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Optimal Scheduling of Level 5 Electric Vehicle Chargers Based on Voltage Level

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〈Abstract〉

This study proposes a solution to the voltage drop in electric vehicle chargers, due to the parasitic resistance and inductance of power cables when the chargers are separated by large distances. A method using multi-level electric vehicle chargers that can output power in stages, without installing an additional energy supply source such as a reactive power compensator or an energy storage system, is proposed. The voltage drop over the power cables, to optimize the charging scheduling, is derived. The obtained voltage drop equation is used to formulate the constraints of the optimization process. To validate the effectiveness of the obtained results, an optimal charging scheduling is performed for each period in a case study based on the assumed charging demands of three connected chargers. From the calculations, the proposed method was found to generate an annual profit of $20,800 for a $12,500 increase in installation costs.

Keywords : Optimal Scheduling, Voltage Regation, Electric Vehicle

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1. Introduction

The demand for electric vehicle (EV) chargers has been continuously increasing. Fast charging typically delivers 50 kW, which is 10 to 15 times greater than the instantaneous power consumption in ordinary households. Fast charging, in different levels up to 400 kW, can satisfy the increased performance requirements of automotive batteries and the fast charging demands of consumers [1].Among the various challenges that could arise from the growing supply of EVs and the increased charging power levels,

this study discusses the situation wherein the feed voltage of EV chargers decreases with increase in charging capacity. The voltage supply standard for power distribution systems varies across countries by ±6%, ±10%, and so on .Therefore, reactive power compensation facilities such as Step Voltage Regulators (SVRs) and Static Var Compensators (SVCs) are generally installed near locations where voltage drops occur [2].

Recent studies have proposed photovoltaic (PV) systems as voltage regulators [3]. Moreover, it has been reported that the installation of energy storage systems (ESSs), which are widely used to mitigate the volatility of active power at the location of voltage drop, can effectively maintain the system voltage [4,5]. Unlike the existing studies, this study introduces a new scheduling technique to maintain

the voltage level of several EV chargers through mutual supplementation, without additional power supply facilities.

2. Motivation

To satisfy consumer demand, the operator of the EV charging station, whom we are collaborating with on a joint project, is planning to install several level 5 EV chargers that can charge in different stages (10, 20, 30, 40, and 50 kW), at a distance of approximately 250 m. In this case, the feed voltage of the individual chargers decreases owing to the distance between the chargers. However, the installation of additional power equipment, such as reactive power compensators and power supply equipment is not allowed at the installation site. Our aim is to provide the most economical charging scheduling algorithm while solving the issue of voltage drop in chargers. Fortunately, in charging stations, vehicles charged using fast chargers are rarely parked only during charging. In other words, as charging is not always performed when the EV is parked, both the charging time and the amount can be adjusted.

3. Proposed Method

An economic scheduling technique is introduced for voltage regulation, by scheduling level 5 chargers without additional power supply facilities such as SVRs, SVCs, PV systems, and ESSs, while ensuring consumer satisfaction. For general scheduling, the maximum charging profit is set as an objective function, whereas the consumer charging requirements, charging limit time, power supply capacity, etc. are set as constraints. In this study, the supply capacity of the level 5 EV chargers and the feed voltage of the chargers are added to the constraints mentioned above.

Fig. 1 shows the schematic of the cables connected to the electric vehicle chargers. R and X are the parasitic resistance and inductance of the charging cable, respectively. P is the effective power required by the charger. When n electric vehicle chargers are connected in series with the three phases, the current flowing through the kth cable can be expressed as

$$I_k = \frac{\sum_{i=k}^{n} p_i}{\sqrt{3}\ V_{k-1}} \tag{1}$$

The voltage drop across each cable is expressed as follows:

$$e_k = V_{k-1} - V_k \tag{2}$$

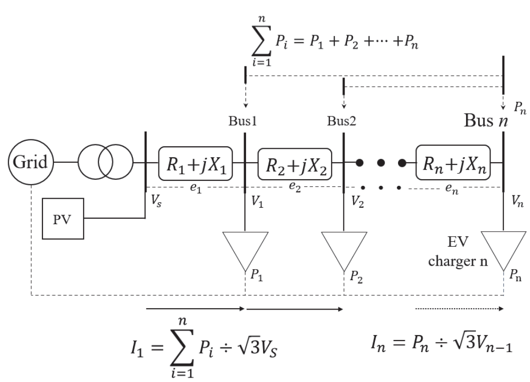

Fig. 1 Voltage drops over the cable when n electric vehicle chargers are connected in series

Assuming the effective power loss in the cables to be insignificant, the power factor angle of the kth bus load in Figure 1 is expressed as follows:

$$\theta_k \fallingdotseq \tan^{-1}\frac{\sum_{i=k}^{n} P_i \tan\theta_i}{\sum_{i=k}^{n} P_i} \tag{3}$$

where θ_i is the power factor angle of ith EV charger. Alternatively, the voltage drop can be expressed similar to the equation formulated for general cables in [6], as follows:

$$e_k \fallingdotseq \sqrt{3} I_k \left(R_k \cos\theta_k + X_k \sin\theta_k\right) \tag{4}$$

If all the EV chargers have the same power factor angle, θ_k can be used as the power factor angle of individual EV chargers.

To stop the charging when the voltage falls below the limit, Eq. (4) is used in defining the constraints of the optimal scheduling algorithm. Fig. 2 shows the voltage drop in cables with optimal scheduling. The charging requirement and the charging allowance time

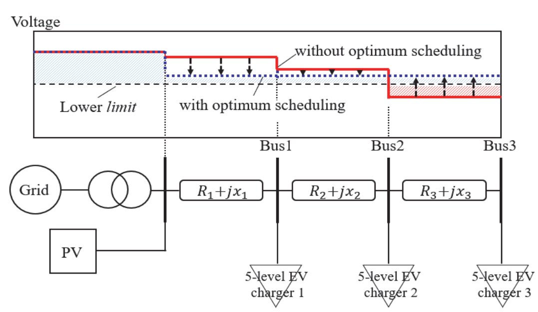

Fig. 2 Diagram of cable voltage drop with optimal scheduling

are selected by the consumers, wishing to charge their vehicles. However, this choice is restricted when the voltage drops below the limit. In this system, EV charging is performed while ensuring maximum economic profit, within the constraints, through mutual communication.

4. Case Study

Three identical EV chargers installed at a distance of 250 m from each other with an arbitrary demand for charging are considered. The profits of two optimally scheduled cases: 1) using a 50-kW normal fast charger and 2) using level 5 EV chargers are calculated and

Table 1. Objective function and constraints for linear optimization used in the case study

Objective $Max\ (P_{sell} - P_{buy} - X\ )$ $^*P_{sell} = \Sigma_{j=1}^{8760}\Sigma_{i=1}^{n=3}(P_{EV,\ i,\ j}\ \times C_{EV,\ i,\ j}\ )$ $^*P_{buy} = \Sigma_{j=1}^{8760}\Sigma_{i=1}^{n=3}(P_{grid,\ i,\ j}\ \times C_{grid,\ i,\ j}\ )$ P: Amount of power, X: Operating costs, C: Unit price	
Constraints $P_{EV,\ i,\ j} \in \{0,\ 10,\ 20,\ 30,\ 40,\ 50\}$ $^*P_{EV,\ i,\ j} = P_{grid,i,j} + P_{PV,i,j}$ $\sum_{j=h}^{h+t} P_{EV,k',j} \leq P_{\neq ed}$ *h: Consumer's charging start time, *t: Consumer's parking time by consumer, *: Consumer's desired charging power *k' $\in\{1,\ 2,\ 3\}$: Consumer's parking charger $\forall\ e_{k,j} \leq V_{reference} - V_{lower\ \lim}$ $^*V_{reference} = 1,\quad V_{lower\ \lim} = 0.94,$ $^*\ e_k = \sqrt{3}I_k\ (R_k\ \cos\theta + X_k\ \sin\theta)$ $^*\ I_k = \Sigma_{i=k}^{n}p_i\ \div\ \sqrt{3}\ V_{k-1},\ ^*k = 1,\ 2,\ 3$	

compared.

The first case involves a normal fast charger, with outputs of 0 or 50 kW, and is immediately charged depending on the consumer demand. In this case, charging does not occur when the voltage supply reference limit is reached. In the second case, the method proposed in this study is applied. As shown in Table 1, the objective

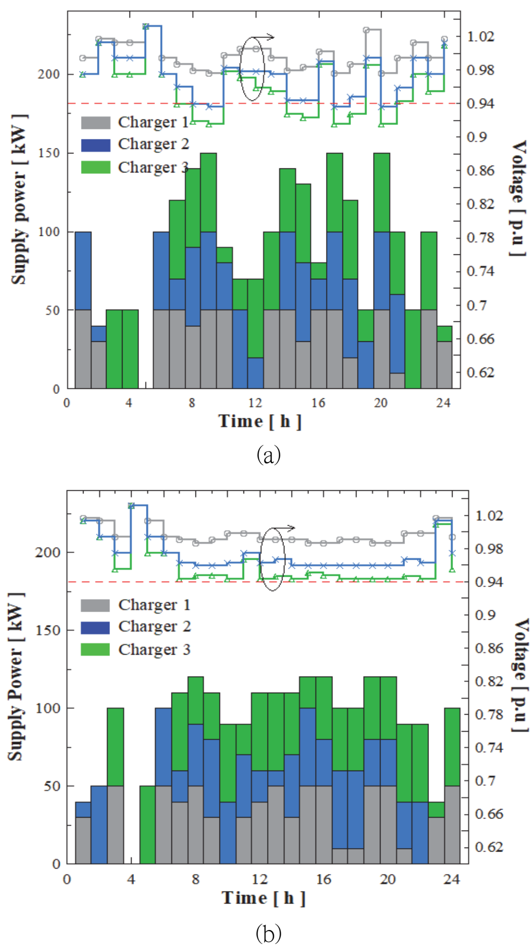

Fig. 3 Charging load and feed voltage to the chargers using (a) normal EV charger and (b) level 5EV charger

function is set so as to realize the maximum economic profit. Conversely, the supply capacity of the electric vehicle chargers, consumer capabilities, and voltage drop limits are included as constraints in the optimization, for each period, over the span of one year. Fig. 3 shows a sample of the results derived through the optimization. The x-axis of the graph is time and the y-axis is the discharge and voltage of the chargers. Although the chargers discharge the same amount of energy over the entire time, Figure 3(b) shows a more spread out charge over time. Both graphs show the chargers' response to the same EV charging demand and both satisfy the demand.

If the feed voltage is less than the minimum voltage limit of 0.94 p.u, the vehicle is not charged in the case of a normal fast charger, as shown in Figure 3(a). Figure 3(b) shows the results after the linear optimization detailed in table 1 is performed, where Eq. (4) is used in the constraints of the scheduling algorithm such that the voltage limit is not reached. If the charging demand (Appendix A) and the available solar power patterns (Appendix B), throughout the year can be assumed, the total economic profit for one year can be calculated, as shown in Table 2. The 2021 unit price of electricity for electric vehicles in South Korea is considered here.

In this case, an additional profit of approximately $20,000 per year can be realized, in comparison with the normal charger.

Table 2. One-year profit and required costs when the scheduling is carried out with normal fast charger and level 5 charger

[Unit: USD]

	Three Fast Chargers (50kW x 3)	Solar Power (20kW)	Sum
Investment Cost	62,500	25,000	87,500
Maintenance Cost	4,500	375	4,875
Conventional fast EV charger			
One-year Profit	99,868	9,357	109,225
One-year electricity cost	30,960		30,960
Proposal scheduling with level 5 EV charger			
Additional Investment	12,500		12,500
One-year Profit	120,755	9,357	130,112
One-year electricity cost	30,960		30,960

5. Conclusion

In this study, we presented a cable voltage drop equation and used it to formulate the constraints for applications in electric vehicle charging stations with large distances between the chargers. The effects over a period of one year were determined through a case study. The results reveal that although the installation cost is slightly increased due to the installation of chargers, the annual profit is remains higher than before. However, as the low electricity rate and the relatively high electric vehicle charging rate in South Korea were used in this case study, slightly different results are to be expected for other countries. In addition, the scheduling performed in this study has limitations since the charging demand is assumed to be accurately predicted.

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Appendix A

Table 3. Consumer's charging requirements and parking times for each individual electric vehicle charger assumed in the case study. The charging pattern was assumed to be identical for 365 days

<table>
<tr><th rowspan="2"></th><th rowspan="2"></th><th>1h</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th></tr>
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<tr><td rowspan="6">Week end</td><td rowspan="2">NO.1</td><td colspan="4"></td><td colspan="3">100</td><td colspan="3">90</td><td colspan="2">80</td></tr>
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Appendix B

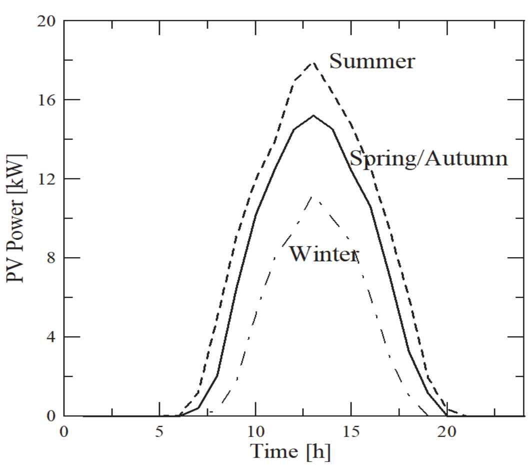

Fig. 4 Solar power pattern assumed in the case study; power generation pattern is assumed to be identical in every season