공학박사 학위논문

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지도교수 문 승 일

이 논문을 공학박사 학위논문으로 제출함
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2021년 12월

위 원 장 _____ 윤 용 태 _____ (인)

부위원장 _____ 문 승 일 _____ (인)

위 원 _____ 한 승 용 _____ (인)

위 원 _____ 원 동 준 _____ (인)

위 원 _____ 김 윤 수 _____ (인)

# Abstract

**Tae-Han Kim**

**School of Electrical and Computer Engineering**

**The Graduate School**

**Seoul National University**

Electric vehicles (EVs) and EV charger markets are rapidly growing along with the growing interest in zero carbon emissions The large penetration of EVs and EV chargers into the distribution network has had a very negative effect on the operation of the distribution network. Therefore, it is important to evaluate the number of EVs that can penetrate the distribution network, that is, to evaluate the hosting capacity. However, it is difficult to evaluate the hosting capacity because EVs have various uncertainties unlike general loads, related to arrival, and departure times, battery state of charge (SOC), and selection of charging stations. Additionally, it is uncertain how many EVs will be penetrated from the system operator's point of view. Considering these uncertainties, it is important to model the load of an EV.

Until now, EVs only charge an electric load upon arriving at a charging station, but recently, they are used to minimize the impact on the distribution network by controlling the charge, or to become a resource for the purpose of flattening the load or minimizing the electric charge through discharging. When charging is controlled, it does not charge unconditionally after arrival, but charges at the optimal time before departure in consideration of the situation of the distribution network. Discharge control transmits the electric power stored in the battery of the EV to the distribution

network, and the EV performs the role of a generator.

In this dissertation, the hosting capacity in the distribution network is evaluated by performing EV load modeling considering the uncertainty. Initially, EV load modeling is performed considering the uncertainty. In particular, it performs modeling of EVs that only conventionally charge, charge control, or perform both charge and discharge control. Uncertainty is the entry/exit time of the EV, SOC of the battery, and total number of EVs, which are modeled using interval and affine arithmetic. Further, by using the interval undervoltage probability (IUP), the number of EVs that can be penetrated into the distribution network and the hosting capacity are evaluated using the EV load model considering uncertainty. Third, I propose a voltage violation index (VVI) that evaluates along with IUP, the hosting capacity of EVs by considering the probability of violating the constraints of the distribution network operation, owing to the EV penetration. Finally, the EV modeling data used in this study and the distribution network data used for evaluating hosting capacity are both based on actual data from Seoul National University. Here, the arrival and departure time of vehicles and the load data for each building of Seoul National University were considered. The distribution network modeling was performed using the data of the buried cables.

The proposed evaluation method was implemented in MATLAB, and a case study was conducted to minimize the cost and reduce the peak load in the charge control and charge/discharge control methods. According to the charging method of EVs, the number of EVs that can be accommodated in the system was compared with the existing method. By using the proposed method, the system operator can consider the maximum number of EVs that the system can accommodate, and when the charge/discharge control method is commercialized, it is expected that the EVs can be accommodated

to the maximum capacity.

**keywords**: Affine arithmetic, distribution network, electric vehicle, electric vehicle hosting capacity, interval arithmetic, uncertainties, under voltage probability.

**student number**: 2016-20883

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# Nomenclature

## SETS

| | |
|---|---|
| $\Omega_D$ | Set of Monte Carlo sampling days |
| $\Omega_{D_1}^t$ | Set of electric vehicle (EV) loads at time period $t$ greater than the average value |
| $\Omega_{D_2}^t$ | Set of EV loads at time period $t$ less than the average value |

## INDICES

| | |
|---|---|
| $m$ | Index for the number of EVs |
| $i$ | Bus index |
| $j$ | EV access case index |
| $k$ | EV charging station selection index |
| $t$ | Time period index |

## PARAMETERS

| | |
|---|---|
| $V^{\min}$ | Minimum voltage constraint |
| $N_{m,total}$ | Total number of Monte Carlo simulations for the $m$-th number of EVs |
| $N_{m,j,total}$ | Total number of Monte Carlo simulations for the $m$-th number of EVs and $j$-th charging station access case |
| $\lambda_{\max}$ | Maximum interval undervoltage probability (IUP) set by the network operator |
| $N_{EV}$ | Total number of EV access cases after the number of EVs are determined |
| $N_{SOC}$ | Total number of state of charge (SOC) cases of each EV after the EV access cases are determined |
| $N_{CH}$ | Total number of charging station selection cases after the SOC cases are determined |

## VARIABLES

| | |
|---|---|
| $\overline{P_{EV}}^{t}$, $\underline{P_{EV}}^{t}$ | Upper and lower bounds of the interval form EV load model at time period $t$ |
| $P_{EV}^{t}$ | Interval form of EV load at time period $t$ |
| $P_{EV}^{t}$ | Affine form of EV load at time period $t$ |
| $N_{\Omega_D}$ | Sizes of sets $\Omega_D$ |
| $N_{\Omega_{D_1}^t}$ | Sizes of sets $\Omega_{D_1}^t$ |
| $N_{\Omega_{D_2}^t}$ | Sizes of sets $\Omega_{D_2}^t$ |

| | |
|---|---|
| $V_{i,j,k}^{t}$ | Interval form voltage of $i$ -th bus and $k$ -th scenario |
| $V_{i,j,k}^{t}$ | Affine form of $V_{i,j,k}^{t}$ |
| $\overline{V_{i,j,k,R}^{t}}$ $\underline{V_{i,j,k,R}^{t}}$ | Real value of voltage in interval form |
| $\overline{V_{i,j,k,I}^{t}}$ $\underline{V_{i,j,k,I}^{t}}$ | Imaginary value of voltage in interval form |
| $V_{\min,k}$ | Minimum interval voltage in $k$ -th scenario |
| $\alpha_{m,j,k}$ | Decision variables (0-1) for calculating $N'_{m,j,over}$ |
| $\beta_{m,j,k}$ | Decision variables (0-1) for calculating $N''_{m,j,over}$ |
| $\gamma_{m,i,j,k}$ | Decision variables (0-1) for calculating $\alpha_{m,j,k}$ |
| $N'_{m,j,over}$ | Total number of "absolute undervoltage" values for evaluating interval form of HC |
| $N''_{m,j,over}$ | Total number of "partial undervoltage" values for evaluating interval form of HC |
| $\delta$ | Voltage violation index, representing the number of buses that violate the voltage constraint. |
| $\overline{\lambda_{m,j}}$ $\underline{\lambda_{m,j}}$ | Interval form of IUP for $j$ -th charging station selection case |
| $\overline{\lambda_{\mathrm{m}}}$ , $\underline{\lambda_{m}}$ | Interval form of IUP for the $m$ -th EV case |
| $\overline{HC}$ $\underline{HC}$ | Upper and lower bounds of interval form of hosting capacity |
| $\underline{EV}$ | Minimum number of EVs |

# Chapter 1

# INTRODUCTION

## 1.1 Motivations and purposes

### 1.1.1 Motivation of evaluating hosting capacity of EV

Carbon free has become a global concern. With the transport sector making the most severe contribution to emissions, interest in electric vehicles (EVs) is growing. Currently, there are 10 million EVs in operation worldwide [1, 2]. As cited in [1], EV registrations have increased by 41% in 2020, in stark contrast to the worldwide downturn in car sales of 16% attributed to the Covid-19 pandemic. According to the Sustainable Development Scenario proposed by the International Energy Agency, the EV market size could reach 230 million by 2030 if countries around the world work to reach their climate goals. The charger market is also developing with the expansion of the EV market [1]. In 2020, the number of publicly accessible chargers reached 1.3 million. Considering the growing EV and charger market, increasing load is being placed on power distribution networks through voltage deviation, power losses, and transformer overheating [3–7]. Given EVs have such a significant effect on distribution networks,

numerous studies have been conducted to calculate the number of EVs a network can accommodate, that is, the EV hosting capacity (HC).

For EV HC, studies have mainly focused on determining the number of EVs, or the chargeable capacity, within a range that does not exceed the voltage constraints. In [8, 9], the load was modeled for domestic EVs in a stochastic manner, with the aim of power loss optimization. Actual system modeling has also been conducted [3,9–14], where the influence of EV and charger penetration on actual distribution networks was analyzed in different locations, including Gothenburg in Germany, Toronto in Canada, and Budapest in Hungary, as well as Britain and America. There are also studies that assume the actual vehicle operation data to be those of an EV [15–17]. In [15], EV demand modeling was performed on randomly selected vehicle operation data from the Atlanta Regional Commission. The EV charging characteristics have also been studied using Guangzhou traffic data [16]. The EV demand modeling was further performed. Using representative load profiles according to the application [18, 19], and in [13], demand modeling was performed using the stochastic method. Other studies have also been conducted to maximize the use of EVs as resources through charging strategies, such as vehicle to grid (V2G), or to evaluate the maximum capacity of EVs through proper placement of chargers [14, 15, 20–27]. However, a common limitation of these studies is that they do not sufficiently consider the uncertainties of EV operation. EVs have an arrival and departure times at the charging stations, state of charge (SOC), and required amount of charge. Considering these factors, a more thorough assessment of the influence of EVs on the system and the use of resources can be made.

In previous studies, probability methods using probability density functions (PDFs) have been used to consider uncertainty. However, the performance is dependent on the accuracy of the PDFs, which is generally difficult to obtain [28]. In these situations, the

interval method is suitable for improving the performance, because it expresses uncertain variables only if the exact lower and upper bounds are clear [28–31]. However, a disadvantage of the interval method is that it usually returns a conservative result when considering uncertainty [29]. This shortcoming can be resolved if interval arithmetic is realized using affine arithmetic [28]. In [31], a three-phase forward-backward sweep power flow method using interval and affine arithmetic was proposed. In addition, the photovoltaics (PV) HC, including load uncertainty, was evaluated using interval and affine arithmetic and interval overvoltage probability (IOP), which is a method of expressing HC by probability as presented in [28]. The interval, affine arithmetic and, IOP evaluation methods are appropriate methods for considering the uncertainties of EVs.

### 1.1.2 Specific topics of this dissertation

EVs typically have five types of uncertainties [32–37]. When an EV arrives at a charger, it can act as an electrical load or be used as a resource. Therefore, the first uncertainty is which charger the EV is connected to. EV owners do not always connect EVs to the same charging station to charge them. Because it is connected to different chargers depending on the situation, one EV can act as a load in various locations. The second uncertainty is the time at which the EV will arrive at the charger. When an EV is connected to a charger, it becomes a load, and the EV is used as a load or a resource when it is parked. For example, if an EV parked from 6 am to 6 pm can be used for 12 hours, an EV parked from 1 pm to 3 pm can only be used for two hours. Next, I consider the state of charge of the EV battery. When an EV is connected to a charger, the amount of load or available resources of the EV is determined according to the output of the EV charger, the state of charge (SOC) of the battery, and battery capacity. For example, if

an EV with a 50 kWh battery is connected to a 10 kW EV charger with a 40% charge and the owner wants it to be charged to 80%, the EV will be a 10 kW, two-hour load. Finally, I consider the total number of EVs in the network. From the perspective of the network operator, it is necessary to know the total number of EVs to be parked in order to manage the load or make it a resource.

In this dissertation, to deal with the uncertainty of EVs, I used the data of practical cars entering and exiting the target system, Seoul National University. According to Seoul National University's car access record, the number of vehicles entering between 8-9 AM increases sharply, approximately 1400, as 9 AM being the start time at the work. The number of outgoing vehicles increases gradually approximately 1100 vehicles, from 6:00 to 7:00 PM, the time after work. The maximum number of cars staying at Seoul National University is approximately 3800. I considered the vehicle access model as EV data. The details will be explained in a later chapter. After generating the access case of the EV in this way, the EV load was modeled using interval and affine arithmetic.

When processing data by sensing various power sources and loads such as EVs or PV, the problem is that the amount of data is generally too large. The amount of computation increases exponentially because many inputs are required to handle even a few uncertainties. Interval arithmetic is an appropriate data processing method in this situation. The interval method can be used only if the boundary is an obvious case. However, the disadvantage of the interval method is that the result of the arithmetic operation is expressed expressed. The affine arithmetic method overcomes disadvantage and expresses it closer to the actual solution. These two methods will be discussed in detail in a later chapter.

The EV HC of the Seoul National University system is evaluated using the EV

load model processed by the interval and affine methods. To evaluate the HC, a method called the interval undervoltage probability (IUP) was proposed. This method divides the cases in which the actual EV is connected to the charger and in some cases evaluates the HC of the EV through the probability of undervoltage in the target system. In addition, by presenting an index that can set the range of probabilities, the system operator can manage the EV load more flexibly. These issues will be dealt with in detail in Chapter 3.

To apply the proposed method, the actual power system of the Seoul National University was modeled. Load modeling was conducted by receiving data on the power consumption of each building over time. In addition, the target system was modeled using the impedance data of cables buried at Seoul National University. The actual load was applied to the Seoul National University power system, and the EV HC was evaluated, by assuming that the data is generated for EVs.

## 1.2 Highlights and contributions

1) EV load modeling using interval and affine arithmetic considering the uncertainties of EV arrival time, SOC, and location of the charging station that did not consider all conditions at the same time in previous studies.

2) The charge control and charge/discharge control methods of EVs were applied for the purpose of minimizing the electricity cost of the distribution network or reducing the peak load, and the HC was evaluated accordingly.

3) Network modeling using practical cable data of Seoul National University, with the load modeled by collecting the power consumption of each building, along with EV load modeling using actual vehicle access data.

4) Calculation of EV HC through IUP evaluation via the number of EVs form the model-based load and network.

5) Provision of an index that allows network operators to offer flexibility in EV load management.

### 1.2.1 EV load modeling considering the uncertainties and charge /discharge control

The EV load was modeled based on the actual vehicle data entering and exiting the target system. Uncertainty of EVs took into account entry and exit time, departure time, charger location selection, and battery charging status, and also took into account uncertainty about the total number of EVs. In addition, i considered how to charge the electric vehicle from the time it arrives to the charging station before it leaves. There are basically three charging methods for electric vehicles. The first method is

to start charging as soon as it arrives at a charging station and is connected, which is the basic method currently used, and completes charging without considering the electric system. The second method is to select the charging time when the EV is parked in consideration of the system situation. The last method can perform both charging and discharging within the time the electric vehicle is parked, and achieves both the purpose of charging the EV and the EV to turn it into a resource. Each method will be referred to as V0G, V1G, and V2G in this paper.

### 1.2.2 Network modeling using practical data of Seoul National University

To apply the proposed EV HC method, the actual system of Seoul National University was modeled. Referring to the Seoul National University power system diagram, the target system was modeled by applying the impedance data, length, and connected structure of the buried cables. Seoul National University consists of three main systems receiving 22.9kV power, and one of the three systems, includes the College of Engineering. This network was considered as a target because a project to install an EV charging station with a V2G function is in progress. In addition, the actual power consumption of the buildings in the target system was analyzed, organized by time units, and applied as a load. However, although a predictive model was used in the project, the predictive model was not applied because the purpose of this study was to evaluate HC

### 1.2.3 Calculation of EV HC through IUP evaluation the number of EVs form the model-based load and network

Existing studies mainly considered the most extreme situation and calculated the HC considering the network voltage and constraints, assuming that the maximum EVs came in at the time of the highest load. Although this method may be suitable for unconditional safety, it may not utilize the load carrying capacity of the system to its full potential and may waste resources. In this paper, I propose a probabilistic method to evaluate EV HC. The IUP method is a probabilistic method for evaluating HC by considering the case of violating the systemic constraint on the number of entire cases. Thus, the system operator can adjust the EV HC according to the situation, allowing the system resources to be used more flexibly.

### 1.2.4 Provision of an index that allows network operators to offer flexibility in EV load management

The IUP method suggested that the system operator allows flexible management of the load, as well as more flexible system operation together with the IUP method by presenting an index that can evaluate the degree of violation of the constraint. By using the index, it is possible to evaluate not only the amount of load that can enter the system, but also the range of the load, so that the operator can manage the system more flexibly and efficiently.

## 1.3 Dissertation organization

- Chapter 1 explains the motivation and purposes of this dissertation.
- Chapter 2 consists of the EV load modeling with uncertainties.
- Charter 3 describes the evaluation method of EV HC using IUP.
- Chapter 4 verifies the proposed method through a case study based on the actual system.
- Chapter 5 is conclusions and future extensions.

# Chapter 2

# Load modeling and characteristics considering the uncertainties of EV

## 2.1 The method of charging EV

The charging method that has been used since the early days of EVs is as simple as charging a cell phone at home. When an EV arrives at a charging station and connects to a charger, it starts charging and charges until the EV's battery is fully charged or the EV driver disconnects the charger. In the past, there were not many EVs and chargers. Also, since the output of the charger is small, charging in this way does not have a significant effect on the power system. In general, one of the reasons for the most reluctance to purchase an EV is that charging speed is slow due to a low-output charger. Manufacturers have developed technologies to solve this problem, and Hyundai Motor Company recently introduced a Hi charger, which has a whopping 350kW output [38, 39]. If such a charger is penetrated into the power system on a large scale, it can have a big impact, so it is necessary to apply a charging method that minimizes the impact on the EV and makes it a resource.

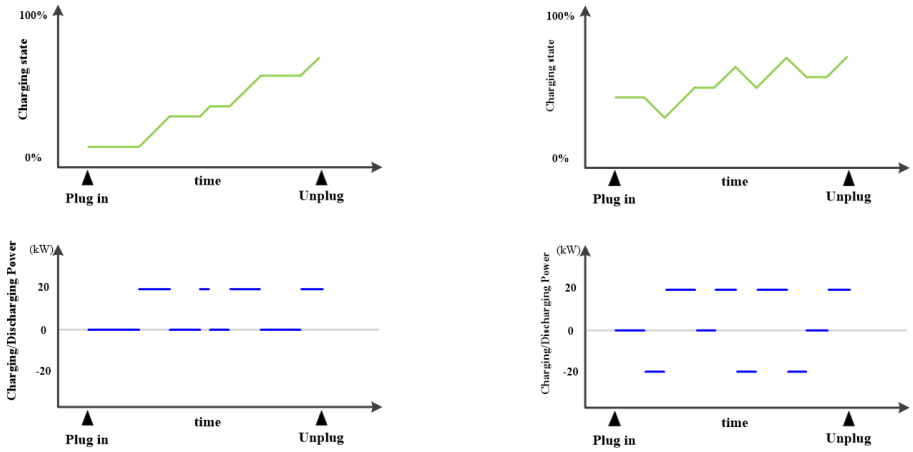


Figure 2.1: V1G and V2G Scheme

A more advanced method than the conventional charging method is the controlled charging method. The controlled charging method will be referred to as V1G in this paper, and the conventional charging method will be referred to as V0G. V1G is a method of determining the optimal charging time using optimization or a rule base [40]. Figure 2.1 shows the charging method of V1G and V2G and the amount of charging accordingly. As an example of V1G, Figure 2.2 shows different electricity rates for each time zone used by Seoul National University, the target system, and Table 2.1 is showing this. Since Seoul National University uses a power rate system with different rates for each time zone, in order to minimize the charging cost of EV, EVs must be charged in the order of the cheapest time within the time the EV is parked. If an EV is connected to the charger at 8 am and disconnected at 5 pm and the time required for charging is 3 hours, the EV is the cheapest at 40.3 won/kWh at 8 am, and the second at 85 won/kWh. It charges at 9 o'clock and 12 o'clock, which is cheap.

In this way, the cost can be minimized, and the EV can be used for the purpose of

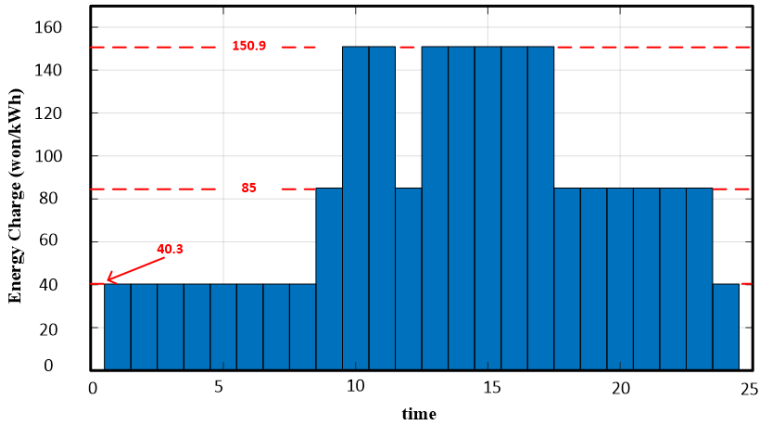


Figure 2.2: Electric rate of time of use

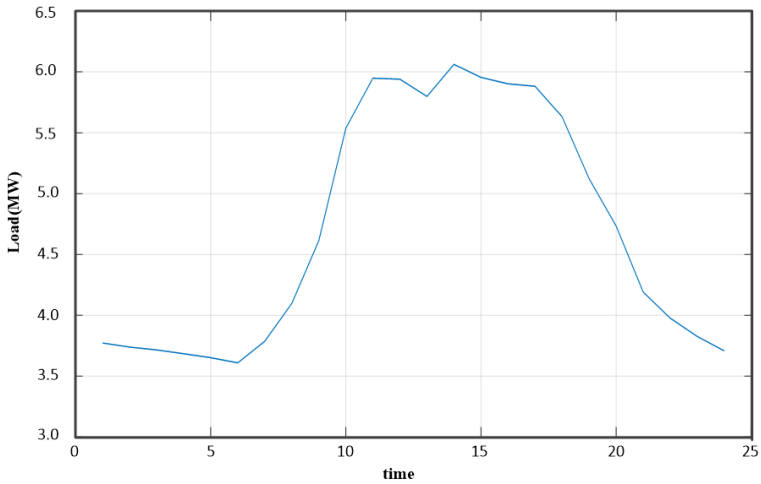


Figure 2.3: Second power plant total load

peak load reduction on the system. Figure 2.3 shows the electricity usage for a specific day of the target grid. The peak load is about 6 MW. Based on the previous day's load data or forecast data, if you charge from the time when the load is light within the park-

Table 2.1: Electric rate of time of use

| Classification | | Demand charge(won/kW) | Energy Charge (won/kWh) | | | |
|---|---|---|---|---|---|---|
| | | | Time period | summer (Jun.1∼Aug.31) | spring/fall (Mar.1∼May.31/ Sep.1∼Oct.31) | winter (Nov.1∼Feb.28) |
| High-Voltage A | option I | 6,090 | off-peak load | 44.8 | 44.8 | 48.8 |
| | | | mid-load | 89.5 | 59.2 | 88.0 |
| | | | peak-load | 155.4 | 79.70 | 126.7 |
| | option II | 6,980 | off-peak load | 40.3 | 40.3 | 44.3 |
| | | | mid-load | 85.0 | 54.7 | 83.5 |
| | | | peak-load | 150.9 | 75.2 | 122.2 |
| High-Voltage B | option I | 6,090 | off-peak load | 43.3 | 43.3 | 47.1 |
| | | | mid-load | 86.8 | 57.5 | 85.1 |
| | | | peak-load | 149.7 | 77.3 | 122.4 |
| | option II | 6,980 | off-peak load | 38.8 | 38.8 | 42.6 |
| | | | mid-load | 82.3 | 53.0 | 80.6 |
| | | | peak-load | 145.2 | 72.8 | 117.9 |

ing time as a method of minimizing the charge in advance, V1G charging can be performed while minimizing the system burden caused by the penetration of EVs. V2G, which is a bidirectional charging/discharging method, needs to consider discharging differently from the V1G controlled charging method. The reason for discharging is to extract the energy built into the battery of the EV and make it a resource for the system. In order to perform V2G, it is necessary to identify the target charging amount desired by the owner along with the expected departure time of the EV. Through the

scheduled departure time and the currently connected time, the time for the EV to be connected to the charger can be known, and the required charging time and discharging time of the EV can be identified by comparing the target charge amount and the current charge amount, so it can be used as a resource. As in the example above, suppose an EV is connected to the charger at 8 o'clock and is scheduled to leave at 5 pm. When comparing the current battery charge state and the target charge amount, when the charging time is 3 hours, the charging time is 6 hours out of the 9 parking hours, and the discharge time is 3 hours.

$$
\begin{aligned}
charging\,duration &= (parking\,duration + required\,charge\,duration/2] \\
discharging\,duration &= (parking\,duration - required\,charge\,duration)/2]
\end{aligned}
\tag{2.1}
$$

In the parking time, if you list the hours in the order of the lowest price, select the amount of time for the charging duration, list the times in the order of the highest price, and then select the time for the discharge duration then, i can know the required charge duration and discharge duration. In addition, discharge should be considered in consideration of whether the battery of the EV can be discharged. If the charge and discharge duration are the same, charging and discharging are not performed. Figure 2.4 shows the results of charging/discharging scheduling for a randomly generated EV based on the Seoul National University electricity rate system. -1 is charging, 1 is discharging. Yellow, orange, and red are the most expensive in order.

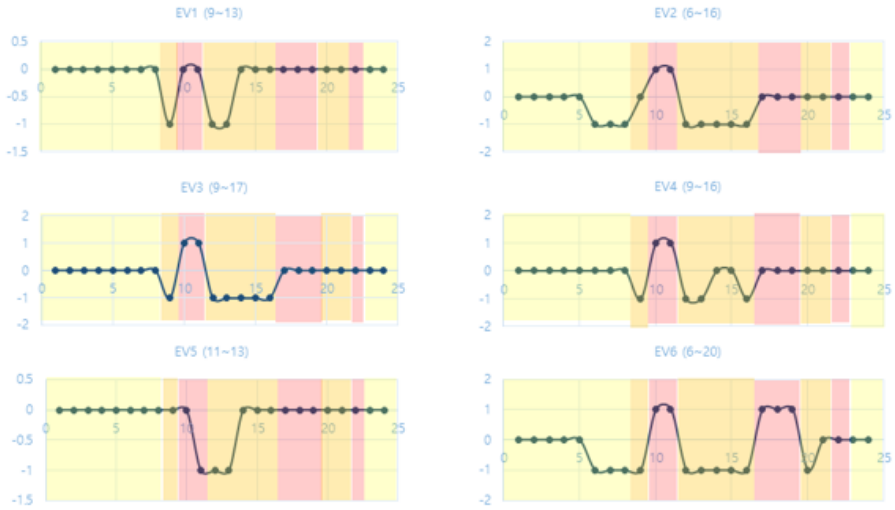


Figure 2.4: Example of EV charging schedule

## 2.2 The method to deal with uncertainties of EVs using interval computaion

As mentioned earlier, EVs have various uncertainties. By installing an accurate smart meter in all EVs and chargers, it is not only impossible to collect data, but also to process such a large amount of data, and the suitable method in this situation is the interval computation method. Interval computation can be processed if only the upper and lower boundaries of uncertainty are clearly known. This interval computation can be implemented through interval arithmetic and affine arithmetic.

### 2.2.1 Interval arithmetic

Interval arithmetic is a suitable method for solving uncertainty problems. The interval method can be used to calculate wide range of numbers over a define range simultaneously. The basic form of interval arithmetic is presented in equation 2.2; further, equation 2.3-2.4 are the real and imaginary components of the complex number, respectively.

$$\widehat{x} = x_r + ix_i \tag{2.2}$$

$$x_r = \left[\underline{x_r}, \overline{x_r}\right] = \left\{\underline{x_r} \in \mathbb{R} \mid \underline{x_r} \leq x_r \leq \overline{x_r}\right\} \tag{2.3}$$

$$x_i = \left[\underline{x_i}, \overline{x_i}\right] = \left\{\underline{x_i} \in \mathbb{R} \mid \underline{x_i} \leq x_i \leq \overline{x_i}\right\} \tag{2.4}$$

Here, $x_r$ and $x_i$ have upper and lower limits, which are given by $\overline{x_r}$, $\underline{x_r}$ and $\overline{x_i}$, $\underline{x_i}$

respectively. Interval arithmetic has four basic arithmetic operations: addition, subtraction, multiplication and division [29]. Let $x$ and $y$ be interval number such that basic operations are defined as

$$X = [\underline{x}, \overline{x}] \tag{2.5}$$

$$Y = \left[\underline{y}, \overline{y}\right] \tag{2.6}$$

$$X + Y = [\underline{x}, \overline{x}] + \left[\underline{y}, \overline{y}\right] = \left[\underline{x} + \underline{y}, \overline{x} + \overline{y}\right] \tag{2.7}$$

$$X - Y = [\underline{x}, \overline{x}] - \left[\underline{y}, \overline{y}\right] = \left[\underline{x} - \overline{y}, \overline{x} - \underline{y}\right] \tag{2.8}$$

$$\begin{aligned} X \times Y &= [\underline{x}, \overline{x}] \times \left[\underline{y}, \overline{y}\right] \\ &= \left[min\left\{\underline{x}\underline{y}, \underline{x}\overline{y}, \overline{x}\underline{y}, \overline{x}\overline{y}\right\}, max\left\{\underline{x}\underline{y}, \underline{x}\overline{y}, \overline{x}\underline{y}, \overline{x}\overline{y}\right\}\right] \end{aligned} \tag{2.9}$$

And if, $0 \notin \left[\underline{y}, \overline{y}\right]$

$$X \div Y = [\underline{x}, \overline{x}] \div \left[\underline{y}, \overline{y}\right] = [\underline{x}, \overline{x}] \times \left[\frac{1}{\overline{y}}, \frac{1}{\underline{y}}\right] \tag{2.10}$$

If the unknown is a complex number, it can be expressed as

$$X = X_r + iX_i \tag{2.11}$$

$$X_r = \left[\underline{x_r}, \overline{x_r}\right] = \left\{x_r \in \mathbb{R} \mid \underline{x_r} \leq x_r \leq \overline{x_r}\right\} \tag{2.12}$$

$$X_i = \left[\underline{x_i}, \overline{x_i}\right] = \left\{x_i \in \mathbb{R} \mid \underline{x_i} \leq x_i \leq \overline{x_i}\right\} \tag{2.13}$$

The four basic arithmetic operations for interval complex numbers $X$ and $Y$ are defined below

$$\begin{aligned} X + Y &= \left(\left[\underline{x_r}, \overline{x_r}\right] + \left[\underline{y_r}, \overline{y_r}\right]\right) + i\left(\left[\underline{x_i}, \overline{x_i}\right] + \left[\underline{y_i}, \overline{y_i}\right]\right) \\ &= \left(\left[\underline{x_r} + \underline{y_r}, \overline{x_r} + \overline{y_r}\right]\right) + i\left(\left[\underline{x_i} + \underline{y_i}, \overline{x_i} + \overline{y_i}\right]\right) \end{aligned} \tag{2.14}$$

$$\begin{aligned} X - Y &= \left(\left[\underline{x_r}, \overline{x_r}\right] - \left[\underline{y_r}, \overline{y_r}\right]\right) + i\left(\left[\underline{x_i}, \overline{x_i}\right] - \left[\underline{y_i}, \overline{y_i}\right]\right) \\ &= \left(\left[\underline{x_r} - \overline{y_r}, \overline{x_r} - \underline{y_r}\right]\right) + i\left(\left[\underline{x_i} - \overline{y_i}, \overline{x_i} - \underline{y_i}\right]\right) \end{aligned} \tag{2.15}$$

$$XY = \left(X_r Y_r - X_i Y_i\right) + i\left(X_r Y_i + X_i Y_r\right) \tag{2.16}$$

And if, $0 \notin \left({Y_r}^2 + {Y_i}^2\right)$

$$\frac{X}{Y} = \frac{XY^\star}{YY^\star} = \frac{\left(X_r Y_r + X_i Y_i\right) + i\left(X_i Y_r - X_r Y_i\right)}{{Y_r}^2 + {Y_i}^2} \tag{2.17}$$

As a demonstration of interval arithmetic, considering the following example, where

$$f = \left(\widehat{x_1}, \widehat{x_2}\right) = \widehat{x_1} \times \widehat{x_2} \tag{2.18}$$

$$\widehat{x_1} = [3, 5] + i\,[2, 4] \tag{2.19}$$

$$\widehat{x_2} = [5, 9] + i\,[5, 11] \tag{2.20}$$

$$\widehat{y} = f = \left(\widehat{x_1}, \widehat{x_2}\right) = [25, 89] + i\,[-45, 21] \tag{2.21}$$

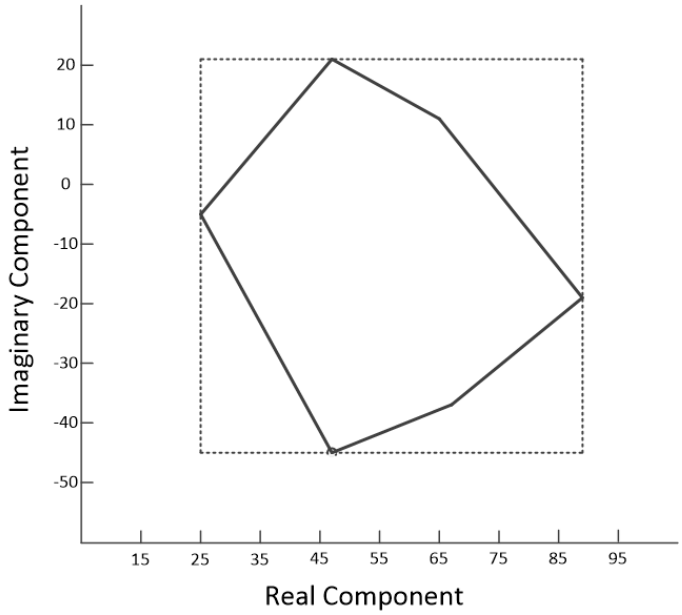


Figure 2.5: Example solution boundary for interval multiplication

### 2.2.2 Affine arithmetic

As can be seen from Figure 2.5, the disadvantage of interval arithmetic is that the calculation result is expressed conservatively. It can be seen that the range of dashed lines, the result of interval arithmetic, is much larger than that of the solid line, which is the actual value. Affine arithmetic is a method that returns a much tighter solution boundary in the same situation. The basic form of affine arithmetic is given in equation 2.22. $x_0$ is a central value, and $\varepsilon_{new_i}$ is an error variable whose values are unknown and lie in the range of [-1, 1]. The interval form and affine form can be converted between each other using basic formulas equation 2.23-2.24.

$$\widehat{x} = x_0 + x_{new_1}\varepsilon_{new_1} + x_{new_2}\varepsilon_{new_2} \tag{2.22}$$

$$x_0 = \frac{(\underline{x_r} + \overline{x_r}) + i(\underline{x_i} + \overline{x_i})}{2} \tag{2.23}$$

$$x_{new_1} = \frac{\overline{x_r} - \underline{x_r}}{2} \tag{2.24}$$

$$x_{new_2} = \frac{i(\overline{x_i} - \underline{x_i})}{2} \tag{2.25}$$

As a demonstration of interval and affine arithmetic, considering the following example, where $f = (\widehat{x_1}, \widehat{x_2}) = \widehat{x_1} \times \widehat{x_2}$, $\widehat{x_1} = [3, 5] + i[2, 4]$ and $\widehat{x_2} = [5, 9] + i[5, 11]$. In interval form, that the result is $\widehat{y} = f = (\widehat{x_1}, \widehat{x_2}) = [25, 89] + i[-45, 21]$. This can be converted to affine form $\widehat{x_1}$ and $\widehat{x_2}$ using equation 2.23-2.25.

$$\widehat{x_1} = (4 + \varepsilon_1) + i(3 + \varepsilon_2) \tag{2.26}$$

$$\widehat{x_2} = (7 + 2\varepsilon_3) - i(8 + 3\varepsilon_4) \tag{2.27}$$

Figure 2.6 shows multiplication results for the example using interval and affine along with the true solution boundary, depicted by dotted, dashed, and solid lines, respectively. The example show that the affine method returns a much tighter solution boundary than the interval method

### 2.2.3 Comparison of interval and affine arithmetic

Relative accuracy can be defined as the ratio of the range of the actual value to the range of the calculated value in all range types of calculations such as affine and interval arithmetic. It is defined as conservative as the difference in length and area in the dimension increases. The disadvantage of the interval arithmetic is that the relative

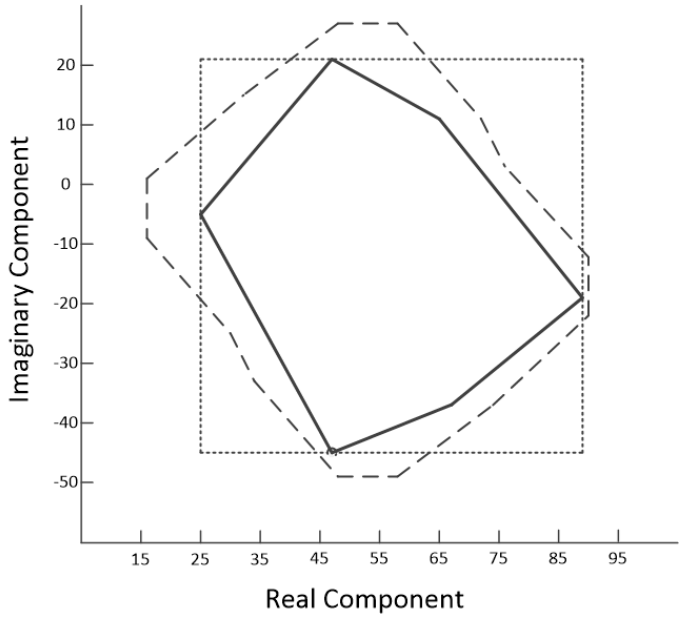


Figure 2.6: Example solution boundary for interval and affine multiplication

accuracy of repeated calculations gradually decreases due to the basic assumption that all data in the range are independent. A simple example is below.

$$
\begin{aligned}
f_{real}(x) &= x - x = 0 \\
f_{affine}(x) &= x - x = (x_0 + \sum_{i=1}^{k} x_i \varepsilon_i) - ((x_0 + \sum_{i=1}^{k} x_i \varepsilon_i)) = 0 \\
f_{interval}(x) &= x - x = [a, b] - [a, b] = [a - b, b - a]
\end{aligned}
\tag{2.28}
$$

As such, when there is a dependency between operands such as subtraction of the same operand, the interval operation is less accurate. In addition, when there is a dependency between operands, the accuracy of the solution gradually decreases in iterative calculations, which is called error explosion. The example below is the operation

result for $g(x)$ and $g(g(x))$ of interval and affine in the interval [-2,2].

$$g(x) = \frac{\sqrt{x^2 - x + 1/2}}{\sqrt{x^2 + 1/2}} \tag{2.29}$$

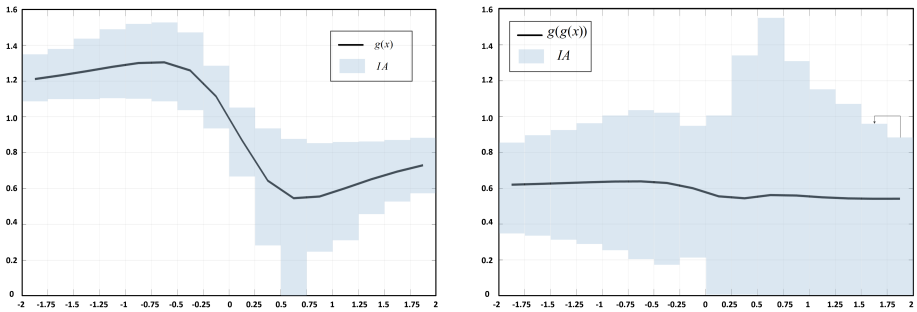


Figure 2.7: Error explosion example of interval arithmetic

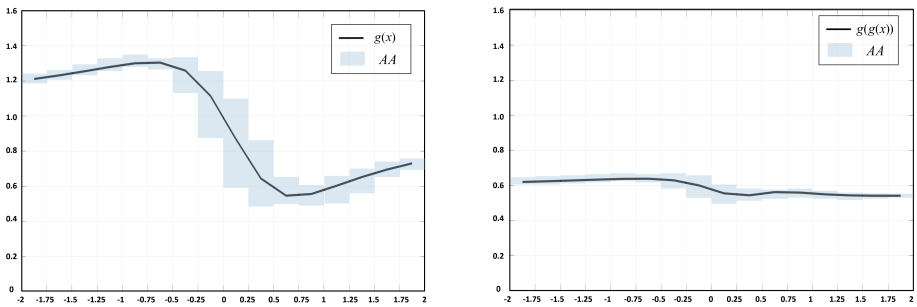


Figure 2.8: Error explosion example of affine arithmetic

The error explosion problem of interval arithmetic also occurs in power flow calculation. A dependency problem occurs when iteration is repeated in the backward-forward power flow that can be applied to the the radial network as follows.

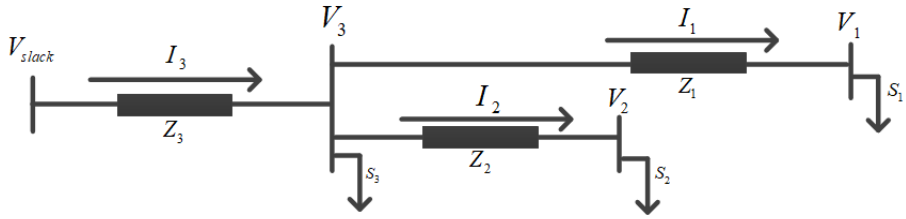


Figure 2.9: A typical radial network

$Iteration1$

$$
\begin{aligned}
&1.S_1, S_2, S_3 -> [S_1], [S_2], [S_3] \\
&2.[I_1] = \left(\frac{[S_1]}{V_1}\right)^*, [I_2] = \left(\frac{[S_2]}{V_2}\right)^*, [I_3] = \left(\frac{[S_3]}{V_3}\right)^* \\
&3.[V_3] = V_{slack} - Z_3[I_3], [V_1] = [V_3] - Z_1[I_1], [V_2] = [V_3] - Z_2[I_2]
\end{aligned}
\tag{2.30}
$$

$Iteration2$

$$
\begin{aligned}
1.[I_1] &= \left(\frac{[S_1]}{[V_1]}\right)^* \\
&= \left(\frac{[S_1]}{V_{slack} - Z_3[I_3] - Z_1[I_1]}\right)^* \\
&= \left(\frac{[S_1]}{V_{slack} - Z_3\left[\left(\frac{[S_3]}{V_3}\right)^* + \left(\frac{[S_2]}{V_2}\right)^* + \left(\frac{[S_1]}{V_1}\right)^*\right] - Z_1\left[\left(\frac{[S_1]}{V_1}\right)^*\right]}\right)^*
\end{aligned}
\tag{2.31}
$$

$$
\begin{aligned}
2.[I_2] &= \left(\frac{[S_2]}{[V_2]}\right)^* \\
&= \left(\frac{[S_2]}{V_{slack} - Z_3[I_3] - Z_2[I_2]}\right)^* \\
&= \left(\frac{[S_2]}{V_{slack} - Z_3\left[\left(\frac{[S_3]}{V_3}\right)^* + \left(\frac{[S_2]}{V_2}\right)^* + \left(\frac{[S_1]}{V_1}\right)^*\right] - Z_2\left[\left(\frac{[S_2]}{V_2}\right)^*\right]}\right)^*
\end{aligned}
\tag{2.32}
$$

After converting the load $S1$, $S2$, $S3$, of each bus into interval and affine form $[S1]$, $[S2]$, $[S3]$ and calculating the current using the backward sweep method, the interval and affine form current can be obtained. Also, the voltage in interval and affine form can be obtained by the forward sweep method. Dependency problem does not occur in the first iteration, but dependency problem occurs from the second iteration. When $[I1]$ and $[I2]$ are obtained using the voltage obtained in the first iteration and the interval and affine form load of each bus, the same $[S1]$ and $[S2]$ are entered in the numerator and denominator at the same time, so a dependency problem and error explosion occurs.

## 2.3 Mathematical formulation

In this section, i formulate an equation to calculate the HC of an EV using interval and affine arithmetic. The HC is determined by the number of EVs that can be accommodated in the case where the voltage constraint of the target network is not violated. The main procedure of EV HC evaluation is as follows.

### 2.3.1 power flow using affine arithmetic

For a radial LV distribution network, a method of calculating the forward-backward sweep power flow by applying affine arithmetic is as proposed in [31]. The net power injection for power flow expressed as a complex affine variable as

$$\widehat{S_b} = (S_b)_0 + (S_b)_n \varepsilon_n \tag{2.33}$$

Equation 2.33 is based on the general forward-backward sweep power flow, wherein the power flow to which the affine variable is applied is calculated using the following three steps.

#### Nodal current calculation

Set the initial voltage of the terminal bus and determine the affine form of the current equation 2.34

$$\widehat{I_b} = \left(\frac{\widehat{S_b}}{\widehat{U_b}}\right)^{\star} = [(I_{m+1})_0 + (I_{m+1})\varepsilon_1 + \cdots + (I_{m+1})_n \varepsilon_n] \tag{2.34}$$

**Backward sweep calculation**

Starting from the terminal bus, update the current using Kirchhoff's current law to calculate the branch current equation 2.35

$$\begin{aligned}\widehat{I_{m+1}} &= -\widehat{I_b} + \sum_{j \in A_l} \widehat{I_j} \\ &= [(I_{m+1})_0 + (I_{m+1})\varepsilon_1 + \cdots + (I_{m+1})_n \varepsilon_n]\end{aligned} \tag{2.35}$$

**Forward sweep calculation**

Update the nodal voltage from the starting bus and terminal bus using equation 2.36

$$\begin{aligned}\widehat{U_{m+1}} &= \widehat{U_m} - Z_{m,m+1}\widehat{I_m} \\ &= [(U_{m+1})_0 + (U_{m+1})\varepsilon_1 + \cdots + (U_{m+1})_n \varepsilon_n]\end{aligned} \tag{2.36}$$

Stop the iteration following the three steps if the iterative value calculated satisfies equation 2.36

$$max\left(|(\overline{U_b})_k - (\overline{U_b})_{k+1}|, |(\underline{U_b})_k - (\underline{U_b})_{k+1}|\right) < \varepsilon_{err} \tag{2.37}$$

### 2.3.2 Uncertainty consideration method

The IOP based HC has previously been proposed to evaluate the maximum penetration level of PV systems [28]. In this paper, EV penetration level is evaluated using a modified IOP method as follows.

Load uncertainty on the bus is dependent on the required charging time for an EV arriving at a charging station. Considering the output of the charger and the battery ca-

pacity of the EV, the time required for charging the EV is distributed within a specified range for which it is assumed that the charging time is uniformly distributed.

**EV charging load interval uncertainty modeling**

In the interval uncertainty modeling of the EV charging load, the SOC of each EV is generated by random numbers. If the upper and lower limit of the SOC is determined from such randomly generated SOC, the interval load of the EV can be determined in proportion to the EV charger output. The load interval of the EV required by each bus can thus be expressed as

$$\begin{cases} \overline{P_{EV}^{t}} & = \frac{1}{N_{\Omega_{D_1}}^{t}} \sum\limits_{d \in \Omega_{D_1}^{t}} P_{EV,d}^{t} \\ \underline{P_{EV}^{t}} & = \frac{1}{N_{\Omega_{D_2}}^{t}} \sum\limits_{d \in \Omega_{D_2}^{t}} P_{EV,d}^{t} \\ P_{EV,avg}^{t} & = \frac{1}{N_{\Omega_D}} \sum\limits_{d \in \Omega_D} P_{EV,d}^{t} \end{cases} \tag{2.38}$$

$$\begin{cases} \Omega_{D_1}^{t} & = \left\{ d_1 \in \Omega_D | P_{EV,d_1}^{t} \geq P_{EV,avg}^{t} \right\} \\ \Omega_{D_2}^{t} & = \left\{ d_2 \in \Omega_D | P_{EV,d_2}^{t} < P_{EV,avg}^{t} \right\} \end{cases} \tag{2.39}$$

Based on equation 2.38 and 2.39, i convert $\widehat{P_{EV}^{t}}$ to the affine form $\widehat{P_{EV}^{t}}$ , as in equation 2.40, according to the conversion method that is detailed in [29]. If the power flow calculation is performed using equation 2.40, the output variable is as presented in equation 2.41, according to the affine arithmetic power flow method that is discussed in [31]. In [18], $\varepsilon_p$ is the polynomial of the k-th scenario $\varepsilon_{EV}$ with the detailed basis of such noise element calculations described further in [29].

$$\widehat{P_{EV}^{t}} = \frac{1}{2} \cdot (\overline{P_{EV}^{t}} + \underline{P_{EV}^{t}}) + \frac{1}{2} \cdot (\overline{P_{EV}^{t}} - \underline{P_{EV}^{t}}) \cdot \varepsilon_{EV} \tag{2.40}$$

$$\widehat{Vi,j,k^{t}} = \left(V_{i,j,k,R}^{t,0} + iV_{i,j,k,I}^{t,0}\right) + \sum_{p=1}^{P} \left(V_{i,j,k,R}^{t,p} + iV_{i,j,k,I}^{t,p}\right) \cdot \varepsilon_{p} \tag{2.41}$$

$$\varepsilon_{p} = F_{p}(\varepsilon_{EV}), \forall p = 1, 2, ..., P \tag{2.42}$$

Interval $\widehat{V_{i,j,k}^{t}}$ is acquired using equation 2.43-2.48, which are converted from affine form $\widehat{V_{i,j,k}^{t}}$ equation 2.41. Equation 2.49 is the minimum interval voltage for the k-th scenario, which can be obtained using equation 2.48.

$$\widehat{V_{i,j,k}^{t}} = \left[\underline{V_{i,j,k,R}^{t}}, \overline{V_{i,j,k,R}^{t}}\right] + i\left[\underline{V_{i,j,k,I}^{t}}, \overline{V_{i,j,k,I}^{t}}\right] \tag{2.43}$$

$$\underline{V_{i,j,k,R}^{t}} = V_{i,j,k,R}^{t,0} - \sum_{p=1}^{P} |V_{i,j,k,R}^{t,p}| \tag{2.44}$$

$$\overline{V_{i,j,k,R}^{t}} = V_{i,j,k,R}^{t,0} + \sum_{p=1}^{P} |V_{i,j,k,R}^{t,p}| \tag{2.45}$$

$$\underline{V_{i,j,k,I}^{t}} = V_{i,j,k,I}^{t,0} - \sum_{p=1}^{P} |V_{i,j,k,I}^{t,p}| \tag{2.46}$$

$$\overline{V_{i,j,k,I}^{t}} = V_{i,j,k,I}^{t,0} + \sum_{p=1}^{P} |V_{i,j,k,I}^{t,p}| \tag{2.47}$$

$$|\widehat{V_{i,j,k}^{t}}| = \sqrt{\left[\underline{V_{i,j,k,R}^{t}}, \overline{V_{i,j,k,R}^{t}}\right]^{2} + \left[\underline{V_{i,j,k,I}^{t}}, \overline{V_{i,j,k,I}^{t}}\right]^{2}} \tag{2.48}$$

$$\widehat{V_{min,k}} = \left[ \min_{\substack{1 \leq t \leq t_{max} \\ 1 \leq i \leq N_{bus} \\ 1 \leq j \leq N_{case}}} |\underline{V_{i,j,k}^{t}}|, \min_{\substack{1 \leq t \leq t_{max} \\ 1 \leq i \leq N_{bus} \\ 1 \leq j \leq N_{case}}} |\overline{V_{i,j,k}^{t}}| \right] \tag{2.49}$$

# Chapter 3

# Hosting Capacity Evaluation Considering Probability of Violating Constraints

## 3.1 The procedure for EV HC evaluation

The procedure for evaluating EV HC is described in general terms below and depicted in detail by the flowchart in Figure 3.1. First, based on existing vehicle access records, i find the number of EVs entering and exiting based on the time. A case number is generated using a normally distributed random number, according to the average of the existing vehicle access records. Second, i determine the SOC for each EV with a normally distributed random number between the minimum and maximum SOC. Third, i determine the charging stations where each EV will be deployed. For EVs, the charging connection time is determined according to the SOC; if the number of EVs at a charging station exceeds maximum capacity, further EVs cannot be connected. Then, i calculate the interval charging load for each EV deployed at each charging station, and convert the obtained interval charging load into affine form. Subsequently, after obtaining the voltage in the affine form by performing a power flow using the affine

form charge load, i convert the voltage to the interval form. Finally, i evaluate the HC of EVs using the IUP method. The method for IUP calculation is described in detail in Section 3.2.

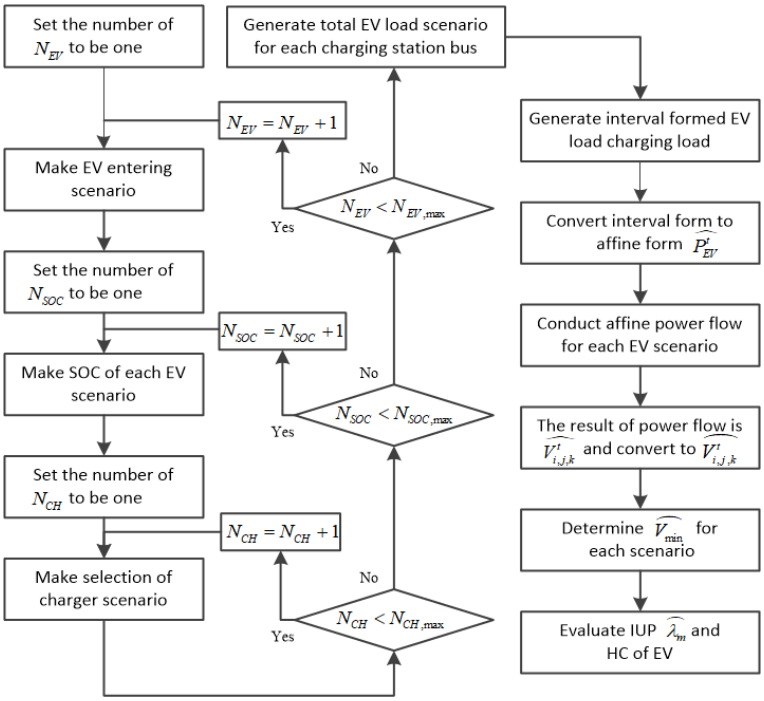


Figure 3.1: Example solution boundary for interval and affine multiplication

## 3.2 Definition and calculation method of IUP

On the foundation of the PV-based IOP that is described in [30]. i propose an IUP to evaluate EV HC. The proposed IUP is based on the probability of occurrence of undervoltage. For example, when 100 EVs enter the network at a specific time, IUP represents the probability of occurrence of low voltage among all cases created by the charger selected by the EV and the required charging times. In equation 3.2, $\beta_{m,j,k}$ is a case where the lower limit of the interval voltage among all buses is lower than $V^{min}$ in the EV charging situation in case j for the k-th scenario. In equation 3.1, $\alpha_{m,j,k}$ is the case where the number of buses whose lower bound voltage is less than $V^{min}$ is greater than the voltage violation index (VVI) that is denoted as $\delta$ , which is determined by the network operator depending on the situation.

$$\alpha_{m,j,k} = \begin{cases} 1, & \sum_{i=1}^{N_{bus}} \gamma_{m,i,j,k} \geq \delta \\ 0, & otherwise \end{cases} \tag{3.1}$$

$$\beta_{m,j,k} = \begin{cases} 1, & \underline{V_{m,j,k}^{min}} < V^{min} \\ 0, & otherwise \end{cases} \tag{3.2}$$

$$\gamma_{m,i,j,k} = \begin{cases} 1, & \underline{V_{m,i,j,k}} < V^{min} \\ 0, & otherwise \end{cases} \tag{3.3}$$

$$\begin{cases} N'_{m,j,over} & = \sum\limits_{k=1}^{N_{m,j,total}} \alpha_{m,j,k} \\ N''_{m,j,over} & = \sum\limits_{k=1}^{N_{m,j,total}} \beta_{m,j,k} \end{cases} \tag{3.4}$$

### 3.2.1 EV HC interval modeling

If the HC for EV is expressed in interval form based on IUP, HC can be evaluated using equation 3.5-3.8. The upper bound of the IUP $\overline{\lambda_m}$ is the probability that $N'_{m,j,over}$ which is 3.4 occurs for the entire scenario. The lower bound of IUP for the entire scenario, refers to the probability that occur $N''_{m,j,over}$ , which is the case where the smallest lower bound voltage on each bus violates the voltage constraint. The upper bound of HC equation 3.7 is value the value of the minimum number of EVs whose lower bound of IUP is greater than $\lambda_{max}$ which is determined by the network operator.

$$\begin{cases} \overline{\lambda_{m,j}} & = \frac{N'_{m,j,over}}{N_{m,j,over}} \\ \underline{\lambda_{m,j}} & = \frac{N''_{m,j,over}}{N_{m,j,over}} \end{cases} \tag{3.5}$$

$$\begin{cases} \overline{\lambda_m} & = \frac{1}{N_{case}} \sum_{j=1}^{N_{case}} \overline{\lambda_{m,j}} \\ \underline{\lambda_m} & = \frac{1}{N_{case}} \sum_{j=1}^{N_{case}} \underline{\lambda_{m,j}} \end{cases} \tag{3.6}$$

$$\overline{HC} = \min_{m \leq m \leq m_{max}} \left\{ \underline{EV} | \underline{\lambda_m} \geq \lambda_{max} \right\} \tag{3.7}$$

$$\underline{HC} = \min_{m \leq m \leq m_{max}} \left\{ \underline{EV} | \overline{\lambda_m} \geq \lambda_{max} \right\} \tag{3.8}$$

## 3.3 Evaluation of EV HC considering cable capacity constraints

Basically, the voltage constraint is considered in the evaluation of HC of the distribution network. However, when the size of the distribution network is small and the cable is short, the impedance of the cable becomes small, and a violation of the cable capacity that is lines congestion occurs before the voltage violation. In this case, the condition that is violated above all is considered first by considering both the voltage constraint and the cable capacity constraint.

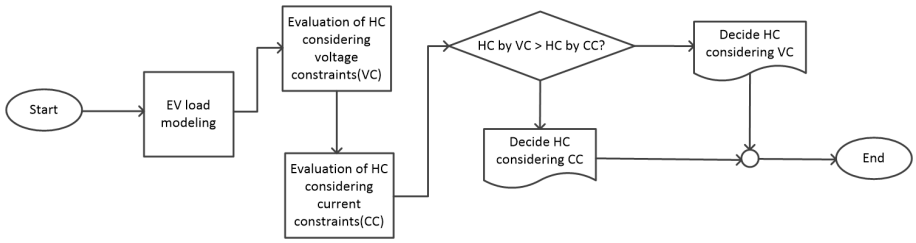


Figure 3.2: Determining HC criteria

# Chapter 4

# Case Study

## 4.1 Network modeling

The proposed method was applied to data from the campus microgrid network of Seoul National University in South Korea. Although Seoul National University comprises several networks, the College of Engineering, which is conducting a project related to EV chargers, was set as the test system. This system is a 22.9 kV feeder, as shown in Figure 4.1.

The majority of the system is composed of 6.6 kV terminals, although some terminals are at 220V. On each bus in Figure 4.1, the upper number is the building number and the lower number is the bus number. For the dataset obtained at 16:00 on June 24, 2018, the total load was 6301 kVA. To perform simulations using the proposed method, it was assumed that six charging stations were installed in 6.6 kV lines, where each station could accommodate up to 500 EVs.

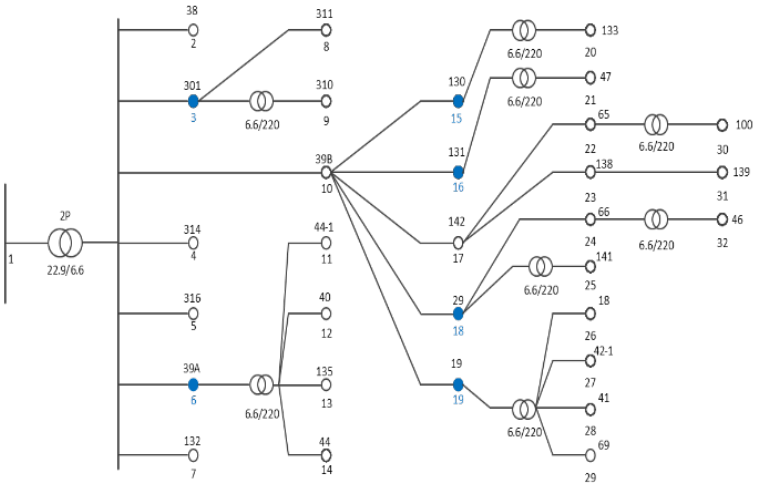


Figure 4.1: Seoul National University campus microgrid test system

## 4.2 EV scenario generation and interval formulation using vehicle access records

Thehe test system is a microgrid system, servicing a consistent number of members, i.e., the daily entry and exit records of the vehicles were similar. Therefore, the EV access scenario was assumed, based on the obtained vehicle access records. The average access value was determined using a proportional formula, are compared the number of assumed EVs to the actual number of vehicles entering and existing in, the network. The EV access scenario was then constructed using normally distributed random numbers around this average. To calculate the power flow to which affine arithmetic is applied, the net power injection equation 2.33 must be expressed in affine form. The uncertainties considered were those typical for EVs: arrival time, SOC, and charger station location. As vehicle access is regular owing to the characteristics of the test

system, normally distributed random numbers were used.

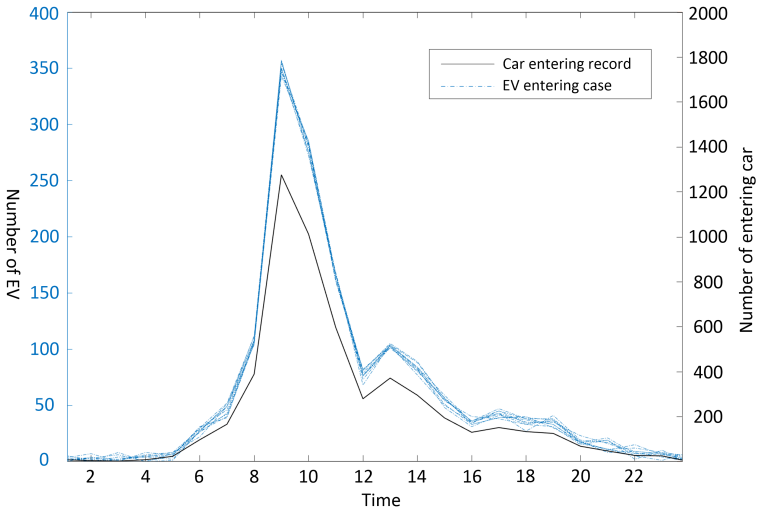


Figure 4.2: EV access scenarios created virtually with vehicle access records

### 4.2.1 Arrive time

Using the entry record of existing vehicles, the average value of EV entry and exit was calculated using a proportional formula according to the number of EVs. $N_{EV}$ cases were then generated using a normally distributed random number around the average value. In Figure 4.2, the black line is the actual number of vehicles entering the test network totaling 3800, and the blue lines are the $N_{EV}$ cases generated based on 1500 EVs

### 4.2.2 SOC

The SOC is directly related to the required charging time. Considering the battery capacity and charger output of the latest EVs, the required charging time was set between

1 and 4.

### 4.2.3 Location of charger station

It was assumed that the charging stations were located in six areas, where the main building of the test system was located, and that 500 EVs could be accommodated per charging station. By generating an EV scenario using interval formulation, data on the required amount of charge can be set, that is, the load for each time on the bus where the charger is installed. I obtain the interval form using equations 2.38 and 2.39 for the load data, and calculates the power flow that is introduced in Chapter III.

## 4.3 V0G IUP

### 4.3.1 V0G algorithm explanation

In V1G and V2G, charging and discharging must be determined according to the purpose, but V0G is simple as described earlier. When the time the EV arrives and the location of the charging station to the park is determined, it is connected to the charging station and starts charging. It aims to be fully charged from the moment it is connected, whereas sometimes the owner may disconnect it before being fully charged. Thus, the moment the EV is connected, it charges for the required time and acts as an electric load at the location of the connected charging station.

### 4.3.2 Conventional EV HC evaluation method

The conventional method to evaluate HC is to calculate and display voltages for all cases and analyze the violation of voltage accordingly. The EVs were increased from 500 to 1500 at intervals of 10 units, and 101 such cases were calculated. For each case unit, $N_{EV}$ is 10, $N_{SOC}$ is 10, and $N_{CH}$ is 50, forming 505,000 scenarios. In figure 4.3, I follow this approach and plot the minimum voltage according to the number of EVs. The minimum number of EVs that violate the voltage constraint 0.95 p.u. is represented by the red dotted line in figure 4.3, which equals 1120 according to the conventional HC evaluation method.

### 4.3.3 IUP-based EV HC evaluation method

The scenario for the IUP-based evaluation was identical to that of the conventional method. The IUP was calculated for each number of EVs, considering the undervoltage risk. Figure 4.4 shows the IUP after calculating the lower bound, for each case unit,

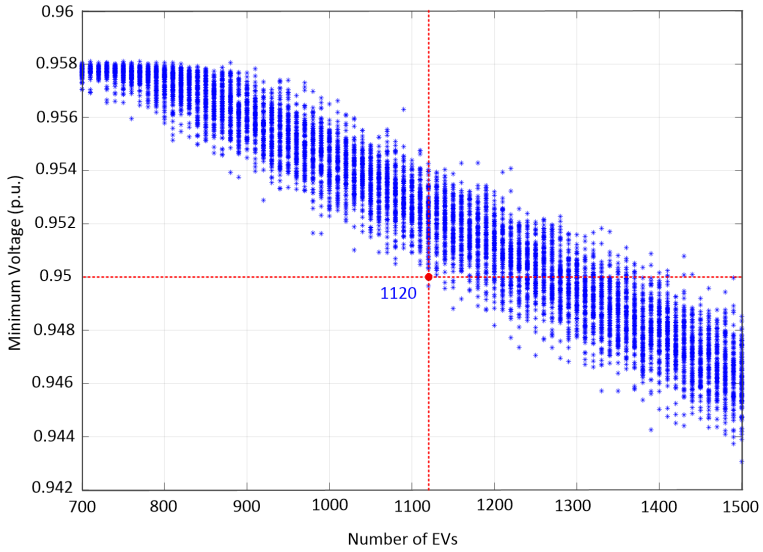


Figure 4.3: Chart of the number of EVs and minimum voltage distribution

which exceeds the voltage limit of the interval value of the bus for each scenario. If the maximum value of the IUP is set to 0.1, the HC is 1150 according to the IUP evaluation method. In a real-world scenario, the maximum IUP value is determined by the network operator.

### 4.3.4 EV HC evaluation based on interval and affine arithmetic

IUP modeling was used to evaluate the EV HC, according to the mathematical formulation provided in Section III. Considering the uncertainties specified for EV, the charging load is expressed in interval form as given by equations 2.39 and 2.40. The lower bound is the case where the lower bound of the interval voltage values of the bus is smaller than $V^{min}$, using equation 3.8, whereas the upper bound uses equation 3.7; $\delta$ is set to 3, which is the number of buses whose lower bound voltage is less than

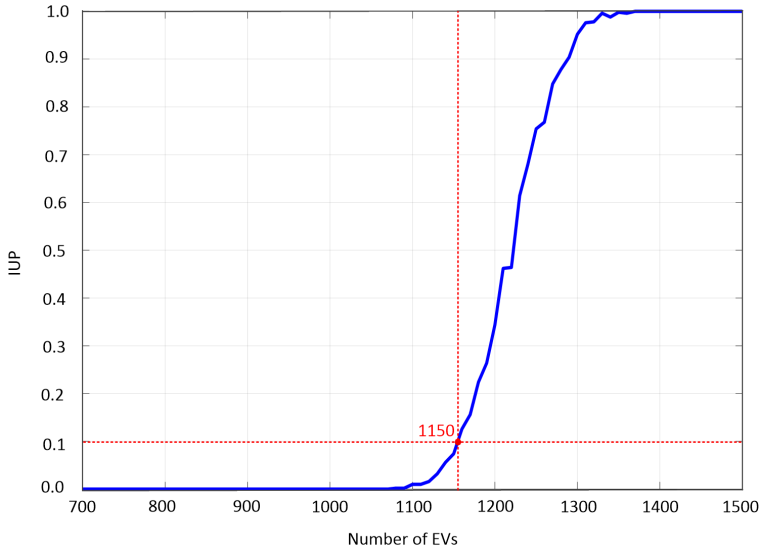


Figure 4.4: IUP chart according to the number of EVs

$V^{min}$ .

Figure 4.5, is a plot of EV HC evaluation for the upper and lower bounds using only interval and affine methods and without using the IUP evaluation method. Within these bounds, the minimum number of EVs that violated the same voltage constraint of 0.95 p.u., as set for figure 4.3, was between 1060 to 1080. The lower bound of 1060 is less than the lower bound of 1120 that is calculated conventional method, owing to the process of calculating the interval form of EV using equations 2.39 and 2.40.

Figure 4.6, shows the EV HC using the IUP evaluation method. The IUP, which represents the voltage violation probability, increased sharply beyond a certain number of EVs. As the maximum IUP is determined by the network operator, it seems correct to set it to approximately 0.1, as beyond this value it increases rapidly. With the IUP set to a maximum value of 0.1, the test network can be penetrated by EV's between

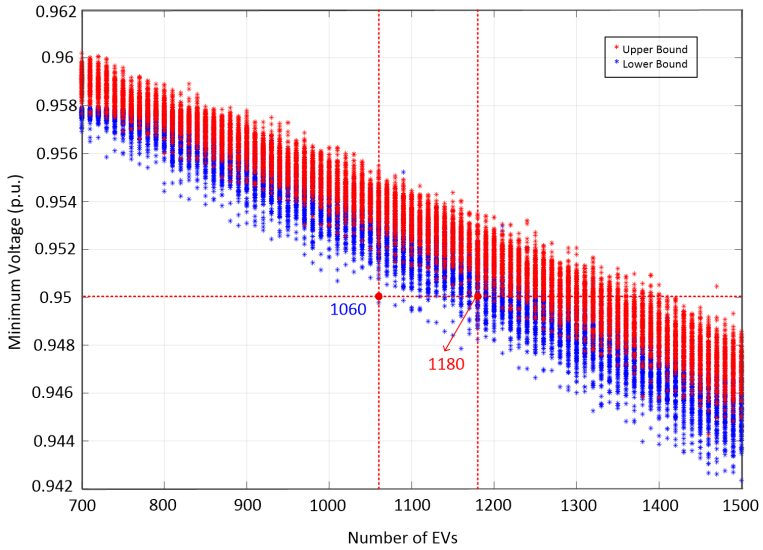


Figure 4.5: Chart of the number of EVs and minimum voltage based on interval uncertainty

1155 to 1269.

### 4.3.5 EV HC evaluation according to VVI change

The EV HC evaluation was performed according to the upper bound change by incrementally altering the VVI, as shown in figure 4.7. The VVI can be set by the network operator, the value is smaller, it is closer to the lower bound, and a narrower, achieving more conservative range for EV HC. For example, if $\delta$ is set to 2 instead of 3 in the above scenario, the EV HC falls in the range of 1155 to 1228, not 1155 to 1269. The IUP value is zero in the range of 1500 EV units from VVI above 5, which means that the 5-th bus in the test network needs more than 1500 EVs, for the voltage to violate the voltage constraint. That is, it is a good condition for the operator of the test network to

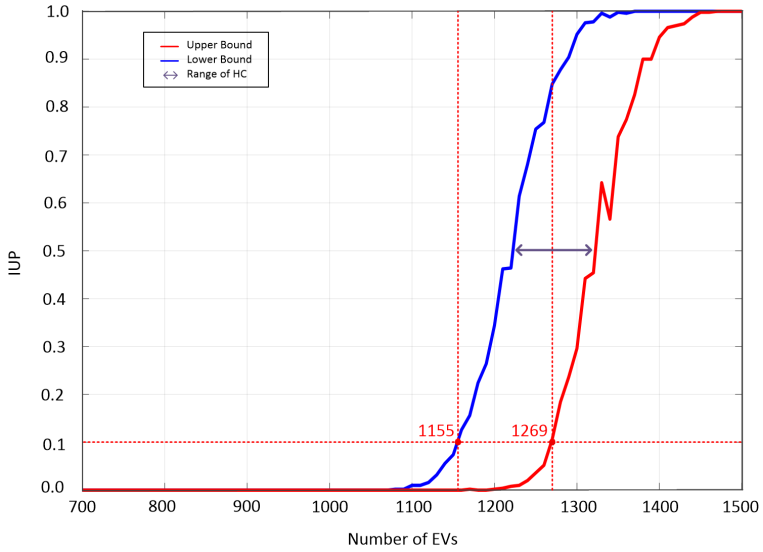


Figure 4.6: IUP chart according to the number of EVs based on interval uncertainty

set VVI between 1 and 4. Table 4.1 shows the EV HC values according to VVI change for the given IUP application. The HC evaluation method to which the IUP is applied indicates the acceptable number of EVs within a given range that the network operator can afford. Consequently, when the IUP according to the network simulation is set and applied to network planning, the degree of impact of EVs with large uncertainties on the network can be more sensitively evaluated.

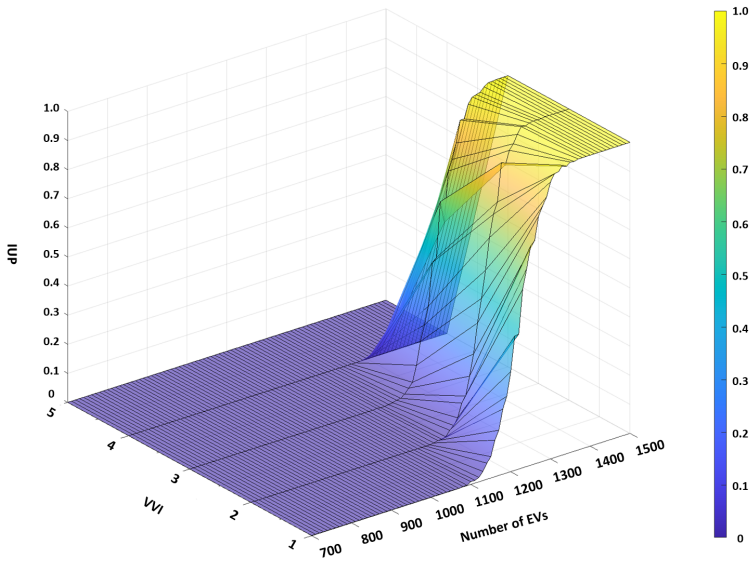


Figure 4.7: IUP chart according to the number of EVs and VVI

Table 4.1: HC according to each maximum IUP value

| $\lambda_{max}$ | IUP based HC | HC according to VVI change | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| 0.01 | 1100 | 1100 | [1100 1190] | [1100 1230] |
| 0.02 | 1122 | 1122 | [1122 1196] | [1122 1124] |
| 0.03 | 1128 | 1128 | [1128 1202] | [1128 1246] |
| 0.04 | 1133 | 1133 | [1133 1210] | [1133 1253] |
| 0.05 | 1137 | 1137 | [1137 1215] | [1137 1259] |
| 0.06 | 1142 | 1142 | [1142 1219] | [1142 1261] |
| 0.07 | 1147 | 1147 | [1147 1222] | [1147 1263] |
| 0.08 | 1151 | 1151 | [1151 1224] | [1151 1265] |
| 0.09 | 1153 | 1153 | [1153 1226] | [1153 1267] |
| 0.1 | 1155 | 1155 | [1155 1228] | [1155 1269] |

## 4.4 V1G IUP

Unlike the V0G method described above, the V1G and V2G methods require time to be determined, so an optimization or rule-based method must be used. If an optimization or rule-based method is used, the corresponding objective function is required. In this chapter, the EV HC of the target line was calculated using IUP using the V1G method.

### 4.4.1 Description of the first objective function algorithm

V1G, a charging control method, was simulated for two purposes. The first objective is to minimize the electricity bill of the test system. Seoul National University uses a variable rate system for each time period, and the EV is charged from the time when the electric rate is low within the time when it is disconnected from the time it is connected to the charging station. For example, suppose an EV that is in at 8 am leaves the car at 17:00, and the time required to charge is three hours. The following table lists the times when electric rates are cheaper within the time when EVs are parked.

Table 4.2: Example of EV charging time according to the first objective function

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Rate (won/kWh) | 40.3 | 85 | 85 | 150.9 | 150.9 | 150.9 | 150.9 | 150.9 | 150.9 |
| Time | 8 | 9 | 12 | 10 | 11 | 13 | 14 | 15 | 16 |

In other words, charging EV from 8:00 to 10:00 and from 12:00 to 13:00 is the lowest electric charge required for charging.

### 4.4.2 Description of the second objective function algorithm

In the current electric rate platform, the network operator is most beneficial when operating with a minimum electricity rate. However, considering the future network that will have a large penetration of distributed power, maximizing the penetration of EVs can maximize social welfare. If it is operated for the purpose of minimizing charging charges, it will affect the grid voltage more than V0G and will show less acceptability of EVs. In order to maximize the penetration of EVs in the network, EVs should be charged for the purpose of peak load reduction. The basic algorithm is the same as the charging electric rate minimization principle. Using the predicted load of the grid or using the before day load, the charging is determined from the time when the load is light between the time the EV is connected to and disconnected from the charger.

### 4.4.3 Conventional EV HC method

#### The first objective function

The basic principle is the same as the V0G conventional method of chapter 4.3.2. However, the system impact is analyzed by modeling the EV load using the charging control method.

Looking at the results of figure 4.8, when the V1G charging method is applied for the purpose of minimizing the electricity cost, the EV HC of the test network is 810. It can be seen that a much smaller number of HCs than about 1100 of the V0G conventional method is evaluated. This is because the EVs connected to the charger are not charged immediately, but are charged at a time when electricity rates are low, so charging time is concentrated. It can be seen that the effect as an electrical load on

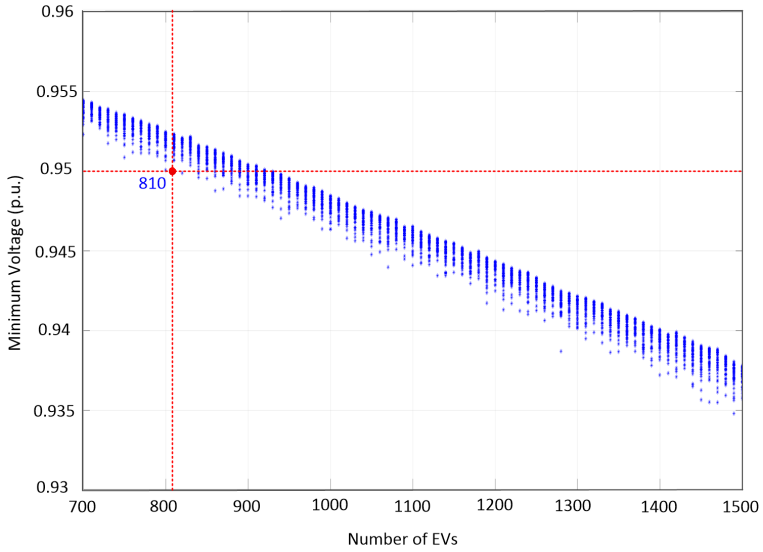


Figure 4.8: Chart of the number of EVs and minimum voltage distribution (V1G, Cost minimization)

the network is much greater, and thus EVs can be penetrated.

**The second objective function**

The basic principle is the same as the V1G conventional in chapter 4.4.3.1, but charging control is performed with the purpose of charging the EV as peak load reduction and the network impact is analyzed.

Looking at the results in figure 4.9, when the V1G charging method is applied for the purpose of peak load reduction, the EV HC of the test network is 2,260. It can be seen that about 1100 units of the V0G conventional method or a much larger number of HCs than the cost minimization of V1G are evaluated. This is because the voltage constraint, which is the evaluation of EV HC, is directly affected by the load. In other

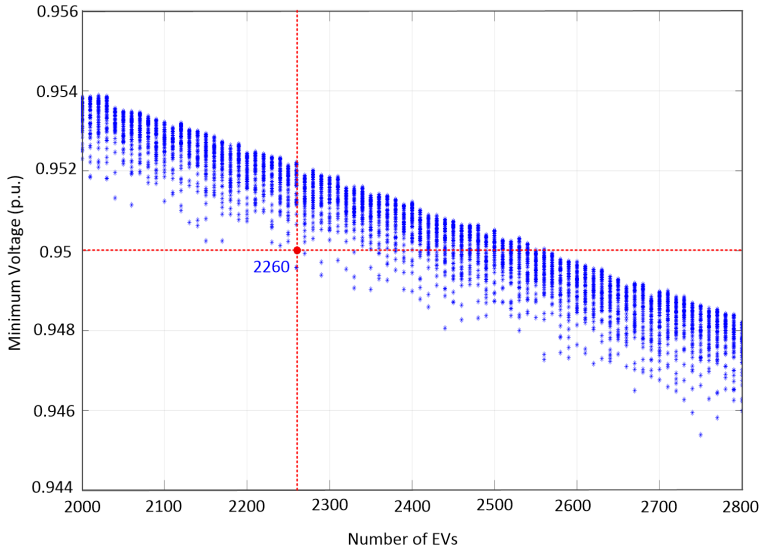


Figure 4.9: Chart of the number of EVs and minimum voltage distribution (V1G, Peak load reduction)

words, it can be seen that if the charging of EVs is concentrated during a time when the load is low, much more EVs can be penetrated in the same network.

### 4.4.4 IUP-based EV HC evaluation

The basic principle is the same as the V0G IUP-based EV HC evaluation method of chapter 4.3.3. However, the network impact is analyzed by modeling the EV load using the charging control method.

#### The first objective function

When EV HC is evaluated by IUP method, if charging is controlled for the purpose of cost minimization of V1G, the result shown in figure 4.10 can be obtained. When

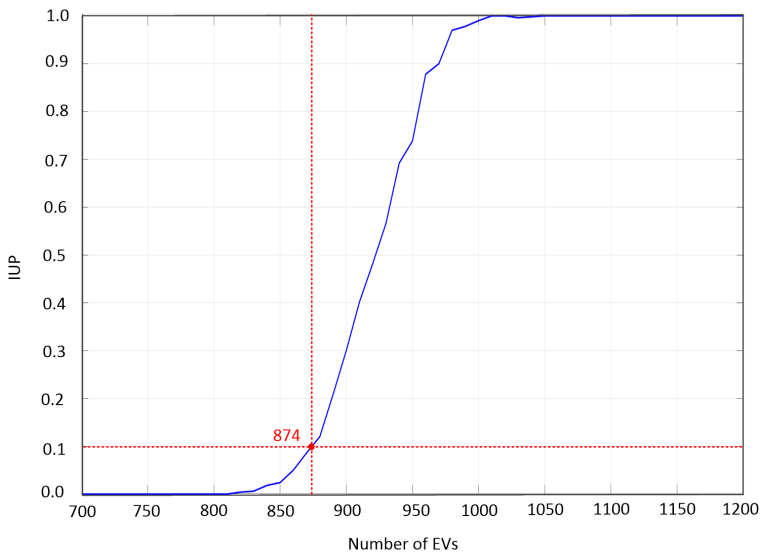


Figure 4.10: IUP chart according to the number of EVs (V1G, Cost minimization)

the IUP becomes 0.1, the EV HC is 874 units, which is also much smaller than the 1150 units evaluated during the V0G IUP analysis. As in the conventional evaluation method, it showed much less penetration because the EVs which is connected to the charger charged at a time when the electricity rate is low.

**The second objective function**

When EV HC is evaluated by the IUP method, if charging is controlled for the purpose of V1G peak reduction, the result shown in figure 4.11 can be obtained. When the IUP becomes 0.1, the EV HC is 2,413 units, which is much more than the 1150 units evaluated during the V0G IUP analysis or 874 units evaluated for the purpose of minimizing the electricity cost. Since the EV is charged intensively during a time when the load is low, the voltage effect on the network is much less, and as a result,

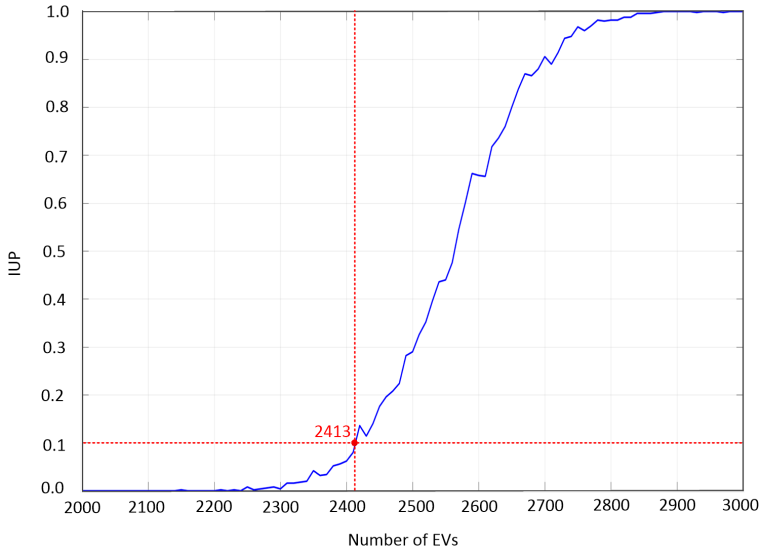


Figure 4.11: IUP chart according to the number of EVs (V1G, Peak reduction)

the EV HC is dramatically improved.

### 4.4.5 EV HC evaluation based on interval and affine arithmetic

#### The first objective function

Figure 4.12 shows the result of evaluating EV HC for cost minimization using the IUP method considering the interval uncertainty. The method was evaluated in the same way as the IUP method considering the interval uncertainty of V0G. The lower boundary represents the number of voltage violations due to the penetration of EVs among all buses in the test network, and the upper boundary indicates the voltage violations of the test network due to the penetration of EVs. It represents the number of EVs appearing on these three or more buses.

Figure 4.13 shows that the EV HC is from 810 to 930. In the previous chapter,

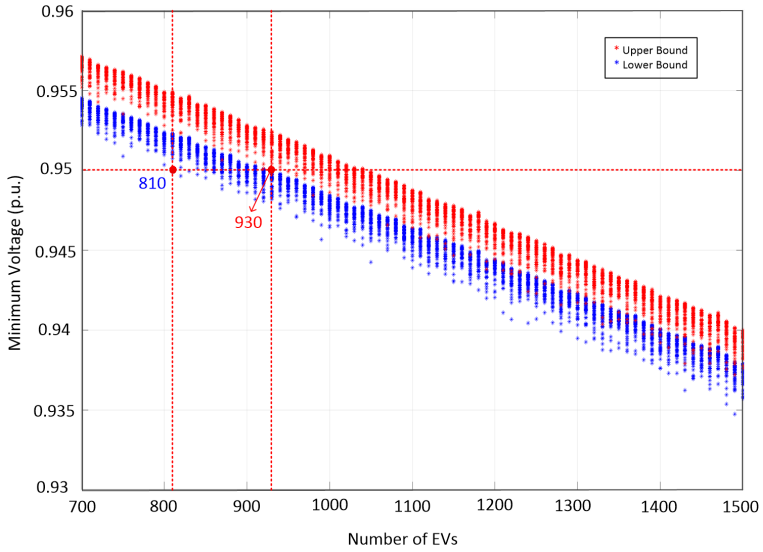


Figure 4.12: Chart of the number of EVs and minimum voltage based on interval uncertainty (V1G, Cost minimization)

in the case of V0G, the results were much smaller than those shown in the 1,060s to 1,180s. Again, for the same reason, the charging time of EVs connected to the charger is controlled, but since all EVs are charged at a time when electricity rates are low, the time period is concentrated and has a greater effect on the network, which significantly reduces the EV HC.

**The second objective function**

Figure 4.14 shows the result of evaluating EV HC for peak reduction using the IUP method considering the interval uncertainty. The method was also evaluated in the same way as the IUP method considering the interval uncertainty of V0G. The lower boundary represents the number of voltage violations due to the penetration of EVs

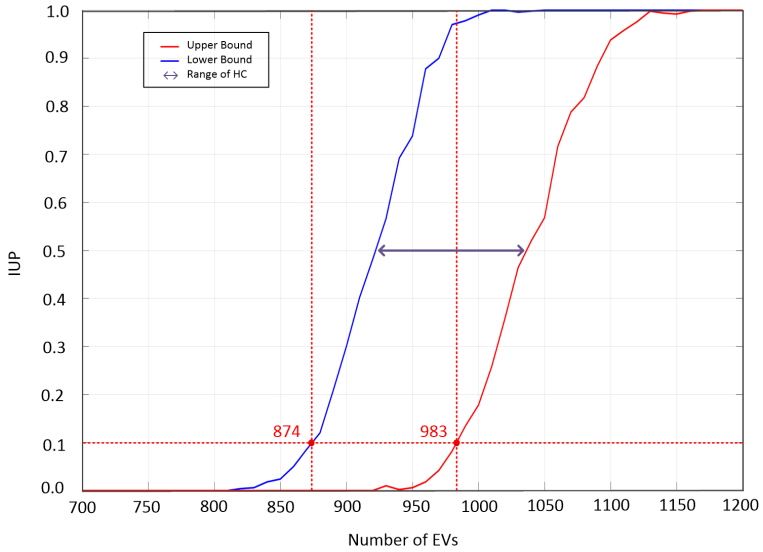


Figure 4.13: IUP chart according to the number of EVs based on interval uncertainty (V1G, Cost minimization)

among all buses in the test network, and the upper boundary indicates the voltage violations of the test network due to the penetration of EVs. It represents the number of EVs appearing on these three or more buses.

Figure 4.15 shows that the EV HC is from 2,413 to 2,857. In the previous chapter, in the case of V0G, there were far more results from 1,060 to 1,180 and from 874 to 983 for the purpose of minimizing V1G rates. Again, for the same reason, while controlling the charging time of the EV connected to the charger, the EV was charged at a time when the load was low, so the effect on the network was much less, and the penetration of the EV was greatly evaluated.

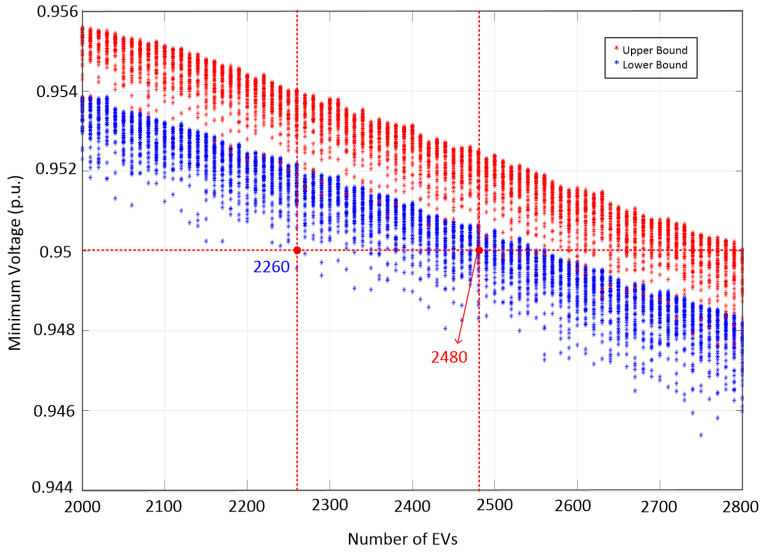


Figure 4.14: Chart of the number of EVs and minimum voltage based on interval uncertainty (V1G, Peak reduction)

### 4.4.6 EV HC evaluation according to VVI change

The basic principle is the same as the EV HC according to VVI change method in V0G of chapter 4.3.5. However, the network impact is analyzed by modeling the EV load using the charging control method. VVI is the total number of buses that have voltage violations in the network.

#### The first objective function

Figure 4.16 is a graph showing the result of changing the upper bound through VVI change while performing EV HC for the purpose of minimizing the electric cost. It was evaluated that the larger the VVI, the more EVs could be penetrated. However, the result is not visible from VVI of 5, that is, it can be seen that much more EVs

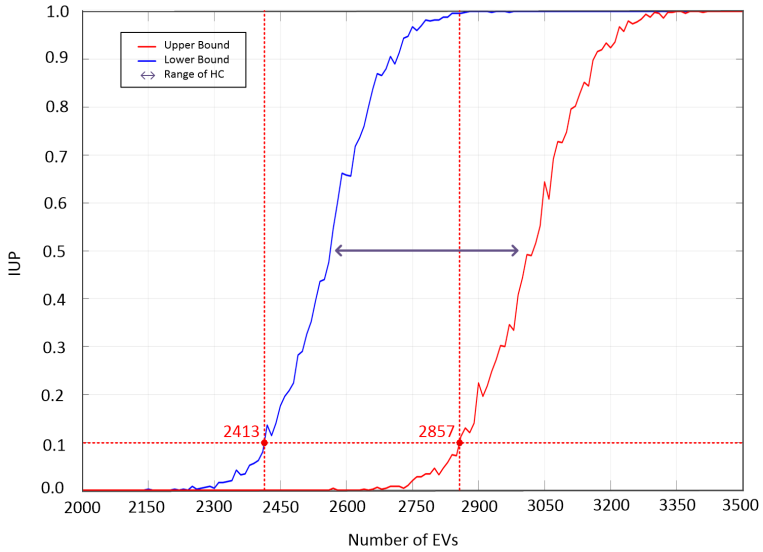


Figure 4.15: IUP chart according to the number of EVs based on interval uncertainty (V1G, Peak reduction)

must be penetrated in for the voltage violation of the 5th bus to appear. In other words, voltage violation appears well up to the 4th bus, but the 5th bus is more robust.

**The second objective function**

Figure 4.17 shows the IUP change according to the VVI change for the purpose of peak load reduction. Again, similar results were obtained, but the EV HC was highly evaluated due to the characteristics of charging intensively at a time when the load was low.

### 4.4.7 Result table of V1G EV HC evaluation

Summarizing the information obtained above in a table, it is as follows.

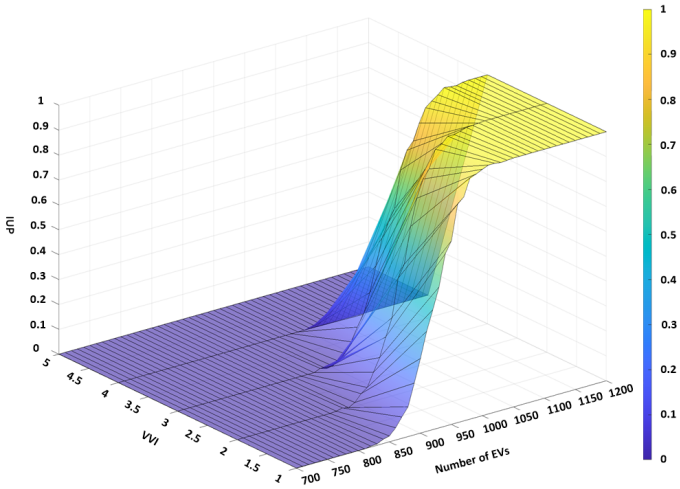


Figure 4.16: IUP chart according to the number of EVs and VVI (V1G, Cost minimization)

**The first objective function**

Table 4.3 shows the HC of EVs according to changes in VVI when the acceptability of EVs is evaluated for cost minimization using the V1G method. The previous chapter showed the EV HC from 874 to 983 by fixing IUP max to 0.1 and VVI to 3, but the flexibility of EV acceptability can be determined by considering the network according to the judgment of the network operator. For example, if you decide to operate the network by setting VVI to 2 and IUP max to 0.05, the number of EVs in the test network that can accommodate EVs is 860 to 903.

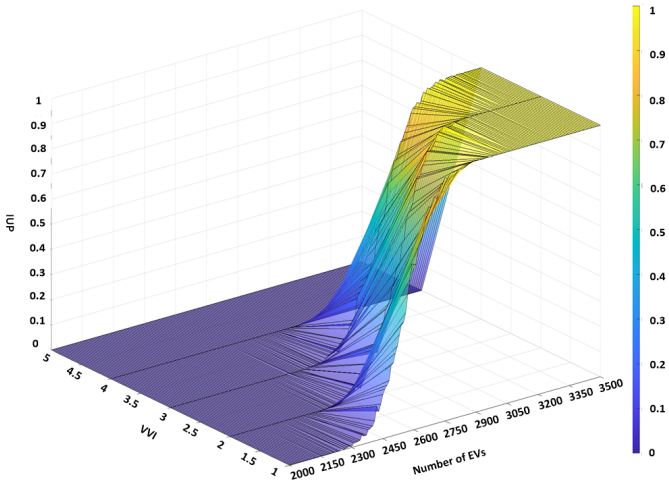


Figure 4.17: IUP chart according to the number of EVs and VVI (V1G, Peak reduction)

**The second objective function**

Table 4.4 shows the HC of EVs according to the VVI change when the acceptability of EVs was evaluated for the purpose of peak load reduction using the V1G method. As in chapter 4.4.7.1, the flexibility of acceptability of EVs can be determined by considering the network according to the judgment of the network operator. For example, if you decide to operate the network by setting VVI to 2 and IUP max to 0.07, the number of EVs that can be accommodated in the test network is 2,404 to 2,635.

Table 4.3: HC according to each maximum IUP value (V1G Cost minimization)

| $\lambda_{max}$ | IUP based HC | HC according to VVI change | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| 0.01 | 833 | 833 | [833 886] | [833 930] | [833 1750] | [833 1997] |
| 0.02 | 843 | 843 | [843 891] | [843 960] | [843 1785] | [843 -] |
| 0.03 | 852 | 852 | [852 895] | [852 965] | [852 1771] | [852 -] |
| 0.04 | 856 | 856 | [856 899] | [856 969] | [856 1773] | [856 -] |
| 0.05 | 860 | 860 | [860 903] | [860 972] | [860 1775] | [860 -] |
| 0.06 | 863 | 863 | [863 909] | [863 975] | [863 1778] | [863 -] |
| 0.07 | 866 | 866 | [866 911] | [866 977] | [866 1780] | [866 -] |
| 0.08 | 868 | 868 | [868 913] | [868 980] | [868 1791] | [868 -] |
| 0.09 | 871 | 871 | [871 915] | [871 982] | [871 1793] | [871 -] |
| 0.1 | 874 | 874 | [874 917] | [874 983] | [874 1795] | [874 -] |
| 0.2 | 889 | 889 | [889 934] | [889 1003] | [889 1821] | [889 -] |
| 0.3 | 900 | 900 | [900 948] | [900 1014] | [900 1829] | [900 -] |
| 0.4 | 910 | 910 | [910 956] | [910 1024] | [910 1843] | [910 -] |
| 0.5 | 922 | 922 | [922 967] | [922 1036] | [922 1855] | [922 -] |
| 0.6 | 933 | 933 | [933 976] | [933 1052] | [933 1874] | [933 -] |
| 0.7 | 942 | 942 | [942 984] | [942 1059] | [942 1891] | [942 -] |
| 0.8 | 954 | 954 | [954 995] | [954 1074] | [954 1903] | [954 -] |
| 0.9 | 970 | 970 | [970 1014] | [970 1093] | [970 1919] | [970 -] |
| 1 | 1010 | 1010 | [1010 1100] | [1010 1170] | [1010 1990] | [1010 -] |

Table 4.4: HC according to each maximum IUP value (V1G Peak load reduction )

| $\lambda_{max}$ | IUP based HC | HC according to VVI change | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| 0.01 | 2305 | 2305 | [2305 2536] | [2305 2740] | [2305 -] | [2305 -] |
| 0.02 | 2340 | 2340 | [2340 2553] | [2340 2750] | [2340 -] | [2340 -] |
| 0.03 | 2345 | 2345 | [2345 2574] | [2345 2773] | [2345 -] | [2345 -] |
| 0.04 | 2349 | 2349 | [2349 2595] | [2349 2795] | [2349 -] | [2349 -] |
| 0.05 | 2379 | 2379 | [2379 2604] | [2379 2823] | [2379 -] | [2379 -] |
| 0.06 | 2397 | 2397 | [2397 2633] | [2397 2831] | [2397 -] | [2397 -] |
| 0.07 | 2404 | 2404 | [2404 2635] | [2404 2838] | [2404 -] | [2404 -] |
| 0.08 | 2410 | 2410 | [2410 2637] | [2410 2852] | [2410 -] | [2410 -] |
| 0.09 | 2412 | 2412 | [2412 2639] | [2412 2855] | [2412 -] | [2412 -] |
| 0.1 | 2414 | 2414 | [2414 2651] | [2414 2857] | [2414 -] | [2414 -] |
| 0.2 | 2463 | 2463 | [2463 2695] | [2463 2897] | [2463 -] | [2463 -] |
| 0.3 | 2503 | 2503 | [2503 2744] | [2503 2949] | [2503 -] | [2503 -] |
| 0.4 | 2531 | 2531 | [2531 2779] | [2531 2989] | [2531 -] | [2531 -] |
| 0.5 | 2563 | 2563 | [2563 2821] | [2563 3024] | [2563 -] | [2563 -] |
| 0.6 | 2580 | 2580 | [2580 2842] | [2580 3045] | [2580 -] | [2580 -] |
| 0.7 | 2617 | 2617 | [2617 2874] | [2617 3072] | [2617 -] | [2617 -] |
| 0.8 | 2650 | 2650 | [2650 2898] | [2650 3117] | [2650 -] | [2650 -] |
| 0.9 | 2698 | 2698 | [2698 2947] | [2698 3161] | [2698 -] | [2698 -] |
| 1 | 2880 | 2880 | [2880 3140] | [2880 3350] | [2880 -] | [2880 -] |

## 4.5 V2G IUP

What is different from V1G in Chapter 4.4 is that V2G can discharge. It is based on the method described in Chapter 2.1.

### 4.5.1 Description of the first objective function algorithm

The purpose is important when determining the charging and discharging of an EV connected to a charger. The first objective function in this chapter is cost minimization, which is the same as the first objective function of V1G. Since the basic principle of V2G has been explained previously, I will give an example of the algorithm applied.

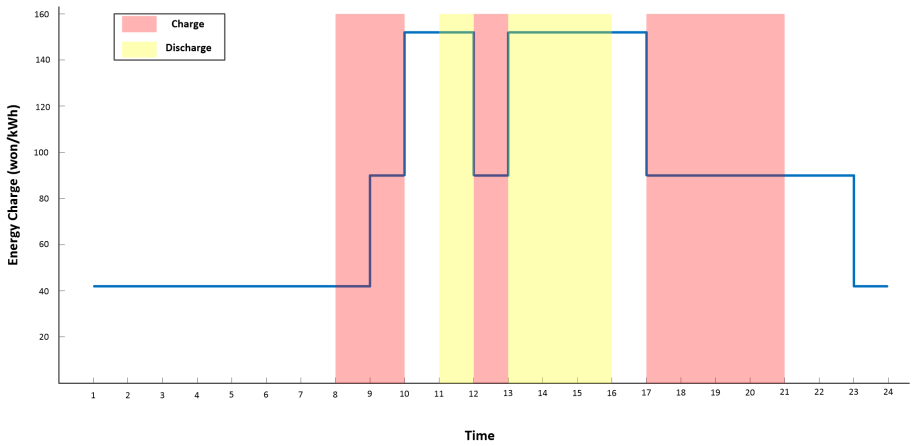


Figure 4.18: Example of V2G algorithm(V2G, Cost minimization)

The electric rate of the test network is shown in figure 4.18. Let's take an EVs as an example here. The EV entered the network at 8 o'clock and connected to the charger,

Table 4.5: Example of EV charging time according to the first objective function

| Charge order | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| rate | 40.3 | 85 | 85 | 85 | 85 | 85 | 85 | 150.9 | 150.9 |
| time | 8 | 9 | 12 | 17 | 18 | 19 | 20 | 10 | 11 |
| Discharge order | | | | | | | | | |
| rate | 150.9 | 150.9 | 150.9 | 150.9 | 150.9 | 150.9 | 85 | 85 | 85 |
| time | 16 | 15 | 14 | 13 | 11 | 10 | 20 | 19 | 18 |

and the departure time set by the driver is 21:00. And according to the SOC, the time required for charging is 3 hours. If I calculate the charging time and discharging time according to equation 2.1, the charging time is 8 hours and the discharge time is 5 hours. Now, let's decide the charging time and discharging time according to the purpose of minimizing the cost. Once the EV is connected to the charger in the order of the lowest price, it is the same as the charge order in table 4.5. Also, if the charges are listed in the order of the most expensive, it is the same as the discharge order. Here, you need to charge for 8 hours, so choose 8 in the order of charging. Also, select 5 time zones in the order of discharge. If you choose that way, 150.9 won/kWh determined for the charging time zone overlaps with 150.9 won/kWh determined for the discharge time zone. That is, charging is performed at 8, 9, 12, 17, 18, 19, and 20 o'clock and discharging is performed at 15, 14, 13 and 11 o'clock. If the algorithm is applied in this way, there is a case where the discharge occurs first. If the battery of the EV is sufficient, it can discharge first, but there are cases when it is not enough. In this case, if the battery discharge time is shorter, the discharge order is deleted from the beginning and the charger order is deleted from the end.

### 4.5.2 Description of the second objective function algorithm

The second objective function is peak load reduction as in the V1G method, and since it is the same as the algorithm described above, an example will be explained immediately.

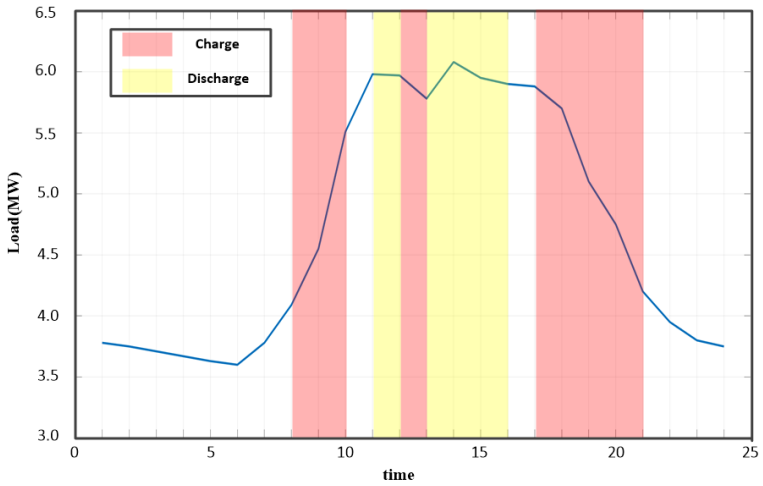


Figure 4.19: Example of V2G algorithm(V2G, Peak load reduction)

An arbitrary daily total load of the test network is shown in figure 4.19. The basic principle is the same as for cost minimization. First, the required charging time, discharging time, and total parking time are calculated by referring to equation 2.1 through the time connected to the EV's charger, the time to get out of the vehicle determined by the owner, and the state of charge of the EV's battery. The charge order in table 4.5 is the order of the large load between the time when the EV is connected and the time when the EV is disconnected from the predicted or previous day's load

Table 4.6: Example of EV charging time according to the second objective function

| Charge order | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| load(MW) | 4.09 | 4.55 | 4.75 | 5.1 | 5.51 | 5.7 | 5.78 | 5.9 | 5.95 |
| time | 8 | 9 | 20 | 19 | 10 | 18 | 13 | 16 | 15 |
| Discharge order | | | | | | | | | |
| load(MW) | 6.08 | 5.98 | 5.97 | 5.95 | 5.90 | 5.88 | 5.78 | 5.70 | 5.51 |
| time | 14 | 11 | 12 | 15 | 16 | 17 | 13 | 18 | 10 |

profile, and the discharge order is the order of the light load. In the charge order, the EV is charged for the required charging time, and in the discharge order, the EV is discharged for as long as it can be discharged. For example, if an EV connected to a charging station leaves the car at 8 o'clock and the charging time is 3 hours, the parking time is 13 hours, the charging time is 8 hours, and the available discharge time is 5 hours. Referring to table 4.5, it can be seen that EVs charge at 8, 9, 20, 19, 10, 18, 13 and 16 o'clock and discharge at 14, 11, 12, 15 and 16 o'clock.

### 4.5.3 Conventional EV HC method

**The first objective function**

The first objective function of the V2G method is also cost minimization, like the first objective function of V1G. In the cost minimization method applying V2G, the distribution network voltage constraint 0.95 p.u. As a result of introducing EVs to the limit, 640 results were obtained as shown in figure 4.20. When V0G was applied, about 1,110 units were accepted, compared to 810 units when V1G technology was applied. Because EVs with V2G technology can discharge, they discharge when electricity

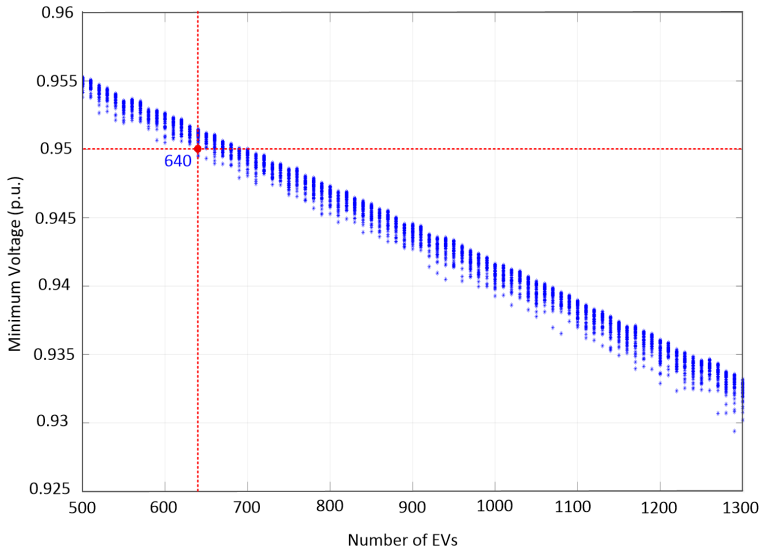


Figure 4.20: Chart of the number of EVs and minimum voltage distribution (V2G, Cost minimation)

rates are high and charge when electricity rates are low. Even if several EVs enter the grid at different times and are connected to the charger, using V2G technology has a big impact on the grid voltage because electricity charges are concentrated at a time when cost is low. Therefore, if V2G is used for the purpose of minimizing electricity rates, it will be beneficial in terms of minimizing the charges, but it will be a burden to the system.

**The second objective function**

The second objective function of the charging method to which V2G technology is applied is peak load reduction, similar to the second objective function of V1G. Figure 4.21 shows that, while charging and discharging for the purpose of peak load reduction,

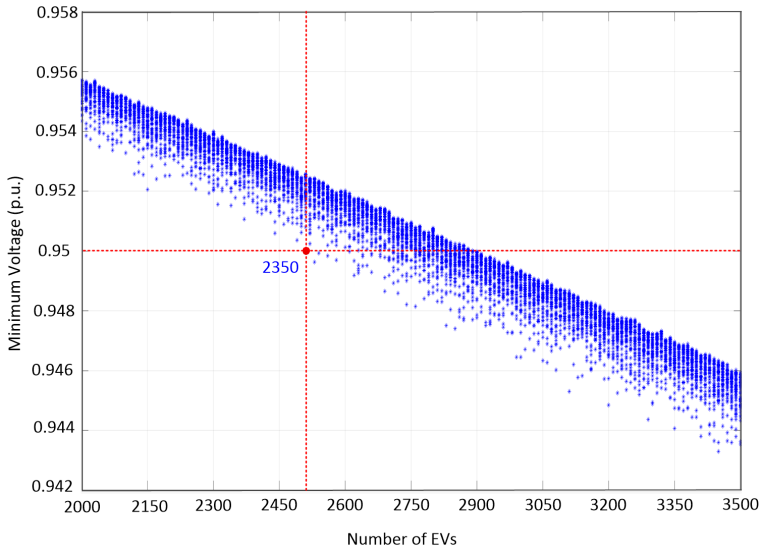


Figure 4.21: Chart of the number of EVs and minimum voltage distribution (V2G, Peak load reduction)

it can accommodate up to 2,350 EVs, which can accommodate up to 640 electric vehicles when cost minimization is applied to V2G. As the peak load reduction applied with V1G can accommodate 2,260 EVs, the load has a direct effect on the voltage, so it was confirmed that the V2G peak reduction can accommodate a very large number of EVs, 2,350. It can be seen that it can accommodate a little more EVs than the V1G because it not only charges during the light load time, but also reduces the load by discharging it during the heavy load time.

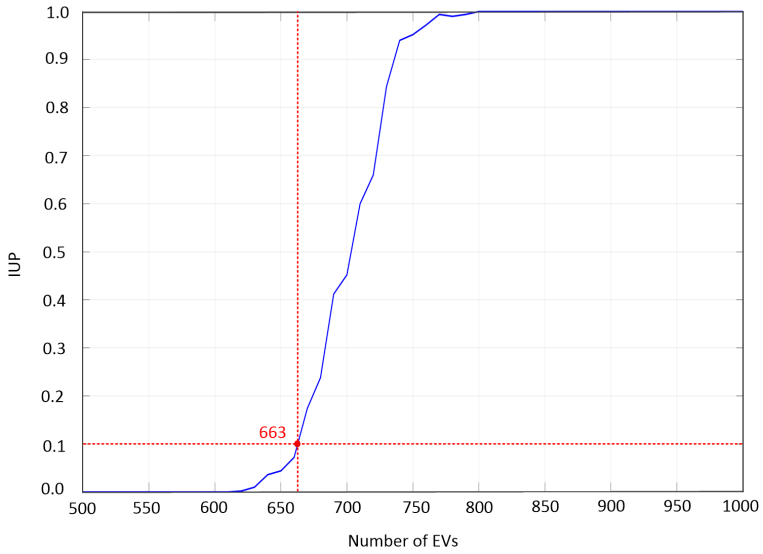


Figure 4.22: IUP chart according to the number of EVs (V2G, Cost minimization)

### 4.5.4 IUP-based EV HC evaluation

**The first objective function**

As in the calculation of the V1G fee minimization IUP, the IUP for the cost minimization purpose using V2G was calculated. When the IUP reached 0.1, that is, the number of cases in which the voltage constraint was exceeded by 10% or more among the total number of cases was evaluated as 663 EVs. In the IUP evaluation of the first objective function of V1G, when it was 0.1, it was 810 units, and when it was 0.1 in the IUP evaluation of V0G, it was evaluated as a much smaller number than 1,150 units. Again, this is because it was applied for the purpose of minimizing charges using V2G. The IUP can be determined by the network operator considering the situation. Considering the IUP chart of figure 4.22, it seems appropriate that the voltage violation probability

rapidly increases around 0.1.

### The second objective function

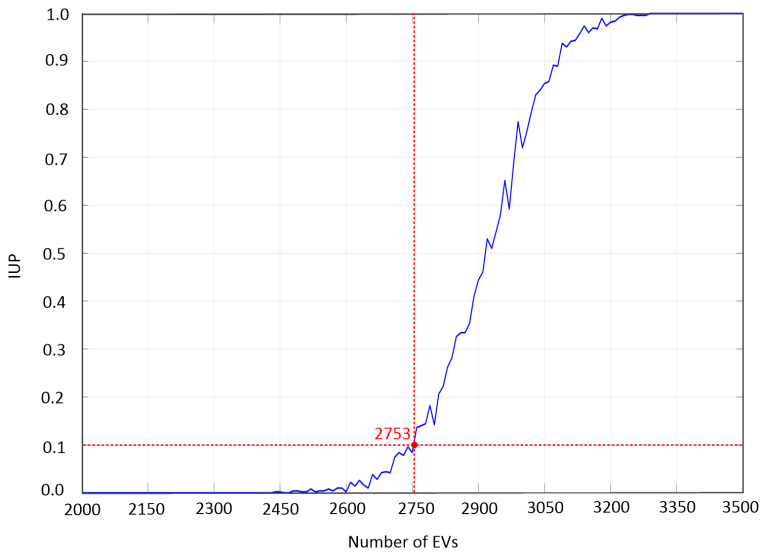


Figure 4.23: IUP chart according to the number of EVs (V2G, Peak load reduction)

In this chapter, IUP was obtained by applying V2G as the objective function of peak load reduction, and the result is figure 4.23. V2G IUP to which peak load reduction is applied has a result of accommodating 2,753 units when it is 0.1, and the previously obtained HC of 0.1 IUP is the largest compared to 1,150 units in V0G and 2,413 units in V1G. Contrary to general expectations, when V1G and V2G are applied as peak load reduction, there is no significant difference in EV HC. The biggest factor in this is that the Seoul National University power network currently selected as the test network has sufficient capacity to accommodate EVs. In this case, in terms of HC, V2G does not seem to have an advantage compared to V1G, but an EV with

V2G technology has the advantage of supplying power to the network in an emergency situation.

### 4.5.5 EV HC evaluation based on interval and affine arithmetic

**The first objective function**

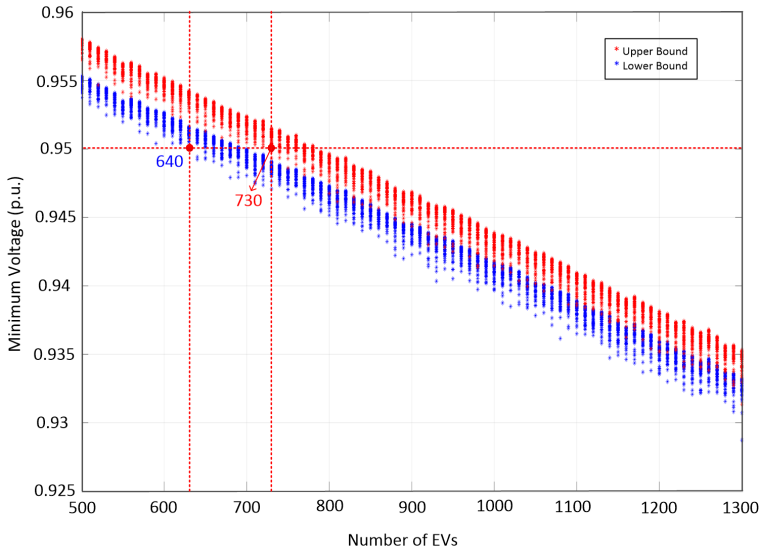


Figure 4.24: Chart of the number of EVs and minimum voltage based on interval uncertainty (V2G, Cost minimization)

Figure 4.24 shows the results of considering EV HC by applying V2G for the purpose of cost minimization and applying uncertainty as an interval method. For the interval method to consider uncertainty, refer to equations 2.38 and 2.39. As with the interval and affine arithmetic EV HC of V1G, it can be seen that the voltage decreases linearly as the number of EVs increases. When the voltage decreases and reaches the constraint of 0.95 p.u., the number of EVs is 640 to 730. The blue dot, the lower

boundary, represents the minimum voltage among all buses in the total number of cases. The red dot, upper boundary, represents the third lowest voltage among all buses in all cases. Unlike V0G, which was able to accommodate about 1,000 units, and V1G, which showed capacity for about 800 units, V2G showed capacity of about 600 units.

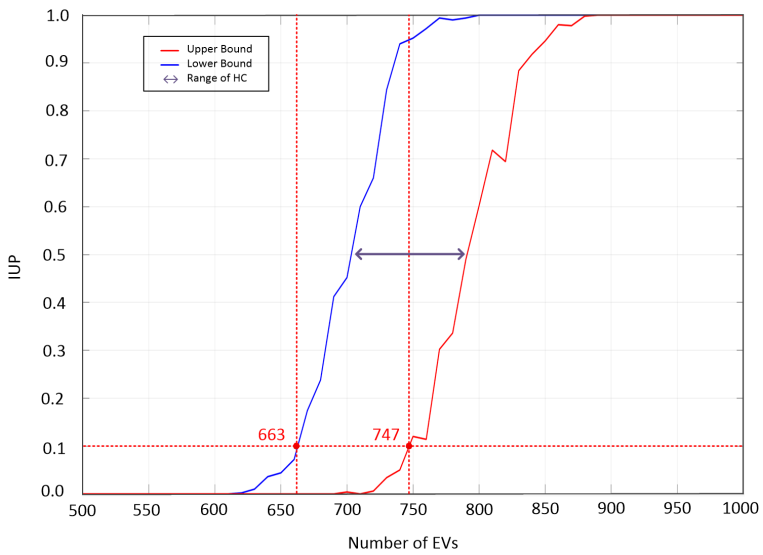


Figure 4.25: IUP chart according to the number of EVs based on interval uncertainty (V2G, Cost minimization)

Figure 4.25 shows the results of interval IUP for the purpose of minimizing the cost of V2G. According to the definition of IUP, when the ratio of voltage violation occurs among the total number of cases, when the IUP is 0.1 and the probability of violation is 10%, the EV HC was between 663 and 747 units. IUP showed a sharp increase with the increase of EVs from 0.1, and it was shown that voltage violation occurred in all cases with V2G for the purpose of cost minimization from the moment it exceeded about 800.

**The second objective function**

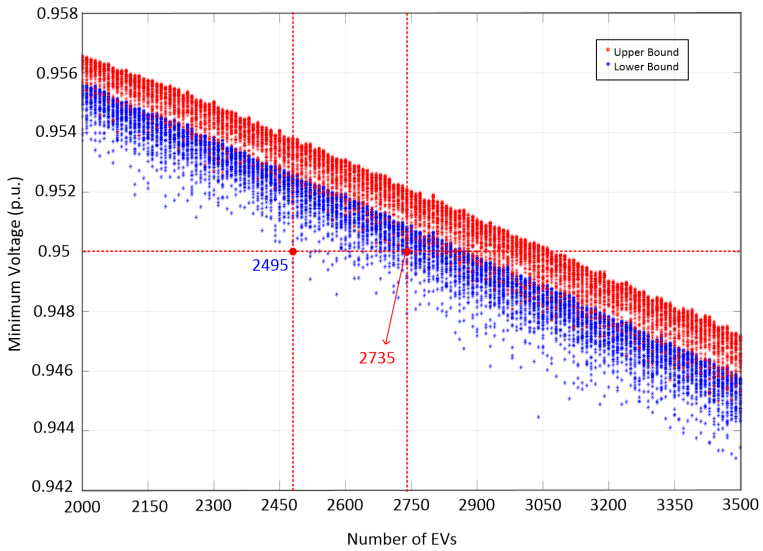


Figure 4.26: Chart of the number of EVs and minimum voltage based on interval uncertainty (V2G, Peak load reduction)

As with cost minimization, it was applied in the same way for the purpose of peak load reduction. As the voltage dropped to 0.95 p.u., the acceptability of EVs between 2,495 and 2,735 from VVI 1 to 3, that is, from the lower boundary to the upper boundary, was evaluated. Considering that the EV market is growing, V2G must be introduced to accommodate the maximum number of EVs without network reinforcement. It can be inferred by comparing the results of V1G and V2G do not look much different, but in situations in which power is urgently needed in the network, V2G can be used as a resource because it can draw power instantaneously. However, in the current market, V2G technology is not commercialized and cannot be utilized because there is no market for V2G.

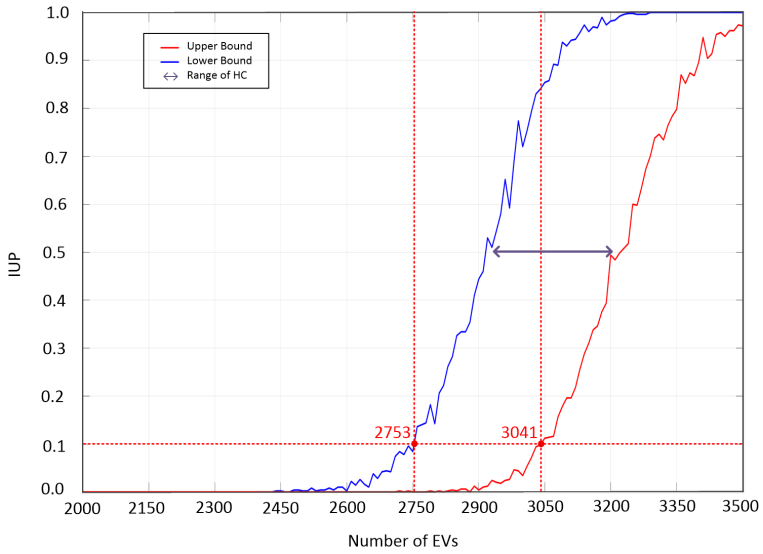


Figure 4.27: IUP chart according to the number of EVs based on interval uncertainty (V2G, Peak load reduction)

Figure 4.27 shows the results of calculating the interval IUP with peak load reduction of V2G. Again, like the V1G, it came out that much more EVs could be accommodated. For the total number of cases, the number of EVs with an IUP of 0.1 was 2,753 units. Also, when VVI is 3, the number of EVs with IUP of 0.1 was 3,041 units. When the number of EVs with an IUP of 0.1 or more was accommodated, the IUP increased rapidly, and when about 2,900 EVs were accommodated, the IUP of the lower boundary reached 0.5, and when about 3,200 EVs were accommodated, the IUP of the upper boundary reached 0.5. In addition, when more than 3,300 EVs are accommodated, it can be seen that the voltage constraint violation occurs unconditionally in all cases.

### 4.5.6 EV HC evaluation according to VVI change

**The first objective function**

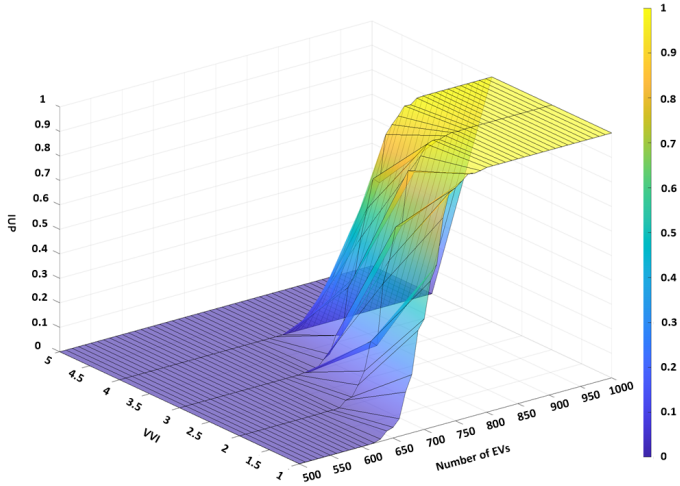


Figure 4.28: IUP chart according to the number of EVs and VVI (V2G, Cost minimization)

In this chapter, I confirmed the change in the acceptability of EVs by changing the VVI for the purpose of cost minimization in V2G. Figure 4.28 shows these results. The lower boundary was fixed at VVI 1, and the upper boundary was changed from 1 to 5. However, in figure 4.28, the value is not shown from VVI of 4, because the voltage constraint is violated when EV are penetrated into the network than 1,000 EVs in the graph range. The network operator can set the VVI by themselves to add flexibility to the network operation, and it is desirable to set a value between 1 and 3 according to the result of figure 4.28.

**The second objective function**

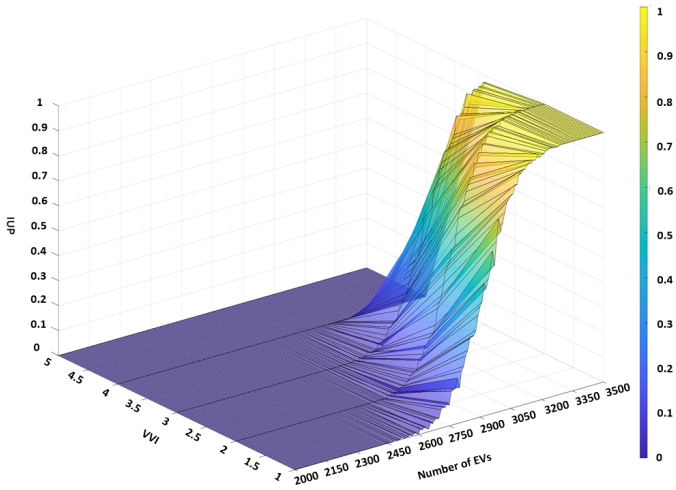


Figure 4.29: IUP chart according to the number of EVs and VVI (V2G, Peak load reduction)

figure 4.29 is a graph showing the acceptability of EVs while changing VVI when applied for the purpose of V2G peak load reduction. The lower bounary was fixed at 0 and the acceptability was evaluated by changing the VVI of the upper boundary from 1 to 5. When the VVI was 1 to 3, the EV HC was evaluated to be between about 2,500 and 3,500. In order for VVI to show acceptability in 4 and 5, much more EVs must be penetrated. In the actual test network, when the number of vehicles in the system is about 3,500 and the number of EVs is about 3,500, the probability of voltage violation in VVI reaches 100%. Therefore, only the range of VVI 1 to 3 is shown in the graph.

### 4.5.7 Result table of V2G EV HC evaluation

Summarizing the information obtained above in a table, it is as follows.

**The first objective function**

Table 4.7 is a table showing the acceptability of EVs by IUP when V2G is applied for the purpose of minimizing cost. Unlike figure 4.20, 4.22, 4.24 and 4.28, the 0.01 to 0.1 section of the IUP is shown in detail. Due to the nature of the test network, VVI 1 to 2 shows a small difference of 30 EVs in HC, but VVI 2 to 3 shows a difference of about 60. IUP is 0.01, that is, the number of EVs in which the EV is driven to one charger and the voltage violation starts is 630. Also, the number of violations of two buses is 663 vehicles. And the number of 3 bus voltage violations is 721 units.

**The second objective function**

Table 4.8 shows EV HC when V2G is applied as a peak load reduction method. Unlike figure 4.21, 4.23, 4.26 and 4.29, IUP is subdivided from 0.01 to 0.1 show the section for peak load reduction purposes, the number of EVs at IUP 0.01 at which voltage violations begin to occur is 2,580. Also, 2,738 units when VVI is 2 and 2,888 units when VVI is 3. Like IUP, VVI can be set according to how much flexibility the network operator will add to its operation.

Table 4.7: HC according to each maximum IUP value (V2G Cost minimization)

| $\lambda_{max}$ | IUP based HC | HC according to VVI change | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| 0.01 | 630 | 630 | [630 663] | [630 721] | [630 1310] | [630 1508] |
| 0.02 | 634 | 634 | [634 668] | [634 725] | [634 1329] | [634 1528] |
| 0.03 | 638 | 638 | [638 677] | [638 729] | [638 1350] | [638 1540] |
| 0.04 | 645 | 645 | [645 682] | [645 734] | [645 1352] | [645 1545] |
| 0.05 | 652 | 652 | [652 684] | [652 740] | [652 1353] | [652 1550] |
| 0.06 | 656 | 656 | [656 687] | [656 741] | [656 1355] | [656 1552] |
| 0.07 | 659 | 659 | [659 689] | [659 743] | [659 1356] | [659 1555] |
| 0.08 | 661 | 661 | [661 691] | [661 744] | [661 1358] | [661 1557] |
| 0.09 | 662 | 662 | [662 693] | [662 746] | [662 1359] | [662 1560] |
| 0.1 | 663 | 663 | [663 695] | [663 747] | [663 1361] | [663 1561] |
| 0.2 | 674 | 674 | [674 707] | [674 765] | [674 1374] | [674 1575] |
| 0.3 | 684 | 684 | [684 723] | [684 770] | [684 1394] | [684 1585] |
| 0.4 | 689 | 689 | [689 728] | [689 784] | [689 1403] | [689 1593] |
| 0.5 | 703 | 703 | [703 735] | [703 791] | [703 1414] | [703 1606] |
| 0.6 | 710 | 710 | [710 744] | [710 800] | [710 1423] | [710 1620] |
| 0.7 | 722 | 722 | [722 761] | [722 808] | [722 1435] | [722 1626] |
| 0.8 | 728 | 728 | [728 766] | [728 826] | [728 1446] | [728 1642] |
| 0.9 | 736 | 736 | [736 783] | [736 835] | [736 1467] | [736 1660] |
| 1 | 800 | 800 | [800 840] | [800 890] | [800 1550] | [800 1720] |

Table 4.8: HC according to each maximum IUP value (V2G Peak load reduction)

| $\lambda_{max}$ | IUP based HC | HC according to VVI change | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| 0.01 | 2580 | 2580 | [2580 2738] | [2580 2888] | [2580 -] | [2580 -] |
| 0.02 | 2609 | 2609 | [2609 2785] | [2609 2927] | [2609 -] | [2609 -] |
| 0.03 | 2657 | 2657 | [2657 2809] | [2657 2972] | [2657 -] | [2657 -] |
| 0.04 | 2679 | 2679 | [2679 2827] | [2679 2977] | [2679 -] | [2679 -] |
| 0.05 | 2703 | 2703 | [2703 2840] | [2703 3008] | [2703 -] | [2703 -] |
| 0.06 | 2706 | 2706 | [2706 2847] | [2706 3013] | [2706 -] | [2706 -] |
| 0.07 | 2709 | 2709 | [2709 2856] | [2709 3019] | [2709 -] | [2709 -] |
| 0.08 | 2716 | 2716 | [2716 2877] | [2716 3024] | [2716 -] | [2716 -] |
| 0.09 | 2737 | 2737 | [2737 2882] | [2737 3028] | [2737 -] | [2737 -] |
| 0.1 | 2753 | 2753 | [2753 2884] | [2753 3041] | [2753 -] | [2753 -] |
| 0.2 | 2809 | 2809 | [2809 2953] | [2809 3112] | [2809 -] | [2809 -] |
| 0.3 | 2844 | 2844 | [2844 2980] | [2844 3145] | [2844 -] | [2844 -] |
| 0.4 | 2888 | 2888 | [2888 3011] | [2888 3191] | [2888 -] | [2888 -] |
| 0.5 | 2916 | 2916 | [2916 3045] | [2916 3222] | [2916 -] | [2916 -] |
| 0.6 | 2953 | 2953 | [2953 3074] | [2953 3261] | [2953 -] | [2953 -] |
| 0.7 | 2981 | 2981 | [2981 3110] | [2981 3290] | [2981 -] | [2981 -] |
| 0.8 | 3022 | 3022 | [3022 3153] | [3022 3350] | [3022 -] | [3022 -] |
| 0.9 | 3082 | 3082 | [3082 3198] | [3082 3401] | [3082 -] | [3082 -] |
| 1 | 3290 | 3290 | [3290 3370] | [3290 -] | [3290 -] | [3290 -] |

## 4.6 Hosting capacity evaluation based on violation of cable capacity constraint

### 4.6.1 Comparison of results with voltage constraint violation basis

In the previous chapter, the HC was evaluated based on the voltage. This chapter evaluates the HC of EVs based on the cable capacity constraints. The HC is evaluated based on the current constraint considering the data of the cable actually buried in the target system. The upper boundary of HC is when the current constraint is violated even once, and the lower boundary is when the current constraint is violated twice or more. do. First, when evaluating the HC of V2G peak load reduction performed in Chapter 4.5, it is [663 747], but when evaluated based on the line capacity constraint, it is [487 550].

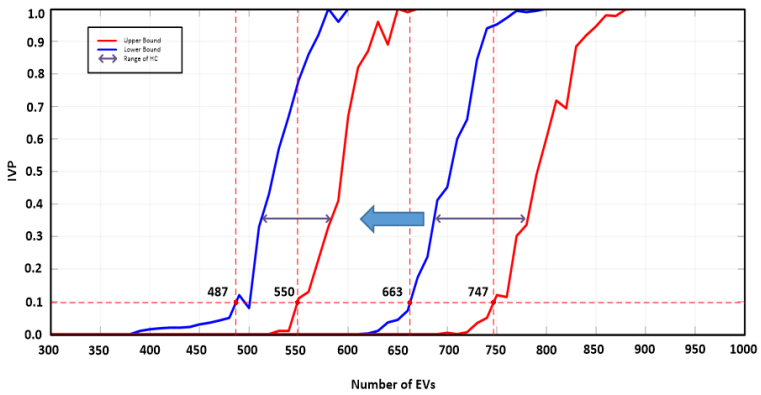


Figure 4.30: EV HC evaluation considering voltage constraints and line capacity constraints

In the case of the target system, it was confirmed that the cable length was short, so that the line capacity constraint was reached first. However, since the voltage constraint

arrives first even when the line length of the target system is increased by only about 16%, in order to evaluate the HC of EVs in the distribution network, both the line capacity and the voltage constraint must be considered and the constraint that violates first must be considered to evaluate HC.

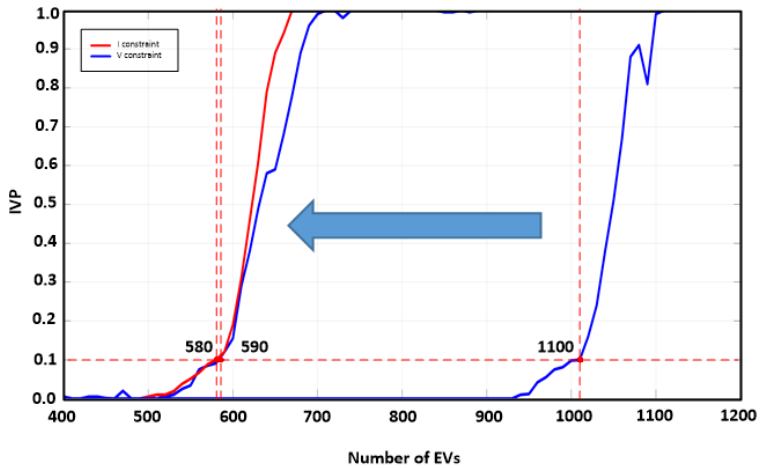


Figure 4.31: Change in HC based on voltage constraint as line length increases

### 4.6.2 Hosting capacity evaluation after reinforcing the cable

When increasing the number of EVs in consideration of the line constraints, the order in which the violations of the line constraints occur in the target system is as shown in figure 4.32. Therefore, the HC was evaluated by reinforcing all the cables with violations by additionally installing one line at a time.

The HC after line reinforcement is [890 1050], which is less than when V1G or V2G was penetrated before line reinforcement. In other words, in order to accommodate all EVs that will be penetrated into the future power distribution network, V1G

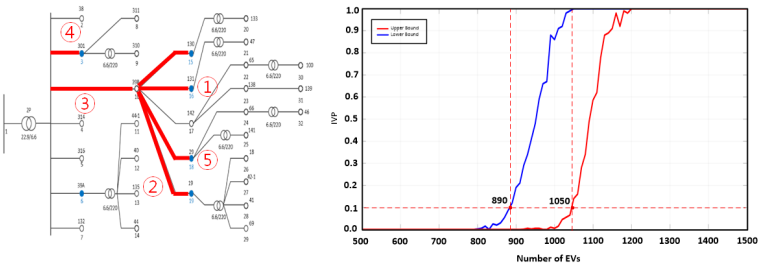


Figure 4.32: HC of EVs by reinforcing lines

and V2G must be actively introduced.

### 4.6.3 Hosting capacity evaluation according to differences in battery capacity

With the development of EVs, the battery capacity has continuously increased. The Ioniq EV, an early EV model, has a battery capacity of 40 kWh, but the recently released Ioniq 5 has a capacity of 58 kWh to 73 kWh, and Tesla's Model S is equipped with a 100 kWh battery. As EVs with various battery capacities can be penetrated into the target system, we evaluated the HC of EVs according to battery capacity.

Table 4.9: Classification according to EV battery capacity)

| | |
|---|---|
| Class A | IONIQ EV(40kWh) |
| Class B | Model3(SR, 50kWh), IONIQ5(SR, 58kWh), EV6(SR, 58kWh) |
| Class C | Model3(LR, 75kWh), KonaEV(64kWh), BoltEV(66kWh), IONIQ5(LR, 73kWh) |
| Class D | EQC(80kWh), ModelS(100kWh) |

After dividing EV models into classes by battery capacity, scenarios were con-

structed with differences in the ratio of each class. Scenario 1 is 40%, 20%, 20%, 20% in the order of Class, and Scenario 2 is 10%, 40%, 40%. 10%, and finally, Sinai 3 is 20%, 20%, 20%, 40%. Rule 1 is cost minimization and Rule 2 is peak load reduction. If the HC is evaluated by setting the upper boundary of HC as a case in which capacity is violated in one line and the lower boundary of HC as a case in which capacity constraint violation occurs in two or more lines, if the EV is charged with V0G, the result is as shown in the figure below. In order of battery capacity, the EV HC of Scenarios 1, 2, and 3 decreases. However, Class D's EV battery capacity is more than twice that of Class A, but the EV HC is not so different. This is because the rated output of the charger has a greater effect on HC than the capacity of the battery.

Table 4.10: HC evaluation results for each charging method according to the scenario

| | V1G | | V2G | |
|---|---|---|---|---|
| | Rule1 | Rule2 | Rule1 | Rule2 |
| Scenario 1 | [510 590] | [1050 1290] | [490 540] | [1140 1370] |
| Scenario 2 | [500 590] | [1030 1250] | [480 520] | [1100 1330] |
| Scenario 3 | [490 580] | [1010 1150] | [480 520] | [1090 1250] |

# Chapter 5

# Conclusions and Future Extensions

## 5.1 Conclusions

This dissertation presents a method to evaluate the hosting capacity of electric vehicles in the distribution network considering the uncertainty of the electric vehicle.

Countries around the world are seriously concerned about the environmental problem of carbon emissions. Many countries, including the United States, Europe, China and South Korea, aim to be carbon neutral by 2050. The transport sector is a huge contributor to carbon emissions. For this reason, the electric vehicle market is growing rapidly in recent years. The battery capacity related to the driving range of an electric vehicle is growing and the output of the charger is getting bigger accordingly. Since the charging of electric vehicles uses electricity, it acts as a load in the network. Due to the introduction of fast chargers, a large penetration of electric vehicles began to burden the network.

Network operators need to figure out how many electric vehicles can be accommodated for efficient and safe operation. It is necessary to determine the size of the load per hour to determine the operation schedule of the system facilities, and also to

reinforce the part with a burden or a risk of fault. In addition, more efficient and safe system operation can be promoted by controlling the charging of electric vehicles or by distributing the electric vehicle load through charge and discharge control. For this reason, it is important to evaluate the number of electric vehicles that the system can accommodate, that is, its hosting capacity.

Electric vehicles have more uncertainty than renewable energy sources, which are said to have large uncertainties. Representative uncertainties are the time to arrive and connect to the charger, the time to disconnect, the state of charge of the battery, the location of the charger to be connected, and the total number of electric vehicles. Considering these uncertainties, the amount of computation increases rapidly. In this paper, i proposed the application of interval and affine arithmetic to reduce the amount of computation in such a situation, and also presented a method to evaluate the network hosting capacity of electric vehicles based on it.

In order to evaluate the hosting capaicty of electric vehicles, general electric vehicle charging methods (V0G), controlled charging methods (V1G), and controlled charging and discharging methods (V2G) were considered. In addition, the purpose of the controlled charging method and the controlled charging/discharging method was evaluated as to the acceptability according to the cost minimization or peak load reduction. For the target system to evaluate the hosting capacity, Seoul National University's actual power system modeling was performed. Cable data buried in Seoul National University was used, and hourly load data of each building was used. In addition, it was modeled using vehicle data entering and exiting Seoul National University.

As a analyzing result of the simulation, it showed about twice the hosting capacity when charging electric vehicles with V2G for the purpose of peak load reduction compared to V0G, which is the conventional method. In addition, V1G, which only

controls charge, and V2G, which also controls discharge, showed similar hosting capacity. It was analyzed that if only a heavy load can be avoided, the hosting capacity itself can be greatly increased even if the charge control is performed without discharging. However, it is a great advantage for network operation that V2G can discharge and resource electric vehicles connected to chargers in situations in which the network urgently needs electric power.

In order to evaluate the hosting capacity of electric vehicles, the concept of interval undervoltage probability (IUP) was introduced, and a method for network operators to add flexibility to electric vehicle load operation by setting an IUP suitable for the operation purpose was presented. In addition, by suggesting a voltage violation index (VVI), a method to add flexibility to the operation of electric vehicle loads was suggested in other ways. The existing hosting capacity evaluation method for electric vehicles has a limitation in that the electric vehicle hosting capacity of the system is very small by not considering the uncertainty of electric vehicles or by evaluating a very extreme situation. In this dissertation, i proposed a method to add realistic flexibility to electric vehicle load management in line with the growing electric vehicle market.

## 5.2 Future Extensions

the proposed methods can be improved considering following contents:

- This dissertation focuses on the method of evaluating the hosting capacity of electric vehicles and analyzes them through randomly generated cases rather than the practical electric vehicle charger connection and disconnection data. Currently, Seoul National University is conducting a demonstration project of an electric vehicle charging station applying V2G, and then using the data to analyze the hosting capacity of the actual electric vehicle data is one of the future work. Also, if the actual demonstration is completed, it will be possible to accurately evaluate the hosting capacity of electric vehicles based on the data of the actually installed charging stations, rather than assuming that they are all fast chargers as in the dissertation.

- In the proposed method, data from the previous day was used as it is to determine the load. However, the load is a factor that can change with temperature, day of the week, and weather conditions. In other words, the hosting capacity of an electric vehicle must be evaluated by predicting the load, and whenever these factors change, the maximum hosting capacity capacity of an electric vehicle will change.

- In Seoul National University, the load usage and vehicle access data are almost constant because the members are constant along with the characteristics of a microgrid. However, it is the general distribution network that needs to be evaluated for the hosting capacity of electric vehicles. The general distribution network will not have constant load usage and data than the Seoul National Uni-

versity network, and the future work is to develop the proposed method to fit the general distribution network well.

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# 초 록

탄소 중립에 대한 관심 증대와 함께 전기차와 전기차 충전기 시장이 빠른 속도로 커지고 있다. 전기차와 전기차 충전기의 배전망 대규모 유입은 배전망 운영에 아주 큰 악영향을 준다. 그렇기 때문에 배전망에 전기차가 몇 대 유입될 수 있는 평가하는 것 즉 hosting capacity 평가를 하하는 것이 배전망 운영 및 설계에 중요하다. 전기차는 일반적인 부하와 다르게 다양한 불확실성을 가지기 때문에 hosting capacity를 평가하는 것이 힘들다. 전기차는 대표적으로 충전소에 도착시간, 떠나는 시간, 배터리의 충전상태 그리고 어떤 충전소를 선택하는지에 대한 불확실성이 있다. 또한 계통 운영자 입장에서는 몇 대의 전기차가 유입될지도 불확실성이다. 이러한 불확실성을 고려해서 전기차의 부하 모델링을 하는 것이 중요하다.

지금까지의 전기차는 충전소에 도착해서 충전만 하는 전기적인 부하였으나 최근에는 충전 제어를 하거나 배전망에 영향을 최소화하거나 혹은 충방전을 통해 피크 부하 감소 혹은 전기 요금 최소화 등의 목적으로 자원화 되기도 한다. 충전제어를 하면 도착 후부터 무조건적인 충전을 하는 것이 아니라 배전망의 상황을 고려하여 출발 전까지 시간 중 최적의 시간에 충전을 한다. 충방전 제어는 계통의 상황을 고려하여 충전하며 전기차의 배터리에 저장된 전력을 배전망으로 보내어 마치 발전기와 같은 역할을 전기차가 수행한다.

본 논문에서는, 전기차의 불확실성을 고려하여 부하 모델링을 수행하여 배전망에서의 hosting capacity를 평가한다. 첫 번째로 전기차의 불확실성을 고려하여 전기차 부하 모델링을 수행한다. 특히 일반적으로 사용해온 방법인 충전만 하거나 충전 제어 혹은 충전과 방전 제어 모두 수행하는 전기차의 모델링을 수행한다. 불확실성은 전기차의 출입시간, 출차 시간, 배터리의 충전상태와 총 전기차의 대수이며 이를 interval과 affine 방법을 이용하여 모델링 한다. 두 번째로 interval undervoltage

probability(IUP)를 이용하여 불확실성을 고려한 전기차의 부하 모델을 이용하여 배전망에 유입 가능한 전기차의 대수, hosting capacity를 산정한다. IUP는 본 논문에서 제안한 저전압이 발생할 확률을 나타내는 지표이다. 계통이 수용한 전기차 각각의 대수에 대해 IUP를 계산할 수 있으며 계통 운영자는 수용 가능한 정도의 IUP를 설정하여 운영함에 따라 계통 운영에 유연성을 더할 수 있다. 세 번째로 voltage violation index(VVI)를 제안한다. VVI는 본 논문에서 제안하는 수용성 평가로 나타내지는 수용성 범위의 넓이를 설정할 수 있다. IUP와 함께 전기차의 유입으로 배전망 운영의 제약조건을 어길 확률을 고려하여 전기차의 hosting capacity를 산정한다. 이를 이용하여 배전망 운영자는 좀 더 유연한 배전망 운영을 할 수 있다. 마지막으로 본 논문에서 사용한 전기차의 모델링 데이터와 hosting capacity를 평가하기 위한 배전망 데이터는 서울대학교의 실제 데이터를 기반으로 한다. 서울대학교 출입하는 차량들의 실제 시간과 서울대학교의 각 건물별 실제 부하 데이터를 고려하였으며 실제로 매설된 케이블 데이터를 이용하여 배전망 모델링을 수행하였다.

마지막으로 제안한 계통 수용성 평가 방법은 MATLAB 상에서 구현되었고 사례연구를 수행되었다. 전기차를 충전하는 방식에 따라 기존 방법과 비교하여 계통에 수용될 수 있는 전기차의 대수를 비교하였다. 충전 제어 방식과 충방전 제어 방식에서 요금 최소화와 피크 부하 감소 목적을 고려하여 사례연구를 진행하였다. 제안한 방법을 활용함으로써 계통 운영자는 계통이 수용할 수 있는 최대의 전기차 대수를 고려할 수 있으며 충방전 제어 방식이 상용화되었을 때, 전기차를 최대한으로 수용해서 자원화 할 수 있을 것으로 기대한다.

**주요어**: 배전망, 저전압 확률, 전기차, 전기차 수용성, affine 연산, interval 연산

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