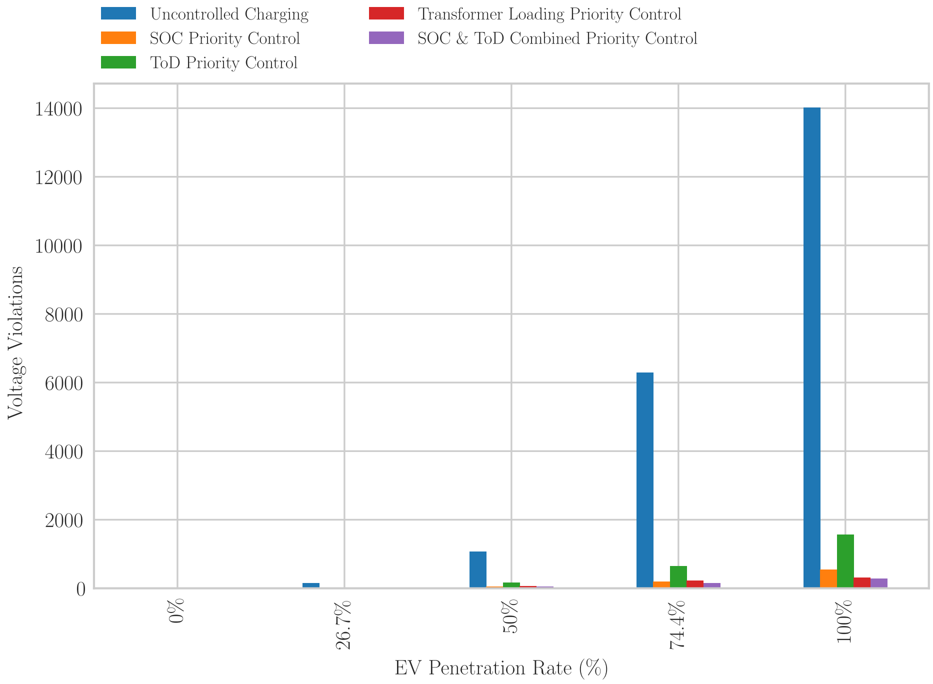


Figure 4.19: This bar chart shows the number of voltage magnitude violations per charging strategy per EV penetration rate in the Future scenario. Uncontrolled EV charging has resulted in more severe impacts than that of any of the other two scenarios per EV penetration rate. Transformer Loading priority control and SOC & ToD Combined priority control have resulted in less voltage magnitude violations than that of the RVO scenario, yet more than that of the Base scenario. Although this scenario has a considerably higher charging power rate than that of the RVO scenario, this scenarios has three-phase household and EV charging connections which can can carry more power and improve the voltage profile; hence, results in lesser voltage magnitude violations.

Table 4.11: Resulting transformer violations per charging strategy per EV penetration rate in the Future scenario.

Strategy	**0%**	**26.7%**	**50%**	**74.4%**	**100%**
Uncontrolled charging	0	159	273	401	464
SOC priority control	0	36	95	188	264
ToD priority control	0	45	142	259	343
Transformer Loading priority control	0	32	91	195	282
SOC & ToD Combined priority control	0	32	101	196	275

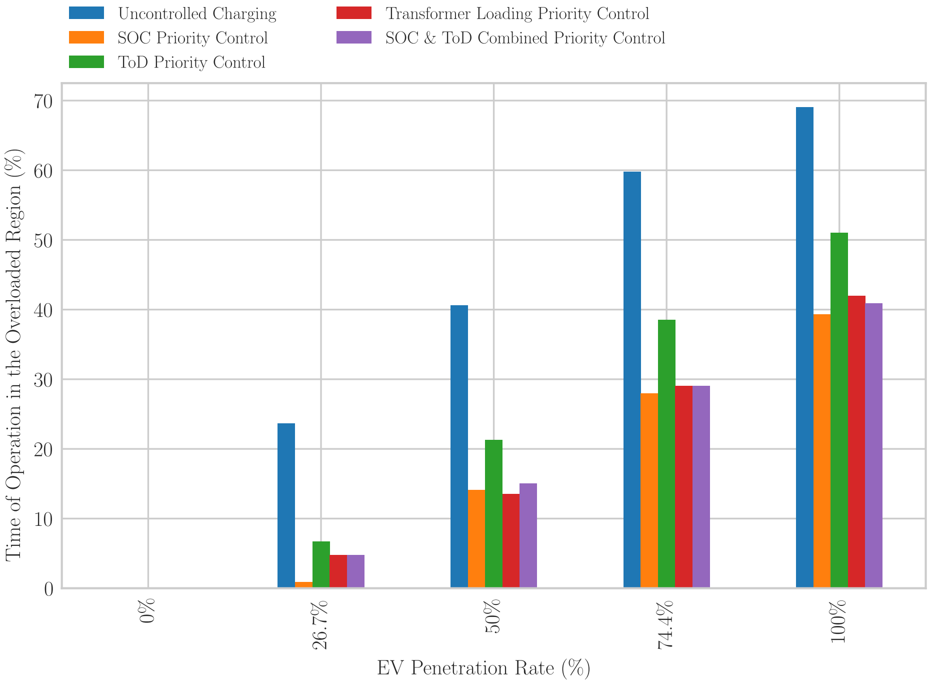


Figure 4.20: This bar chart shows the percentage of time the transformer operated in the overloaded region during the one-week period in the Future scenario. As the EV penetration rate increases, the transformer becomes severely overloaded across all charging strategies.

4.6. Sensitivity Analysis

4.6.1. Determining V_{th}

During the initial stages of the control algorithm development, V_{th} has been set at 0.9 p.u. However, voltage magnitude violations were still present even with low charging powers such as that of the Base scenario and with SOC & ToD Combined priority control. This is because the charging power would not be curtailed to P_{min} up until a voltage magnitude of 0.9 p.u. or less is read by the household's smart meter and communicated to the charge controller. Therefore, no margin is provided for any extra EV charging and household consumption that can occur randomly; thus, voltage magnitude violations were easily triggered. Consequently, the combined priority control algorithm has been evaluated with V_{th} equal to 0.93 p.u. and 0.95 p.u. and plotted against the original V_{th} (0.9 p.u.) for all three scenarios as shown in Figure 4.21, 4.22, and 4.23. The observation is that V_{th} should be set more towards $\hat{V}_{\text{i,t}}{}^{\text{min}}$ than towards 0.9 p.u. especially at higher charging power rates. As a result, V_{th} has been set at 0.95 p.u. which, in turn, provided more room for the charge controller to adjust the charging power before crossing the violation threshold. This observation is not only evident in the plotted figures below, but also in Table 4.12 where the number of voltage magnitude violations are recorded per V_{th} selection per scenario.

Table 4.12: Number of voltage magnitude violations per V_{th} selection per scenario using SOC & ToD Combined priority control.

	Scenario I	**Scenario II**	**Scenario III**
V_{th} **= 0.90 p.u.**	18	1,232	2,034
V_{th} **= 0.93 p.u.**	11	841	1,215
V_{th} **= 0.95 p.u.**	0	580	290

Figure 4.21: Using SOC & ToD Combined priority control, Scenario I has been simulated for one week of operation at V_{th} = 0.9, 0.93, and 0.95 p.u. The resulting voltage profile of User 182 is plotted in this figure.

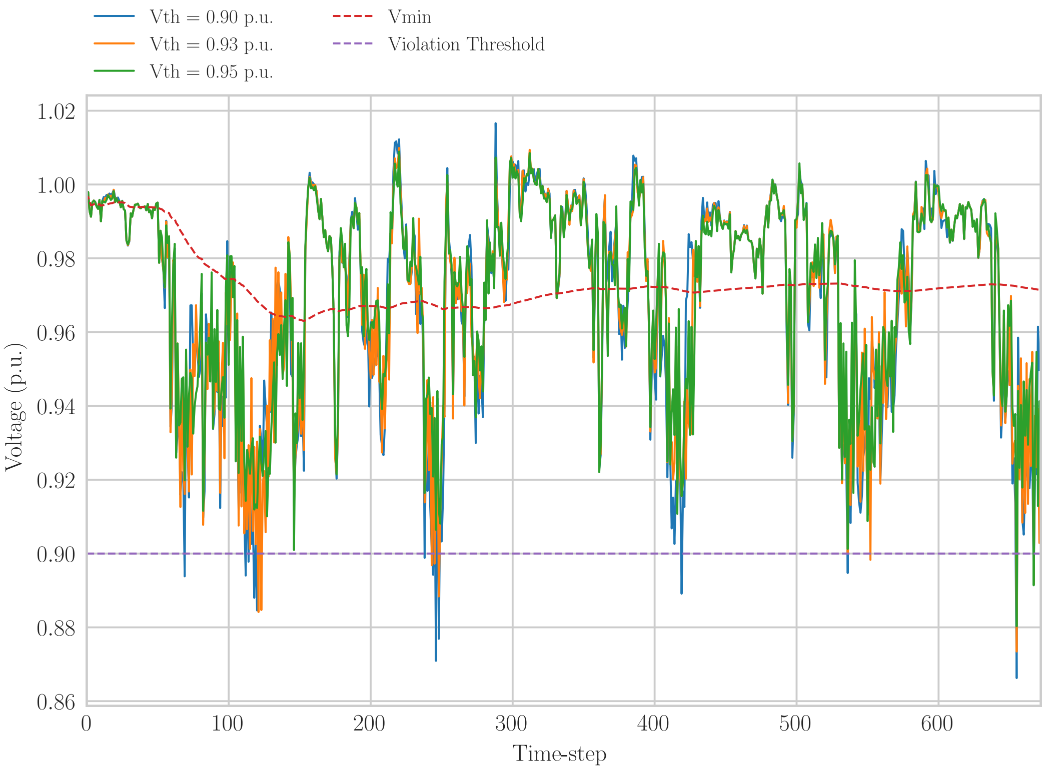


Figure 4.22: Using SOC & ToD Combined priority control, Scenario II has been simulated for one week of operation at V_{th} = 0.9, 0.93, and 0.95 p.u. The resulting voltage profile of User 182 is plotted in this figure.

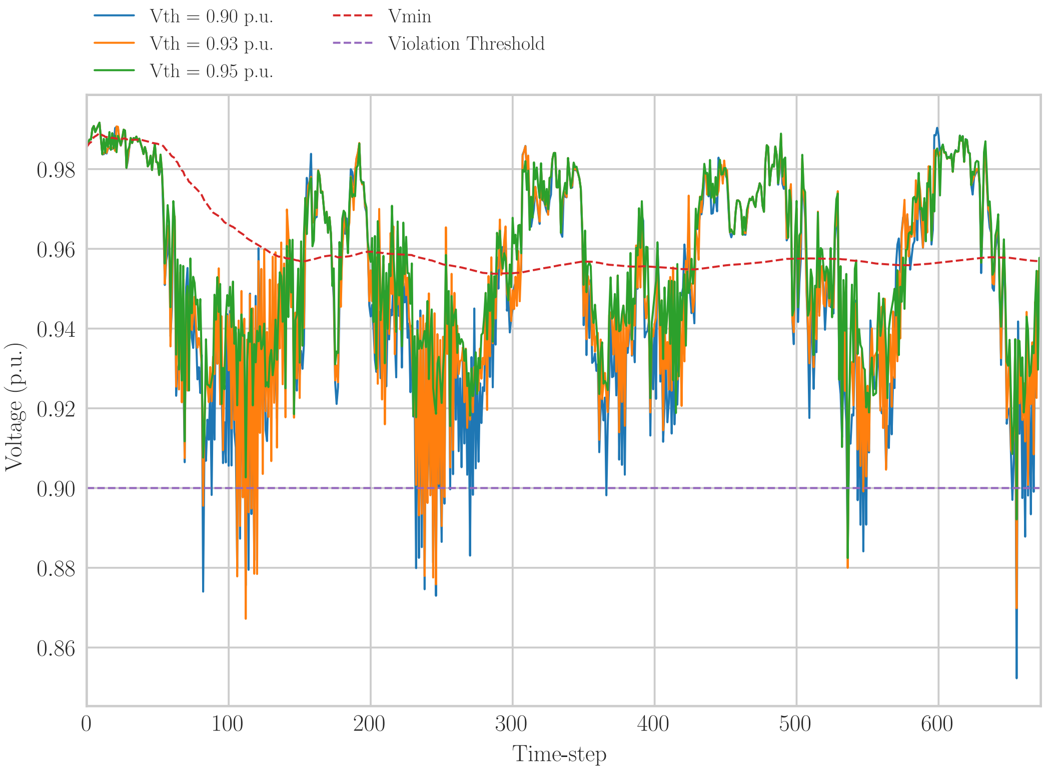


Figure 4.23: Using SOC & ToD Combined priority control, Scenario III has been simulated for one week of operation at V_{th} = 0.9, 0.93, and 0.95 p.u. The resulting voltage profile of User 182 is plotted in this figure.

4.6.2. Determining the window of calculation for ${\hat{V}_{\text{i,t}}}^{\text{min}}$

In Section 4.6.1, the appropriate value for the V_{th} parameter has been determined while the ${\hat{V}_{\text{i,t}}}^{\text{min}}$ parameter was calculated as a cumulative moving average (i.e. the value at a certain time-step is the average of all preceding values). As the number of readings increase, the ${\hat{V}_{\text{i,t}}}^{\text{min}}$ parameter approaches a converged value and therefore ${\hat{V}_{\text{i,t}}}^{\text{min}}$ can be reset at the end of the one-week period of operation. However, in this section, ${\hat{V}_{\text{i,t}}}^{\text{min}}$ will be implemented as a simple moving average that operates over a predefined window. The windows of operation will be one hour, two hours, twelve hours, and one-day. On the other hand, the parameter V_{th} cannot be a preset value and should always have a magnitude lower than that of ${\hat{V}_{\text{i,t}}}^{\text{min}}$ in order for the charging strategies to work. Consequently, the V_{th} parameter is always 0.03 p.u. lower than the ${\hat{V}_{\text{i,t}}}^{\text{min}}$ parameter. Since SOC & ToD Combined priority control has fully mitigated the impact in the Base scenario and resulted in the least impact in the RVO and Future scenarios, this charging strategy has been also employed for this sensitivity analysis. The number of resulting voltage magnitude violations per scenario per ${\hat{V}_{\text{i,t}}}^{\text{min}}$ window selection is tabulated in Table 4.13 and the voltage profile for User 182 under various ${\hat{V}_{\text{i,t}}}^{\text{min}}$ window selections is plotted in Figure 4.24, 4.25, and 4.26 for the Base, RVO, and Future scenarios, respectively.

Table 4.13: Number of voltage magnitude violations per ${\hat{V}_{\text{i,t}}}^{\text{min}}$ window selection per scenario using SOC & ToD Combined priority control.

	Scenario I	**Scenario II**	**Scenario III**
1-hour window	41	1,233	2,672
2-hour window	23	1,055	2,113
12-hour window	12	809	1,468
24-hour window	12	660	1,244

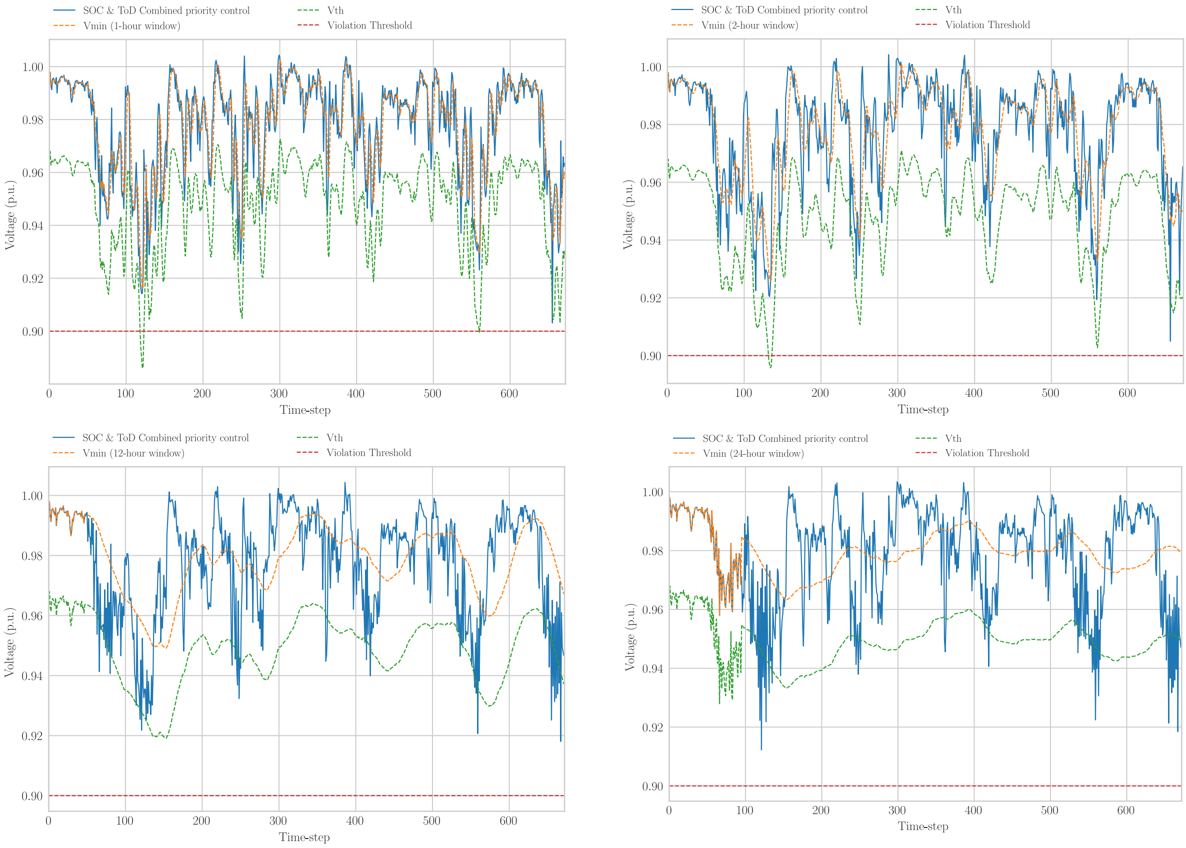


Figure 4.24: The voltage profile of User 182 using SOC & ToD Combined priority control and simulated under various ${\hat{V}_{\text{i,t}}}^{\text{min}}$ windows for the Base scenario. The top-left corner plot has a window of one hour while the adjacent plot in the top-right corner has a window of two hours. The bottom plots located in the left corner and right corner have a window of twelve hours and one day, respectively.

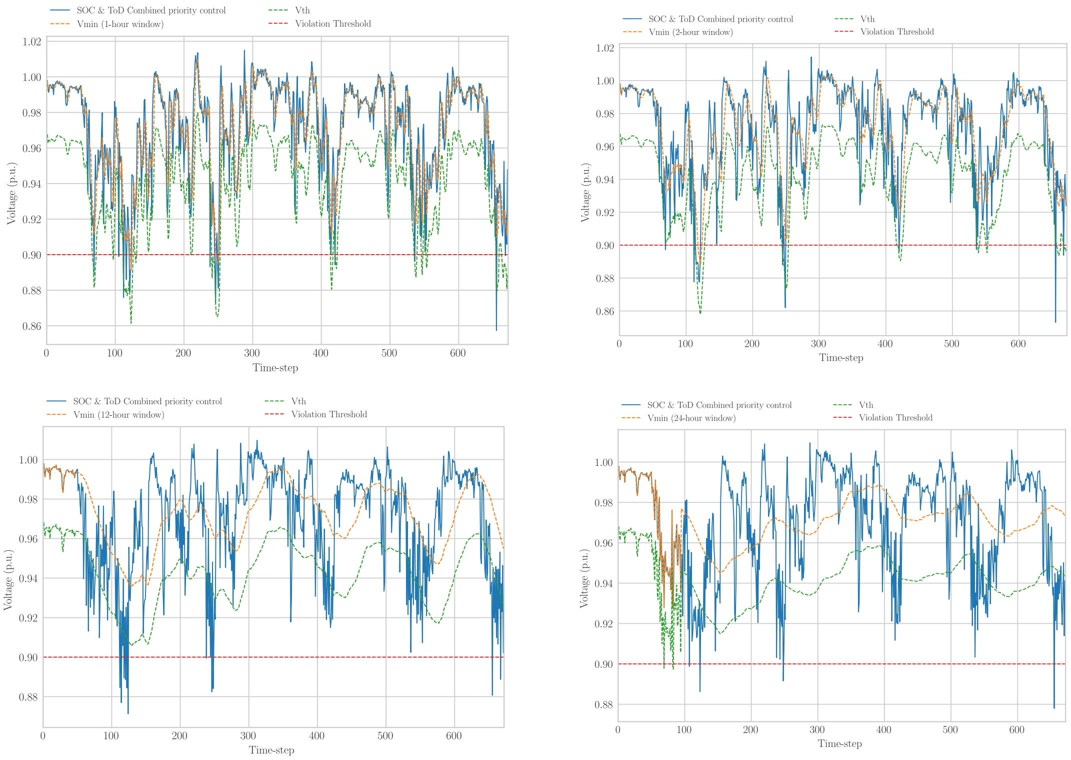


Figure 4.25: The voltage profile of User 182 using SOC & ToD Combined priority control and simulated under various $\hat{V}_{i,t}^{\min}$ windows for the RVO scenario. The top-left corner plot has a window of one hour while the adjacent plot in the top-right corner has a window of two hours. The bottom plots located in the left corner and right corner have a window of twelve hours and one day, respectively.

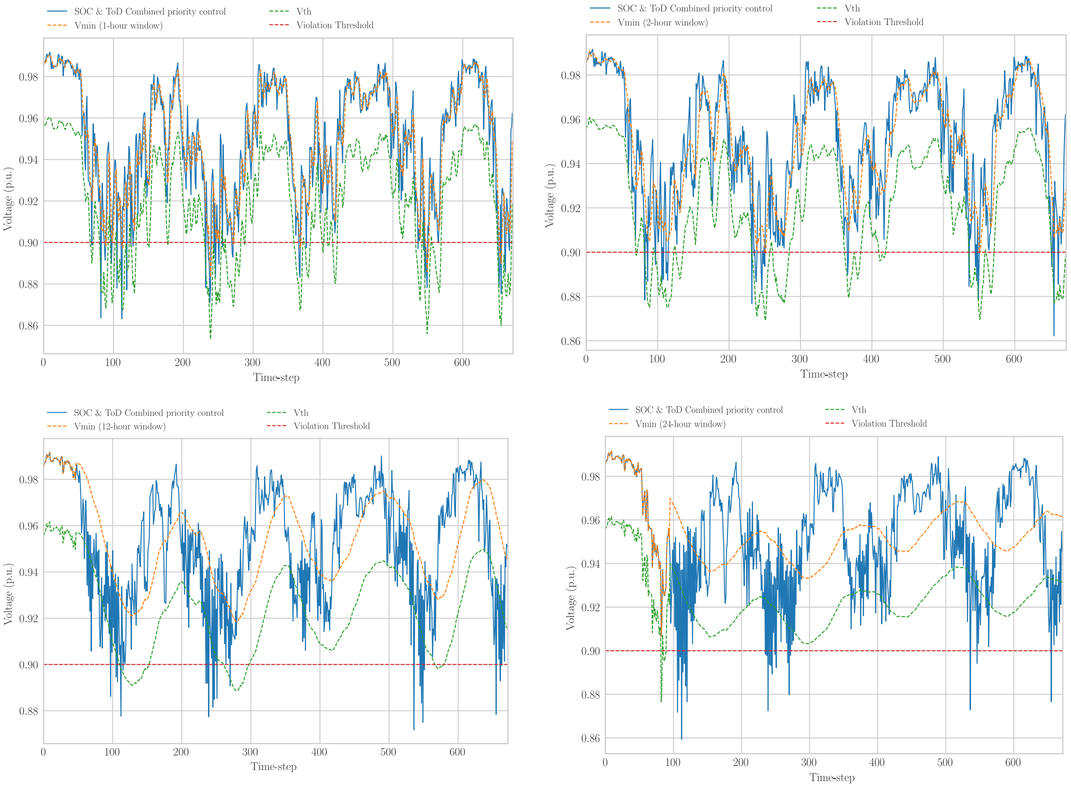


Figure 4.26: The voltage profile of User 182 using SOC & ToD Combined priority control and simulated under various $\hat{V}_{i,t}^{\min}$ windows for the Future scenario. The top-left corner plot has a window of one hour while the adjacent plot in the top-right corner has a window of two hours. The bottom plots located in the left corner and right corner have a window of twelve hours and one day, respectively.

What can be observed across all three scenarios is that the number of voltage magnitude violations decreases considerably as the window duration increases. This is because V_{th} in shorter window selections (such as the one-hour and two-hour windows) has a value lower than that of the violation threshold at certain instants of the week. Regardless of the charging strategy employed, the dispatched charging power will curtail to P_{min} up until a voltage magnitude equal to or less than V_{th} has been recorded. Therefore, this reasoning can be linked to that of Section 4.6.1 where it was concluded that V_{th} should have a magnitude higher than that of the violation threshold in order to accommodate any extra EV charging or day-to-day household consumption (that can randomly occur) without triggering any voltage magnitude violations. Furthermore, it can be observed that the $\hat{V}_{\text{i,t}}{}^{\text{min}}$ parameter has a considerably higher magnitude when a twelve-hour window or a one-day window is selected. As expected, this results in a considerably higher magnitude for the V_{th} parameter when compared to that of the one-hour and two-hour window selections. Ultimately, the charging power will be curtailed to P_{min} at a magnitude that is higher than that of the violation threshold which results in much lower voltage magnitude violations as shown in Table 4.13. However, the number of voltage magnitude violations is even further reduced when $\hat{V}_{\text{i,t}}{}^{\text{min}}$ is calculated as a cumulative moving average that resets at the end of every week along with a V_{th} of 0.95 p.u. as shown in Table 4.12 in Section 4.6.1.

4.7. Conclusion

To sum up, this chapter has employed a real Dutch residential network to evaluate an uncoordinated EV charging strategy along with the coordinated charging strategies developed in Chapter 3. The evaluation included three scenarios, each with various charging power rates. In each scenario, the charging strategies were evaluated with respect to voltage magnitude regulation and transformer loading. The resultant voltage magnitude and transformer violations were recorded and compared at an EV penetration rate of 0%, 26.7%, 50%, 74.4%, and 100%. The aforementioned impacts are highly affiliated with the DSO and do not quantify the impact on EV users; therefore, the impact on EV users was also addressed in this chapter by comparing the resultant SOC percentage of a particular coordinated charging strategy to that of the uncoordinated one. Finally, two sensitivity analysis have been conducted for the V_{th} and $\hat{V}_{\text{i,t}}{}^{\text{min}}$ parameters. The first sensitivity analysis proved a voltage threshold, V_{th}, of 0.95 p.u. provides a better voltage profile with lesser voltage magnitude violations than that of a V_{th} equal to 0.90 p.u. and 0.93 p.u. The second sensitivity analysis proved that employing $\hat{V}_{\text{i,t}}{}^{\text{min}}$ as cumulative moving average that resets at the end of every week has resulted in considerably lower voltage magnitude violations.

Firstly, the Base scenario has shown promising results as none of the charging strategies has resulted in transformer violations across all EV penetration rates. Additionally, the SOC & ToD Combined priority control has fully mitigated all resulting voltage magnitude violations which suggests the current grid capacity does not require a capacity upgrade if this charging strategy is employed. Furthermore, users connected to a charging point for long periods of time recorded an SOC deviation of less than 2.5% from the uncontrolled charging strategy, which indicates users may be highly inclined to enroll in a charging program that would help support the DSO and fully mitigate the impacts on the residential network.

Secondly, the RVO scenario has provided a maximum charging power rate that is double the one provided in the Base scenario. Consequently, voltage magnitude and transformer violations were recorded regardless of the employed charging strategy. The intensity of these violations increased as the EV penetration rate increased which suggests an upgrade to the current grid capacity is only required if complementary strategies such as reactive power compensators, V2G, etc. cannot fully mitigate the resultant impacts. Nevertheless, the SOC deviation between the uncoordinated and coordinated charging strategies during long charging periods has diminished to less than 1% which is owed to the higher charging power rates employed in this scenario.

Finally, the Future scenario has employed the highest charging power rate of all three scenarios which translated into very severe impacts when the uncontrolled charging strategy is employed. Since three-phase household and charging point connections are considered in this scenario, the resultant voltage magnitude violations using coordinated charging strategies were considerably less than that of the RVO scenario. However, when compared to the preceding two scenarios, the distribution transformer was overloaded during most of the one-week operation period and has shown the highest number of transformer violations. As a result, an upgrade to the current grid capacity is urgently required under this scenario. With respect to the impact on EV users, the SOC deviation between the uncoordinated and coordinated charging strategies during long charging periods has further decreased to less than 0.5%.

5

DNV's Next Generation Grid Operations (NextGen GridOps) Knowledge Framework

5.1. Introduction

This chapter introduces DNV's Next Generation Grid Operations (NextGen GridOps or NGGO) Knowledge Framework along with the methodology used to implement the results presented previously in Chapter 4. Firstly, Section 5.2 addresses the need for a framework to run future grid operations and also discusses the building blocks that form the essence of the framework. Secondly, Section 5.3 presents the methodology used to implement results in a practical way that could be of major help for DNV employees in the future. Finally, the chapter concludes in Section 5.4.

5.2. Building the New Grid Operations Machine

Energy markets and systems are becoming more complex as a result of the rise in the number of market players/vendors and the nature of future system requirements. With the Supervisory Control and Data Acquisition (SCADA) control system architecture coming to a crisis, the need for a developing a machine that exchanges information with the market in real-time is of high importance. SCADA projects not only suffer from technical difficulties that include questionable real-time performance and response, but also market-based difficulties such as project realization time and budget. Therefore, the NGGO framework intends to achieve this real-time data exchange with the market by using the existing SCADA infrastructure in addition to employing other Service Oriented Architectures (SOAs) such as Wide Area Measurement Systems (WAMS) and Distributed Energy Resources Management Systems (DERMS) in order to perform real-time operational processes (such as balancing and forecasting energy) with the market as depicted in Figure 5.1.

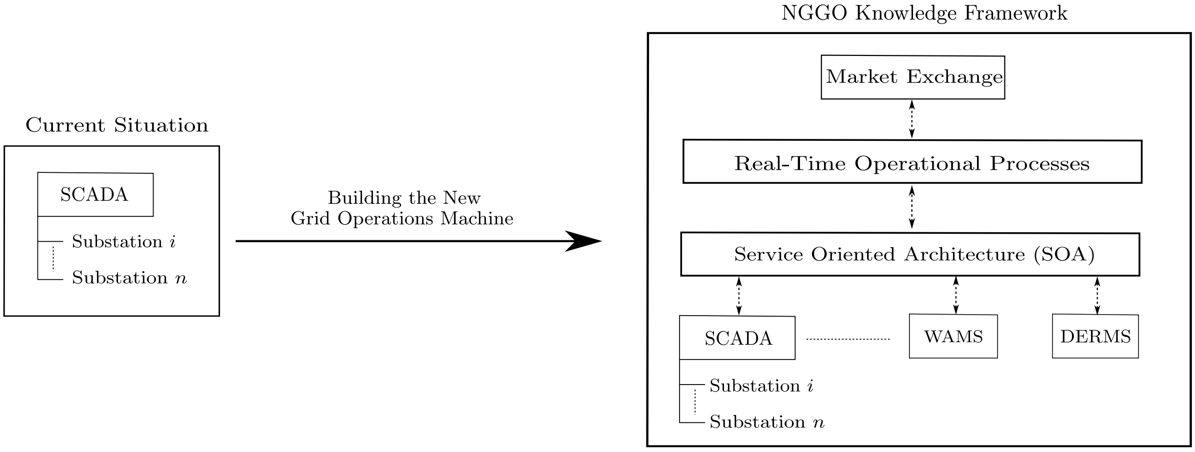


Figure 5.1: The figure describes the transition from the existing SCADA architecture to the new "Grid Operations Machine" known as the NGGO Knowledge Framework. The framework will make use of the existing service oriented architecture (SCADA) along with newly added architectures such as WAMS and DERMS in order to collectively carry-out real-time operational processes with the market.

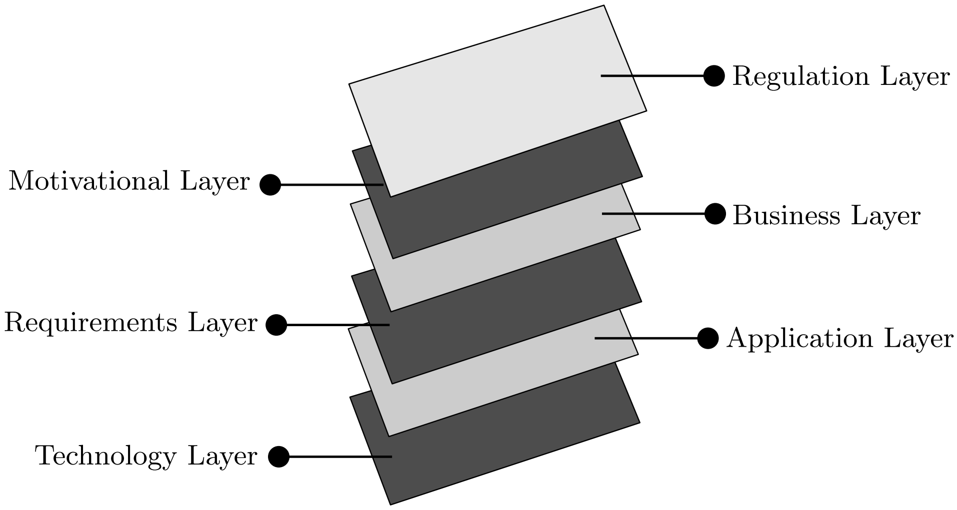


Figure 5.2: The NGGO framework is formed of six layers of which the top one is the regulation layer and the bottom one is the technology layer. Each layer has a specific functionality but can also be dependent on another layer.

The NGGO framework is composed of six layers, each with a specific functionality. The functionality of each layer is as follows:

1. **Regulation layer:** Contains regulations that cover a wide variety of characteristics that are directly related to grid operations. As of now, this layer contains Dutch and European Union regulations with the possibility of adding more regulations in the future.
2. **Motivational layer:** This layer models various aspects that aid in the development of a project. These aspects include technical drivers, market drivers, climate drivers, vendors, Transmission System Operators (TSOs), DSOs, and Dutch stakeholders.
3. **Business layer:** Encompasses all business goals, business processes, and business methodologies that relate to a project.
4. **Requirements layer:** Contains business requirements, functional requirements, and non-functional requirements. Functional requirements include data exchange requirements, WAMS requirements, DERMS requirements, etc. while non-functional requirements include compatibility, reliability, performance, etc.
5. **Application layer:** Comprises of all SOAs that support the business processes in the business layer. SOAs include Energy Management System (EMS), WAMS, DERMS, SCADA, etc.

6. **Technology layer:** Includes all communication networks, servers, and technological functions and processes that interface with the application layer.

5.3. Implementation

As for implementing the findings of this research, the so-called "generic layer" has been used. This generic layer interconnects some or all of the aforementioned six layers depending on the nature and maturity of a certain project. In addition, this layer provides a user-friendly and informative visualization of the modeled project instead of modeling aspects separately in each layer. Furthermore, the approach in which a project is modeled is directly dependent on what the project is about and how the person modeling that project views the bigger picture. To further elaborate on this, Figure 5.3 demonstrates how the type of blocks relate to each other in the generic layer. These blocks can relate to each other in either a unidirectional or bidirectional approach and can be adjusted to meet the project requirements. Nevertheless, the approach in which this research is implemented in the generic layer follows a bidirectional approach in which drivers cause issues that consequently impact grid operations. On the other hand, requirements clearly define a concise goal in order to mitigate the resultant impacts on grid operations.

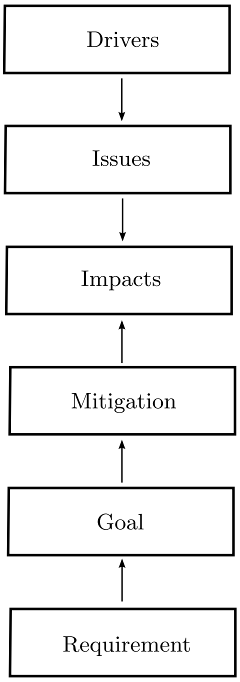


Figure 5.3: This figure demonstrates the approach used in modelling this research in the generic layer of the NGGO framework. A bidirectional approach is used in which the blocks meet somewhere in between. Drivers cause technological issues that impact grid operations, while requirements clearly define a goal to mitigate the resultant impacts.

Before modeling the findings of this research into the generic layer, the following questions need to be answered in order to know which type of blocks to use for relevant aspects of this research:

1. **Drivers:** What market drivers, advancement in technology, and possibly rules and regulations relate to the research?
2. **Issues:** How are those drivers stimulating technical difficulties?
3. **Impacts:** How are those issues impacting grid operations? To what extent?
4. **Mitigation:** How can impacts be mitigated and also comply with the goals set by the requirements?
5. **Goal:** What is the goal of the mitigation technique in relation to the requirements?
6. **Requirement:** What technical and governmental requirements relate to the issue?

The generic model of this research is shown in Figure 5.4 where each block type has a specific color. Blocks within the NGGO framework can be related with numerous connection types. As for this research implementation, the dashed lines represent influential properties while the solid lines represent associative properties. For example, a driver (in blue) such as "Mission Zero" means that a higher EV penetration rate is envisioned in the coming years which therefore relates to voltage regulation issues (in orange) with an associative property. Consequently, voltage violations (in green) are influenced by the voltage regulation issues. On the other hand, the EN50160 requirement (in red) is associated with a clear goal (in purple) of maintaining the operational voltage at a specific node between 0.9 p.u. and 1.1 p.u. This goal and requirement are further associated with the mitigation technique (in pink) that influences the voltage violation impact.

Within each block, a basic description is added along with external references when needed. Additionally, the so-called "child diagram" can be added to every block. This child diagram can basically be another set of blocks or a set of detailed information for further elaboration. Since this research is heavily focused on the impact of voltage magnitude regulation and transformer loading in LV, residential grids, two child diagrams have been added to the generic model; specifically in the "Voltage Magnitude Violation" block (in green) and the "Distribution Transformer Overloading" block (in orange) and are enclosed in red boxes as shown in Figure 5.4. Within each of these two blocks, the relevant findings that were concluded from the three scenarios in Chapter 4 answer a series of questions that provide practical knowledge that can be later on used by DNV employees. As demonstrated in Figure 5.5 and 5.6, these questions have been separated into three sets:

1. **First set:** Addresses what the scenario represents followed by the type and power rating of the employed EV chargers and any other RVO guidelines/requirements that are relevant to this scenario.
2. **Second set:** Addresses the effect of the respective impact along with practical observations that can be made.
3. **Third set:** Addresses the extent in which the current grid capacity can handle various EV penetration rates.

After the three sets of questions have been answered for every scenario, figures that were presented previously in Chapter 4 were also attached in order to visualize the impact. Finally, the scenario then ends with a conclusion and recommendation which directly relate to the findings of this research. Figure A.2 and A.3 in Appendix A.3 present the child diagram implementation in the aforementioned blocks.

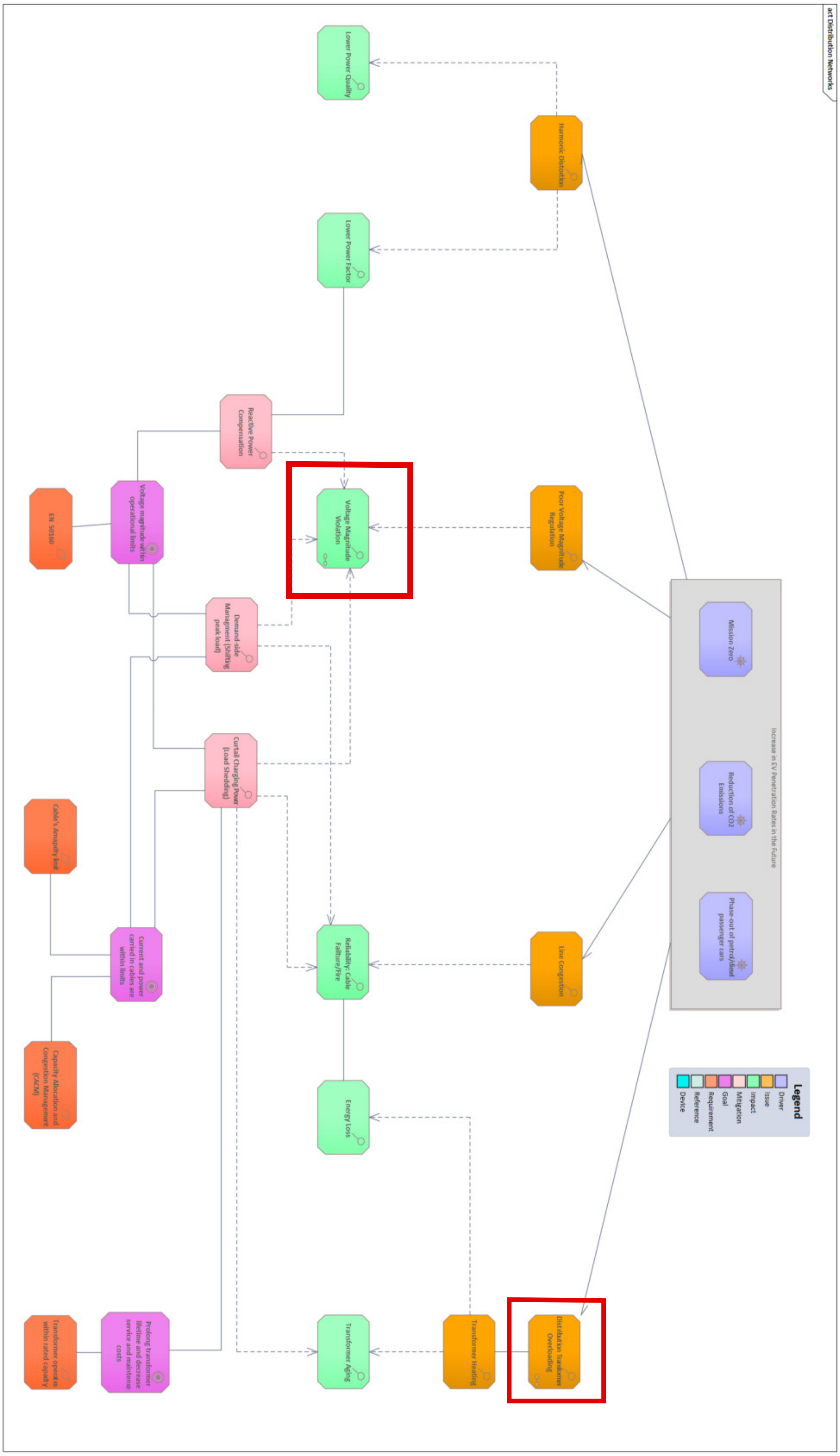


Figure 5.4: This figure presents the generic model that includes the impacts that were heavily discussed in Chapter 4 (enclosed in red boxes) along with other relevant impacts that were obtained from the literature of EV impacts. The figure follows the same bidirectional approach shown in Figure 5.3. The dashed lines represent influential properties while the solid lines represent associative properties.

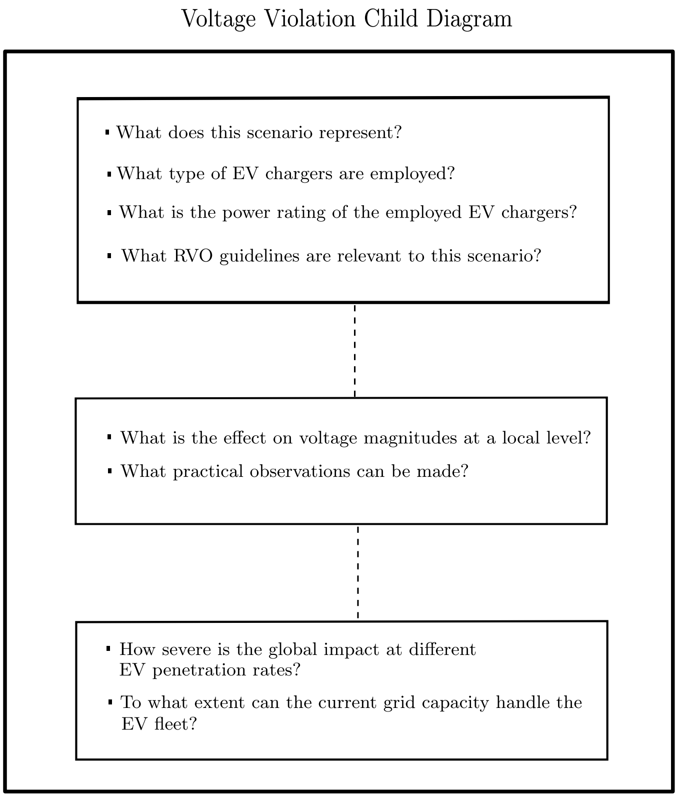


Figure 5.5: This figure shows how the child diagram located in the "Voltage Violation" block has been modeled. This child diagram addresses a series of questions that relate to the scenario modeled, the impact caused, and the severity of the impact at different EV penetration rates.

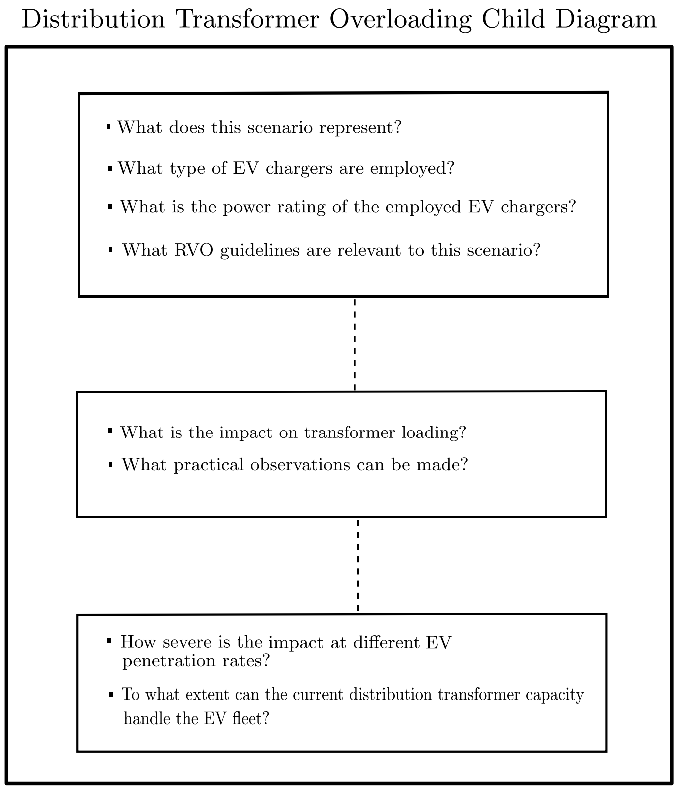


Figure 5.6: This figure shows how the child diagram located in the "Distribution Transformer Overloading" block has been modeled. This child diagram addresses a series of questions that relate to the scenario modeled, the impact caused, and the severity of the impact at different EV penetration rates.

5.4. Conclusion

Grid operations are becoming complex which arises the need to transform the existing SCADA infrastructure. As a result, DNV's NGGO knowledge framework makes use of the existing SCADA infrastructure while also employing other SOAs that carry-out real-time operations with the market. Additionally, this framework aims to present information in a user-friendly and informative way to facilitate work between DNV employees and the client. This is done by creating a database of information in the NGGO framework that is continuously updated to meet the needs and requirements of current and future clients.

Furthermore, the relevant findings from this research were modeled in a generic model that addresses drivers, issues, impacts, mitigation techniques, goals, and requirements. The model then focuses on diving deep into the impacts that were discussed in Chapter 4 in order to integrate all relevant and practical findings into the NGGO framework. DNV employees can not only use the information in this model, but can also build upon this model to tackle more issues with respect to the EV charging infrastructure.

6

Conclusion and Recommendation for Future Work

The mobility sector is responsible for a huge amount of greenhouse gas emissions for the last decades. With the whole energy sector transitioning into a fossil-free future with net-zero CO_2 emissions, the share of EVs is sky rocketing as technology advances and governmental regulations and incentives are acted upon. However, the grid is envisioned to undergo immense stress as the share of EVs continues to grow and consumers demand faster charging times and easily accessible charging stations. The stress on the grid stems from the random nature of EV loads especially when higher power rated EV chargers are installed. Among the most common impacts of EV charging on the grid include poor voltage magnitude regulation, line congestion, distribution transformer overloading, and harmonic distortion. The aim of this research is to investigate and mitigate the impacts of EV charging on residential grids by focusing heavily on voltage magnitude regulation and transformer loading.

Although the easiest solution is to simply upgrade the grid capacity to withstand the incoming large EV fleet , this solution is often used as a last resort when all other solutions fail. Coordinating EV charging among users has proven to greatly relieve stress from the grid. Coordination strategies range from centralized strategies to decentralized strategies and also price-oriented strategies. In this research, a decentralized charging strategy has been proposed in which users set their preferences using an IoT platform to communicate with the charge controller. The charge controller will then set priorities for charging by allocating more charging power to users who urgently require charging while allocating less charging power to users who are flexible. Once a user priority has been defined and the charging power limits have been set, the charge controller dispatches the charging power based on the current voltage magnitude of the household node. The household voltage magnitude gives an insight on the level of loading caused by both, the normal day-to-day household consumption along with the EV charging routine. To further extend this idea of decentralized charging coordination, four strategies are proposed in this research in which priorities either depend on the EV's SOC, ToD, SOC & ToD combined, or current loading on the transformer.

In order to evaluate the proposed charging strategies, three scenarios were developed in which each scenario was evaluated at different EV penetration rates. The first scenario employs the least EV charger power rating and represents the most probable scenario in today's world. The second scenario represents the highest power rating that Mode 2, EV chargers can provide which represents enhanced user satisfaction using the most prominent type of chargers in Dutch residential grids. On the other hand, the third scenario represents the emerging fast chargers in residential grids. Across all scenarios, the SOC & ToD Combined priority control has fully mitigated impacts in the first scenario and resulted in the least voltage magnitude violations and transformer loading percentages in the second and third scenario when compared to the other charging strategies. This suggests that at higher EV charging power rates, complementary strategies such as reactive power compensators, V2G, etc. can be employed to further relieve the impact on the grid. If all else fails, a grid upgrade could be considered. Furthermore, this research extends the idea of coordinated charging through quantifying the impact on the user by comparing the final SOC percentages when using each of the coordination strategies to that of the uncontrolled strategy. Initially, the SOC deviation between a given control strategy and the uncontrolled one is high but starts to decrease as the charging period approaches its end. This is because the coordinated strategies prioritize charging to users in need of charging while also respecting the grid requirements and limits. The resulting SOC deviations at the end of the long charging periods is unnoticeable and therefore users could be inclined to enroll into a coordinated charging routine if the right incentives are given.

Finally, the relevant results from this research were integrated into DNV's NGGO Knowledge Framework. The framework aims to make use of the currently available SCADA infrastructure while employing other service-oriented architectures, such as WAMS and DERMS, in order to effectively carry-out real-time operational processes with the market. The results were modeled in the generic layer with the most prominent impacts on distribution networks from the literature. This generic model includes drivers, issues, impacts, mitigation techniques, goals, and requirements. The model then dives deep into the impacts of interest for this research, namely voltage magnitude regulation and transformer loading. For each of these two impacts, the practical results that were obtained from every scenario were included coupled with a conclusion and recommendation.

To conclude, the staggering rise in the share of EVs among the mobility sector poses many challenges for grid operations. Coordinating EV charging can greatly relive those impacts on the grid. However, the impact caused by the envisioned high EV penetration rate in the future along with employing fast chargers cannot be fully mitigated by coordinating charging alone. Therefore, for future work purposes, students may investigate employing complementary strategies that aid in relieving the grid stress. A suggestion could be to investigate to what extent can V2G be effective in solving local voltage magnitude violations. Furthermore, coupling EV chargers with energy storage technologies or a renewable energy source, such as solar energy, may relieve impacts not only from a voltage magnitude perspective, but also from a distribution transformer perspective. Additionally, students could further investigate the SOH of batteries which can possibly be damaged by control strategies that gradually change the amount of power an EV receives at a certain instant and therefore posing many challenges to the lifespan of EV batteries. Last but not least, intern students/DNV employees can further develop the EV folder in the NGGO Knowledge Framework by not only building upon the modeled impacts from this research, but also by modeling the impacts related to EV charging at the transmission side of the grid.

A

Appendix

A.1. SOC Setting

With relation to the EV charging profile presented in Chapter 4, only the time-of-arrival and time-of-departure of each EV is known. Although this piece of information is very useful, the State-of-Charge (SOC) of each EV at every time-step, $\mathrm{SOC}_{\mathrm{i,t}}$, is not recorded in the data set. As a result, an SOC model has to be developed in which the EV's SOC is set at the beginning of each charging interval while taking into account some form of randomness with regards to the EV's consumption. Assuming an EV arrives at time interval t, the algorithm would decide on what $\mathrm{SOC}_{\mathrm{i,t}}{}^{\mathrm{initial}}$ to set depending on the last time the EV charged as follows:

1. If the EV charged in time-step $t-1$, then $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}} = SOC_{\mathrm{i,t\text{-}1}}{}^{\mathrm{final}}$.
2. If the EV did not charge in the previous time-step, but has charged in the last two hours, then $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}}$ is set as a random number between **40%** and **60%**.
3. If the EV did not charge in more than two hours, then $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}}$ is set as a random number between **20%** and **50%**.

It is worthwhile to note that the SOC setting occurs at the beginning of every time-step before $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ has been dispatched. Therefore, we expect the SOC to increase at the end of every time-step where charging occurs. For example, assume charging has occurred at time-step $t-1$ and will occur in time-step t, the algorithm would carry out the following steps at the beginning of time-step t:

1. Initially, $SOC_{\mathrm{i,t}}{}^{\mathrm{initial}} = SOC_{\mathrm{i,t\text{-}1}}{}^{\mathrm{final}}$ since charging has occurred at time-step $t-1$.
2. Once $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ has been decided upon by the local voltage control algorithm, the added SOC is:

   $$SOC_{\mathrm{i,t}}{}^{\mathrm{added}} = \frac{P_{\mathrm{i,t}}{}^{\mathrm{char}}}{4 * 40},$$

   where $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ is multiplied by a factor of

   $$\frac{1}{4 * 40}$$

   since every time-step is equal to 15-min and the battery pack capacity is equal to 40kWh.
3. Therefore, the updated SOC value at the end of time-step t is:

   $$SOC_{\mathrm{i,t}}{}^{\mathrm{final}} = SOC_{\mathrm{i,t}}{}^{\mathrm{initial}} + SOC_{\mathrm{i,t}}{}^{\mathrm{added}}$$

Although this SOC-setting model is effective, it does not take into account users who may have charged and then disconnected from the charging point and remained idle. Instead, it assumes the EV is being used for at least a fraction of the time it has been disconnected from the charging point; hence, the random SOC percentages set for users who have been disconnected within 2 hours or more. The SOC-setting model is presented in the flowchart in Figure A.1.

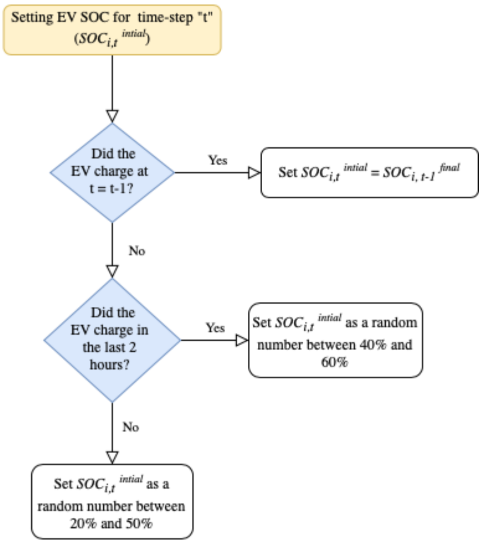


Figure A.1: SOC-setting model dependent on the charging history.

A.2. Charging Power Decay: Choice of Threshold SOC

With relation to the three scenarios presented in Chapter 4, the maximum charging power across all scenarios is equal to 11 kW. Since the simulation is a discrete system composed of 15-min intervals, the maximum $\mathrm{SOC}_{\mathrm{i,t}}$ to be added per interval is equal to:

$$SOC_{\mathrm{i,t}}{}^{\mathrm{added}} = \frac{11}{4 * 40} = 6.875\%,$$

Therefore, 93% was chosen as the threshold SOC. This not only prevents the EV from crossing a 100% SOC from a simulation perspective, but also complies with the third charging phase (Constant-Voltage charging) of a typical Li-ion battery.

A.3. Child Diagram Implementation: Voltage Magnitude Violation & Distribution Transformer Overloading

The integration of the practical findings from Chapter 4 have been included as "child diagrams" within the two blocks: Voltage Magnitude Violation and Distribution Transformer Overloading as depicted in Figure A.2 and A.3, respectively. Firstly, the implementation included a brief guide to the control strategies followed by an explanation of each scenario along with any guidelines provided by the RVO. The implementation then discusses the impact followed by an evaluation at different EV penetration rates. Finally, each scenario ends with a conclusion and recommendation.

motivation Voltage Violation

Quick Quide to the Employed Charging Strategies

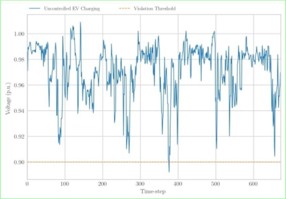
1. State-of-Charge (SOC) Priority Control: Allocates more power to users with lower SOC percentages while allocating less power to users with higher SOC percentages.
2. Time-of-Departure (ToD) Priority Control: Allocates more power to users who are leaving early while allocating less power to users who are leaving in a couple of hours.
3. SOC & ToD Priority Control: Allocates more power to users who are both leaving early and has a lower SOC percentage while allocating less power to users who have a high SOC percentage pr are leaving in a couple of hours.
4. Transformer Loading Priority Control: Allocates power to EV users depending on the current loading on the distribution transformer at the local residential grid. The lower the loading on the transformer, the more power is allocated to the EV users and vice-versa.

Scenario I : Base

Properties

- Maximum Charging Power Rate of 3.7 kW (the so-called Mode 2 chargers).
- Mode 2 chargers are most prominent in NL residential grids.
- Mode 2 chargers normally have a rating of 2.3 - 3.7 kW as per the RVO guidlines.
- 1-phase chargers and household connections.
- This scenario represents the most likely scenario in today's world.

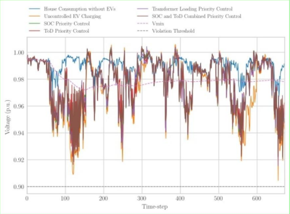
Uncontrolled EV Charging for User A



Observation

- Although the charging power is considerably low, a voltage violation can yet be triggered with uncontrolled EV charging as depicted above.
- Suggests a controlled charging strategy is needed.

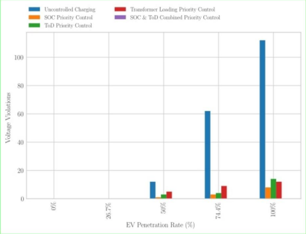
Comparing Various Charging Strategies for User B



Observation

- Although no violations were triggered by User B, uncontrolled charging can trigger violations as proved in User A.
- Nevertheless, controlled charging startegies mitgate impacts across all users in addition to raising the voltage magnitude in non-violating users such as User B.
- Raising the voltage magnitude in non-violating users increases the difference between the current voltage level and the violation threshold.
- This saftey margin can be used for any random, unscheduled heavy load.

Evaluation of an 86-household grid at different EV penetration rates



Conclusion

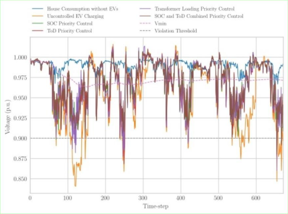
- The study suggests current NL residential grid capacity can handle an EV penetration rate of 26.7% without causing any voltage violations (even in the uncontrolled case).
- As the pentration rate further increases, voltage violations start to appear specifically with uncontrolled charging.
- Controlled charging strategies that depend on only one physical factor did not fully mitigate impacts at an EV penetration rate of 100%.
- The only controlled charging strategy that mitigated all impacts depends on two physical factors before dispatching EV charging. (which in this case is the SOC & ToD Priority control).

Scenario II : RVO Guidelines

Properties

- Maximum Charging Power Rate of 7.4 kW (the so-called Mode 2 chargers).
- Mode 2 chargers are most prominent in NL residential grids.
- Mode 2 chargers normally have a rating of 2.3 - 3.7 kW as per the RVO guidlines.
- 1-phase chargers and household connections.
- However, Mode 2 residential chargers can be rated up to 7.4 kW for a 1-phase connection given that charging is controlled by an In-Cable-Control-Box (ICCB) and the current is rated at 32A as per the RVO guidelines.
- This scenario represents higher customer satisfaction given the same Mode 2 chargers of the Base scenario are employed.

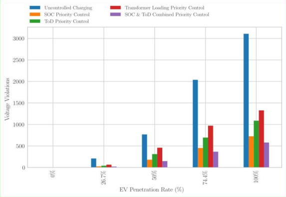
Comparing Various Charging Strategies for User B



Observation

- Since the maximum charging power has been doubled when compared to that of the Base scenario, one would expect to see lower voltage magnitudes throughout the grid.
- Voltage violations can now be seen in User B with voltage magnitudes reaching as low as 0.85 p.u. (in the uncontrolled case) at certain instants of the week.
- In addition, the voltage profile has generally improved while employing controlled charging startegies, however voltage violations were still present as depicted in the figure.

Evaluation of an 86-household grid at different EV penetration rates



Conclusion

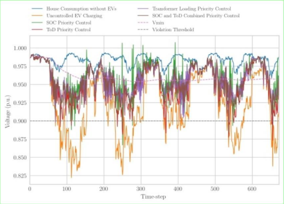
- The study suggests current NL residential grid capacity cannot handle an EV penetration rate of 26.7% or higher without causing any voltage violations (even while using the controlled strategies).
- As the pentration rate further increases, voltage violations start to appear specifically with uncontrolled charging.
- This therefore shows the need for employing other supporting startegies, such as reactive power compensators, along with the charging startegies in order to fully mitagte impacts on the grid.
- A grid capacity upgrade can be considered but is used as a last resort if the other supporting startegies cannot help mitagte the rest of the impacts that the charging strategies could not mitigate.

Scenario III : Future

Properties

- Maximum Charging Power Rate of 11 kW (the so-called Mode 3 chargers).
- Mode 3 chargers can generally have power ratings up to 11 kW, 22 kW, or even 43 kW.
- 3-phase chargers and household connections.
- As per the RVO guidelines, these chargers REQUIRE a communication and control protocol at the charging point so that the EV and the EV charger can effectively communicate with each other.
- This scenario represents the highest customer satisfaction of all three scenarios as Mode 3 chargers are being employed,

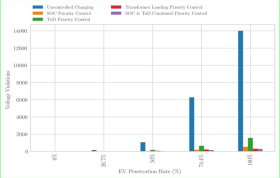
Comparing Various Charging Strategies for User B



Observation

- Since the maximum charging power has been further increased, one would expect to see lower voltage magnitudes throughout the grid.
- Voltage violations are present with voltage magnitudes reaching as low as 0.825 p.u. (in the uncontrolled case) at certain instants of the week.
- Yet again, the voltage profile has generally improved while employing controlled charging startegies, however voltage violations were still present as depicted in the figure.

Evaluation of an 86-household grid at different EV penetration rates



Conclusion

- In this scenario, the household and EV chargers have 3-phase connections and are therefore expected to carry more power and have higher voltage magnitudes when a control strategy is employed (as required by the RVO).
- The study suggests current NL residential grid capacity cannot handle an EV penetration rate of 26.7% or higher without causing any voltage violations (even while using the controlled strategies).
- As the pentration rate further increases, voltage violations start to appear specifically with uncontrolled charging.
- Additionally, uncontrolled charging shall not be carried out with Mode 3 chargers as this would severely affect the grid as depicted in the figure above and to also comply with the RVO guidelines.
- Furthermore, the Transformer Priority Control and SOC & ToD Combined priority control has resulted in lesser voltage violations than that of Scenario II.
- A grid capacity upgrade should be considered due to the enormous power supplied by the EV chargers.
- A capacity upgrade can also be complemented with other supporting startegies, such as reactive power compensators, along with the charging startegies in order to fully mitagte impacts on the grid.

Figure A.2: Child diagram within the "Voltage Magnitude Violation" block.

motivation Distribution Transformer Overloading

Quick Quide to the Employed Charging Strategies

1. State-of-Charge (SOC) Priority Control: Allocates more power to users with lower SOC percentages while allocating less power to users with higher SOC percentages.
2. Time-of-Departure (ToD) Priority Control: Allocates more power to users who are leaving early while allocating less power to users who are leaving in a couple of hours.
3. SOC & ToD Priority Control: Allocates more power to users who are both leaving early and has a lower SOC percentage while allocating less power to users who have a high SOC percentage pr are leaving in a couple of hours.
4. Transformer Loading Priority Control: Allocates power to EV users depending on the current loading on the distribution transformer at the local residential grid. The lower the loading on the transformer, the more power is allocated to the EV users and vice-versa.

Quick Quide to the Regions of Operation in a Transformer

1. Normal Load Region: Transformer loading of less than or equal to 80% of its rated capacity.
2. Heavily Loaded Region: Transformer loading of greater than 80% but less than or equal to 100% of its rated capacity.
3. Overloaded Region: Transformer loading of greater than 100% of its rated capacity.

Scenario I : Base

Properties

- Maximum Charging Power Rate of 3.7 kW (the so-called Mode 2 chargers).
- Mode 2 chargers are most prominent in NL residential grids.
- Mode 2 chargers normally have a rating of 2.3 - 3.7 kW as per the RVO guidlines.
- 1-phase chargers and household connections.
- This scenario represents the most likely scenario in today's world.

Conclusion

- As expected, normal day-to-day household consumption barely loads the transformer to 40% of its capacity which falls in the region of normal operation.
- However, when EVs are introduced in the residential grid (1 per household), the figure proves that most of the loading on the transformer is in direct realtion to the EV loads.
- This therefore concludes the importance of employing coordinated charging strategies as the charging power rate increases in the coming scenarios.
- With the current distribution transformer capacity, the load did not exceed the transformer rating and barely operated in the heavyily loaded region with uncontrolled charging suggesting the transformer capacity is sufficient for this scenario even at a 100% EV penetration rate.
- Nevertheless, coordinated charging strategies have brought down the transformer loading to the normal region of operation (which is the most desirable region of operation as less thermal heating is produced and the internal components are preserved = longer transformer lifetime + less service and maintenance).

Scenario II : RVO Guidelines

Properties

- Maximum Charging Power Rate of 7.4 kW (the so-called Mode 2 chargers).
- Mode 2 chargers are most prominent in NL residential grids.
- Mode 2 chargers normally have a rating of 2.3 - 3.7 kW as per the RVO guidlines.
- 1-phase chargers and household connections.
- However, Mode 2 residential chargers can be rated up to 7.4 kW for a 1-phase connection given that charging is controlled by an In-Cable-Control-Box (ICCB) and the current is rated at 32A as per the RVO guidelines.
- This scenario represents higher customer satisfaction given the same Mode 2 chargers of the Base scenario are employed.

Evaluation of an 86-household grid at different EV penetration rates

Conclusion

- The study suggests the current distribution transformer rated capacity can handle an EV penetration rate of 26.7% without overloading the transformer. Also, an EV penetration rate of 50% can aslo be handeled as the transformer is operating in the overloaded region for less than 0.5% of the time of operation
- As the pentration rate further increases to 74.4% and 100%, the transformer becomes overloaded for longer periods of operation and the need for coordinated charging strategies is high to prevent any damage.
- In the 100% EV penetration rate case (as shown in the first plot), the uncontrolled strategy overloaded the transformer to 140% of its rated capacity while cooridnated charging strategies collectively overloaded the transformer for less than 2.5% of its operation time (as shown in the second figure).
- This concludes that a transformer capacity upgrade is not urgently required if and only if controlled charging strategies are employed.
- This is due to the fact that transformers are allowed to operate in the overloaded region for short periods of time. To what extent the overloading is in that "short period of time" is in direct relation to the type of transformer used and therefore the transformer specifications need to be carefully examined.
- A capacity upgrade can be considered though, in order to bring down the transformer loading to the normal region of operation resulting in lower energy losses, lower heating, lower damage to the internal component = prolonged transformer lifetime.

Scenario III : Future

Properties

- Maximum Charging Power Rate of 11 kW (the so-called Mode 3 chargers).
- Mode 3 chargers can generally have power ratings up to 11 kW, 22 kW, or even 43 kW.
- 3-phase chargers and household connections.
- As per the RVO guidelines, these chargers REQUIRE a communication and control protocol at the charging point so that the EV and the EV charger can effectively communicate with each other.
- This scenario represents the highest customer satisfaction of all three scenarios as Mode 3 chargers are being employed,

Evaluation of an 86-household grid at different EV penetration rates

Conclusion

- In this scenario, the household and EV chargers have 3-phase connections and are therefore expected to carry more power.
- As a result, the load on the distribution transformer solely from day-to-day household consumption has increased when compared to the preceeding scenarios (as shown in the first figure).
- The loading on the transformer from the household consumption also peaked on the 7th day of the one week of operation, driving the transformer to operate at 82% of its capacity (heavily loaded region).
- Uncontrolled charging has resulted in a transformer loading of a staggering 350% which surely suggests such charging routine shall not be taken (also to comply with the RVO guidelines)
- As the pentration rate further increases, it is evident from the second figure that the transformer operated in the overloaded region during most of the time in the one-week operation period even when controlled strategies were employed.
- Also, the controlled charging strategies did not fully mitgate the impact as the transformer was loaded to nearly 200% of its capacity.
- Consequently, coordinating charging alone is not enough to mitgate the impact on the distribution transformer due to the very high load resulting from the EVs.
- Concluding that the transformer capacity needs to be upgraded urgently to ensure safe operation in the residential grids.

Figure A.3: Child diagram within the "Distribution Transformer Overloading" block.

Bibliography

[1] Nissan leaf. URL `https://www.v-database.org/car/1106/Nissan-Leaf`.

[2] A. A. Abdullah Al-Karakchi, G. Putrus, and R. Das. Smart ev charging profiles to extend battery life. In *2017 52nd International Universities Power Engineering Conference (UPEC)*, pages 1–4, 2017. doi: 10.1109/UPEC.2017.8231961.

[3] Netherlands Enterprise Agency. Electric vehicle charging definitions and explanation, 2019. URL `https://www.rvo.nl/sites/default/files/2019/01/ElectricVehicleCharging-DefinitionsandExplanation-january2019_0.pdf`.

[4] Netherlands Enterprise Agency. Mission zero powered by holland, 2019. URL `https://www.rvo.nl/sites/default/files/2019/06/MissonZeroPoweredbyHolland.pdf`.

[5] Mohamed A. Awadallah, Birendra N. Singh, and Bala Venkatesh. Impact of ev charger load on distribution network capacity: A case study in toronto. *Canadian Journal of Electrical and Computer Engineering*, 39(4):268–273, 2016. doi: 10.1109/cjece.2016.2545925.

[6] Tiago Barbosa, José Andrade, Ricardo Torquato, Walmir Freitas, and Fernanda C.l. Trindade. Use of ev hosting capacity for management of low-voltage distribution systems. *IET Generation, Transmission Distribution*, 14(13):2620–2629, 2020. doi: 10.1049/iet-gtd.2019.1791.

[7] O. Beaude, Y. He, and M. Hennebel. Introducing decentralized ev charging coordination for the voltage regulation. In *IEEE PES ISGT Europe 2013*, pages 1–5, 2013. doi: 10.1109/ISGTEurope.2013.6695375.

[8] Olivier Beaude, Samson Lasaulce, Martin Hennebel, and Ibrahim Mohand-Kaci. Reducing the impact of ev charging operations on the distribution network. *IEEE Transactions on Smart Grid*, 7(6):2666–2679, 2016. doi: 10.1109/tsg.2015.2489564.

[9] John Edisson Cardona, Juan Camilo López, and Marcos J. Rider. Decentralized electric vehicles charging coordination using only local voltage magnitude measurements. *Electric Power Systems Research*, 161: 139–151, 2018. doi: 10.1016/j.epsr.2018.04.003.

[10] Giovanni De Carne, Marco Liserre, Konstantina Christakou, and Mario Paolone. Integrated voltage control and line congestion management in active distribution networks by means of smart transformers. *2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE)*, 2014. doi: 10.1109/isie.2014.6865032.

[11] Nan Chen, Taotao Dai, Liancheng Wang, Wei Zhao, and Ke Lu. Overload analysis of distribution transformers based on data mining. *IOP Conference Series: Materials Science and Engineering*, 439:032112, 2018. doi: 10.1088/1757-899x/439/3/032112.

[12] Jean-Michel Clairand, Javier RodrUez-Garc, and Carlos Varez-Bel. Assessment of technical and economic impacts of ev user behavior on ev aggregator smart charging. *Journal of Modern Power Systems and Clean Energy*, 8(2):356–366, 2020. doi: 10.35833/mpce.2018.000840.

[13] European Comission. Paris agreement, 11 2019. URL `https://ec.europa.eu/clima/policies/international/negotiations/paris_en`.

[14] Qiyun Dang. Electric vehicle (ev) charging management and relieve impacts in grids. *2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 2018. doi: 10.1109/pedg.2018.8447802.

[15] Anamika Dubey and Surya Santoso. Electric vehicle charging on residential distribution systems: Impacts and mitigations. *IEEE Access*, 3:1871–1893, 2015. doi: 10.1109/access.2015.2476996.

[16] Markiewicz H. and Klajn A. Guide for the application of the european standard en 50160.

[17] Iea. Transport – topics, . URL `https://www.iea.org/topics/transport`.

[18] Iea. Global ev outlook 2020 – analysis, . URL `https://www.iea.org/reports/global-ev-outlook-2020`.

[19] M. Liu, P. K. Phanivong, and D. S. Callaway. Customer-and network-aware decentralized ev charging control. In *2018 Power Systems Computation Conference (PSCC)*, pages 1–7, 2018. doi: 10.23919/PSCC.2018.8448441.

[20] M. Liu, P. K. Phanivong, Y. Shi, and D. S. Callaway. Decentralized charging control of electric vehicles in residential distribution networks. *IEEE Transactions on Control Systems Technology*, 27(1):266–281, 2019. doi: 10.1109/TCST.2017.2771307.

[21] Gyara Mahendar and G. Yesuratnam. An approach to identify critical on load tap changing (oltc) transformers under network contingencies. In *2016 IEEE 7th Power India International Conference (PIICON)*, pages 1–6, 2016. doi: 10.1109/POWERI.2016.8077226.

[22] Jerome Mies, Jurjen Helmus, and Robert Van Den Hoed. Estimating the charging profile of individual charge sessions of electric vehicles in the netherlands. *World Electric Vehicle Journal*, 9(2):17, 2018. doi: 10.3390/wevj9020017.

[23] Matteo Muratori. Impact of uncoordinated plug-in electric vehicle charging on residential power demand - supplementary data, 06 2017. URL `https://www.osti.gov/dataexplorer/biblio/dataset/1363870`.

[24] E. Ucer, M. C. Kisacikoglu, M. Yuksel, and A. C. Gurbuz. An internet-inspired proportional fair ev charging control method. *IEEE Systems Journal*, 13(4):4292–4302, 2019. doi: 10.1109/JSYST.2019.2903835.

[25] Stijn Vandael, Bert Claessens, Maarten Hommelberg, Tom Holvoet, and Geert Deconinck. A scalable three-step approach for demand side management of plug-in hybrid vehicles. *IEEE Transactions on Smart Grid*, 4(2):720–728, 2013. doi: 10.1109/tsg.2012.2213847.

[26] Else Veldman and Remco A. Verzijlbergh. Distribution grid impacts of smart electric vehicle charging from different perspectives. *IEEE Transactions on Smart Grid*, 6(1):333–342, 2015. doi: 10.1109/tsg.2014.2355494.

[27] Remco A. Verzijlbergh, Marinus O. W. Grond, Zofia Lukszo, Johannes G. Slootweg, and Marija D. Ilic. Network impacts and cost savings of controlled ev charging. *IEEE Transactions on Smart Grid*, 3(3):1203–1212, 2012. doi: 10.1109/tsg.2012.2190307.

[28] Z. Wang and S. Wang. Grid power peak shaving and valley filling using vehicle-to-grid systems. *IEEE Transactions on Power Delivery*, 28(3):1822–1829, 2013. doi: 10.1109/TPWRD.2013.2264497.

[29] Z. Yan, Z. Yin, X. Yang, K. Zhang, J. Shi, and L. Wang. Research and simulation of centralized charge and discharge technology of evs based on mmc. In *2017 2nd International Conference on Power and Renewable Energy (ICPRE)*, pages 800–804, 2017. doi: 10.1109/ICPRE.2017.8390644.