

A Priority Index Method for Efficient Charging of PEVs in a Charging Station with Constrained Power Consumption

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Abstract – The sizable electrical load of plug-in electric vehicles may cause a severe low-voltage problem in a distribution network. The voltage drop in a distribution network can be mitigated by limiting the power consumption of a charging station. Then, the charging station operator needs a method for appropriately distributing the restricted power to all plug-in electric vehicles. The existing approaches have practical limitation in terms of the availability of future information and the execution time. Therefore, this study suggests a heuristic method based on priority indexes for fairly distributing the constrained power to all plug-in electric vehicles. In the proposed method, PEVs are ranked using the priority index, which is determined in real time, such that a near-optimal solution can be obtained within a short computation time. Simulations demonstrate that the proposed method is effective in implementation, although its performance is slightly worse than that of the optimal case.

Keywords: Plug-in electric vehicle, Charging station, Power distribution algorithm, Heuristic algorithm

1. Introduction

Plug-in electric vehicles (PEVs) have recently grown in popularity as an alternative solution to overcome the problems of oil depletion and increased CO₂ emissions [1]. In an effort to address these problems, authorities in many countries have set high goals for increasing the volume of PEVs [2]. For example, the US, which has the largest market share of PEVs, targets more than 1,000,000 PEVs by 2015 [3], and Japan sets an ambitious target of approximately 260,000 PEVs by 2023 [4]. In accordance with the direction of government policies, leading automobile companies have also been trying to invest aggressively in this business [5].

However, the increasing penetration of PEVs may result in significant problems in the current distribution network because the charging demand of PEVs is large, uncoordinated, and random. The large charging demand of PEVs can cause an excessive voltage drop in the radial distribution network [6, 7], which is likely to result in the degradation of system efficiency [8, 9]. Additionally, uncoordinated and random properties of PEV loads cause severe voltage stability problems in the distribution network [9-12] and sub-optimal generation dispatch in the power system operation [13].

To address these problems due to the high penetration of PEVs, various PEV charging methods have been suggested from the perspective of a distribution network operator (DNO). In [9], three coordinated PEV charging methods

are proposed to minimize the loss of the distribution network. A similar coordinated charging method is proposed to minimize the loss in [14], but it adopts a stochastic programming to handle the uncertainty of loads. In [13], a real-time strategy for the coordination of uncontrolled and random PEV charging demand is proposed to minimize not only the loss in the network but also the generation cost. Reference [15] suggests a PEV charging method to minimize the cost, in which inputs are updated and a new optimization is performed at each time step to handle the deviation between the forecast and actual demand. In addition, reference [16] proposes a price-based charging method to avoid line congestions due to the unmanaged PEV charging loads in the distribution network. In the previous studies in [9, 13-16] from the perspective of a DNO, the DNO directly manages and coordinates the charging schedule considering the effect of the charging demand of PEVs on the distribution network.

Instead of the DNO, an intermediate entity can be delegated to manage the charging demand of PEVs. Unlike the DNO, the intermediate entity does not have any duty for stable operation of the whole distribution network. Therefore, the entity simply aims to maximize its profit with a proper management of charging demand of PEVs [17-19]. Specifically, the intermediate entity may bid in the day-ahead or intra-day market and controls the charging loads of PEVs according to the bidding results [17]. While the intermediate entity is regarded as a price-taker in [17], it is considered in [18] as one of the main participants, which is able to affect the market price. Thus, the optimal charging schedule of PEVs is determined by considering the interaction between the charging demand of PEVs and the market in [18]. Further, the intermediate entity

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may decide the optimal charging strategy of PEVs for maximizing its income in the regulation market in [19].

In these researches from the perspective of the intermediate entity, it is assumed that sufficient power can be supplied as needed to the entity in the distribution network. However, a situation may occur particularly during the period of peak demand, when the interaction between the DNO and the intermediate entity is inevitable to maintain the voltage stability in the distribution network. Practically, this interaction can be implemented as an order from the DNO to the intermediate entity for the limited consumption. Then, the intermediate entity needs an appropriate PEV charging method and an associated criterion, by which the limited power should be distributed to all PEVs. However, this situation of the intermediate entity has been rarely addressed in the previous studies.

As a result, this study proposes a PEV charging method of the intermediate entity in the situation with the constraint on consumption. The intermediate entity in this study is assumed to operate a charging station in an office/commercial building, which is denoted as a charging station operator (CSO). The charging demand of PEVs in a building usually occurs during typical office hours, which fall within the peak time of the power system operation. Therefore, the DNO has to restrict the excessive power consumption of the CSO primarily during peak time. In this situation, all charging requests from PEVs may not be served simultaneously. One of the possible charging strategies of the CSO is to distribute the limited power fairly among all PEVs. In particular, if the CSO knows in advance the information on the initial state of charge, battery capacity, arrival time, and departure time, then the optimal charging schedule can be obtained through a typical optimization technique. However, obtaining knowledge of the future uncertain behavior of PEVs is difficult in practice. Even if the CSO can obtain the exact information in advance, an optimization process consumes a great deal of computation time. To address these problems, this study proposes a heuristic method for charging PEVs based on priority indexes (PIs). The method can find a near-optimal solution without future information or the stochastic estimation of the information. Furthermore, we verify that a solution can be efficiently obtained by the proposed heuristic method within a short computation time without compromising the performance in terms of fair charging.

The remainder of this paper is organized as follows: Section 2 describes the overall operation scheme of the CSO. Section 3 presents the mathematical formulation used to obtain the optimal charging schedule under the assumption that all the information is perfectly known in advance. The practical limitations of the mathematical approach are also given in Section 3. Section 4 describes the proposed heuristic method for the fair distribution of the restricted power to all PEVs. In Section 5, the performance of the proposed method is verified through a

comparison with the optimal case. Concluding remarks are given in Section 6.

2. Operation Scheme of Charging Station Operator

The charging station can accept as many PEVs as the number of its slots. Each PEV is charged through a cable at a rated power. The rated charging power of a PEV ranges from 3 kW to 9 kW. This large demand of power for charging PEVs would cause voltage problems in the distribution network. According to [6], the low-voltage problem begins to occur when the penetration level of the PEV charging load exceeds 30% of the total demand of the distribution network. Therefore, a charging station in an office building can cause a substantial voltage drop in the distribution line to which the building is connected. The low-voltage problem affects not only the office building, but also all the nodes in the distribution line. For the radial distribution network shown in Fig. 1, the voltage drop can be approximately calculated by the relationship as [20]

$$\Delta U = U_s - U_r \approx \frac{RP + XQ}{U_s} \quad (1)$$

where is ΔU the voltage drop; U_s is the sending voltage at the main transformer; U_r is the receiving voltage at the load; P and Q are the active and reactive power consumed by the load, respectively; and R and X are line resistance and the line reactance, respectively. Given that R and X are fixed values, the voltage drop is approximately linearly proportional to the power consumed by the load.

As suggested in [6, 9], and [13] from the perspective of the DNO, the problem of voltage drop can be resolved by using a suitable charging algorithm. However, if PEVs are not served by the DNO but are under the control of the CSO, the DNO may choose to use a constraint order for

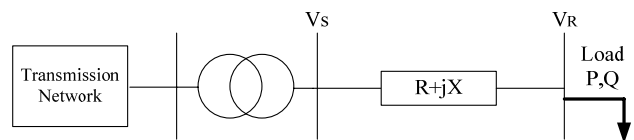


Fig. 1. Simple representation of a distribution network

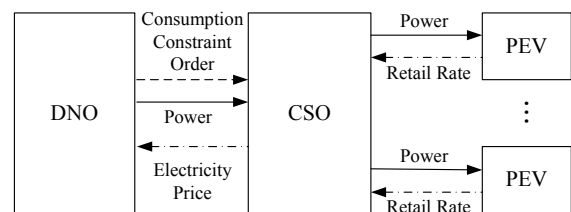


Fig. 2. Structure of PEV charging service through the CSO

power consumption as an indirect method for maintaining stable voltages in the distribution network. Then, PEVs can be collectively considered as one node relative to the DNO. Instead, the CSO takes the responsibility for managing charging requests from PEVs. The control burden of the CSO, however, is significantly smaller than that of the DNO because of the smaller number of PEVs under control. The structure of this indirect method for addressing the voltage drop problem through the CSO is shown in Fig. 2.

The charging method can be categorized into two types according to the strategy for controlling charging current. One type uses on/off charging with a fixed charging current, whereas the other controls the charging current with power electronic devices [21]. This study assumes that the CSO uses the basic on/off control type without additional power electronic devices.

Let P_{max} denote the maximum power consumption requested by the DNO. Then, the constraint on P_{max} can be interpreted as the number of available charging slots, N_{max} , which is determined as

$$N_{max} = \left\lfloor \frac{P_{max}}{P} \right\rfloor \quad (2)$$

where P is the rated power for charging one PEV. At peak time, N_{max} might be smaller than the actual number of PEVs requesting for charging service. If possible, the CSO can satisfy the constraint on N_{max} by shifting the charging demand to off-peak time. However, the time shift of charging demand may be inappropriate when considering the departure time for PEVs. Then, assuming that all the charging requests are not fully satisfied because of insufficient charging power, the CSO can alternatively choose to distribute the power among all PEVs appropriately contingent on a certain criterion.

3. Mathematical Approach

3.1 Criterion for distributing constrained power

Given N_{max} at each time step j , fairly providing the restricted power to all the PEVs seems reasonable. There can be lots of ways to index the fairness of EV charging because fairness is a subjective term in nature. In this study, we assume that the target state of charge (SOC) of a PEV at departure time is given. Thus, we choose to define a fairness index as root-squared shortage of charging compared to the target SOC like the common root-mean-square (RMS) error in engineering studies, which is represented as

$$\text{Fairness Index} = \sqrt{\sum_{i=1}^{N_{slot}} \left(\frac{E_{ic} - E_i(T_{if})}{E_{ic}} \times 100 \right)^2} \quad (3)$$

where N_{slot} is the number of parking lots, E_{ic} is the battery capacity of the i -th PEV, T_{if} is the departure time of the i -th PEV, and $E_i(\cdot)$ is the SOC of the i -th PEV at a certain time. The SOC at the departure time, $E_i(T_{if})$, can be calculated as

$$E_i(T_{if}) = E_{i0} + \sum_{j=T_{is}}^{T_{if}} P \cdot x_{ij} \quad (4)$$

where E_{i0} is the initial SOC, P is the rated charging power, and x_{ij} is the variable that indicates the on/off charging status of the i -th PEV at the time step j . The values of x_{ij} are 0 (off) when the i -th PEV is charged at the time step j , and 1 (on) otherwise. This fairness index means how fairly the PEVs have been charged at their departure time compared with a full SOC of 100%. A power distribution method thus aims to minimize the fairness index.

The minimization of the fairness index can be formulated as a typical constrained optimization problem with respect to x_{ij} . Assuming that all information about the situation in the future, such as the initial SOC, battery capacity, arrival time, and departure time, are known to the CSO, the optimization problem can be formulated as

$$\min_{x_{ij}} \sum_{i=1}^{N_{slot}} \left[\frac{E_{ic} - (E_{i0} + \sum_{j=T_{is}}^{T_{if}} P \cdot x_{ij})}{E_{ic}} \times 100 \right]^2 \quad (5)$$

subject to

$$0 \leq E_i(T_{if}) \leq E_{ic} \quad (6)$$

$$T_{is} \leq T_{ij} \leq T_{if} \quad (7)$$

$$\sum_{i=1}^{N_{slot}} x_{ij} \leq N_{max}[j] \quad (8)$$

where $N_{max}[j]$ is the number of available charging slots at the time step j . The first constraint in (6) indicates that the SOC of the i -th PEV at the departure time has a positive value and does not exceed its capacity E_{ic} . The second constraint in (7) indicates that each PEV has to be charged during its staying time from T_{is} to T_{if} . The third constraint in (8) indicates that the number of slots in the on-state at the time step j is less than or equal to $N_{max}[j]$.

3.2 Practical limitation on implementation

Given the meaning of the decision variable x_{ij} , various binary programming methods [22] can be used to solve the optimization problem in (5)-(8). However, this mathematical approach has two critical limitations. First,

the CSO can hardly know the future information exactly. Only after a PEV arrives at a station can the CSO know the initial SOC, battery capacity, arrival time, and departure time. A stochastic estimation method can be applied on the basis of the probability distribution of many samples to obtain future information in advance. However, apart from the possibility and difficulty in implementing a suitable estimation method, the accuracy of estimation will be a critical factor in successfully solving the problem. Second, even if future information is known to the CSO in advance, execution time prevents the mathematical approach from finding a practical solution because the computation time for solving the optimization problem is proportional to $2^{N_{slot}T}$, where T refers to the whole simulation time step. For example, if the station has 10 slots and the total number of simulation time steps is 100, then the execution time is proportional to 2^{1000} , which is practically equivalent to infinity for a commercial computer. Therefore, the mathematical approach is difficult to implement in the practical operation of the charging station.

As a result, the CSO needs an algorithm that can determine a fair method for distributing the restricted power to each PEV by using only past and current information efficiently within a short execution time in practice. The easiest option for the distribution method is to charge PEVs in the order that they enter the charging station. This approach is commonly called the *first-come first-served* (FCFS) method. In this case, a PEV that arrived late has to wait until the other PEVs in charging operation have completed charging. In this case, the PEV that arrived late might not be sufficiently charged at departure time.

We provide a simple example to demonstrate the problem of charging PEVs on the basis of the FCFS method with the assumption that N_{max} is 2 and that PEVs arrive at the station with different charging information, as given in Table 1.

Table 1. Example case of FCFS for three PEVs.

	Initial SOC [%]	Full capacity [kWh]	Arrival time [min]	Departure time [min]
PEV1	59	30	5	340
PEV2	53	25	35	335
PEV3	33	15	50	345

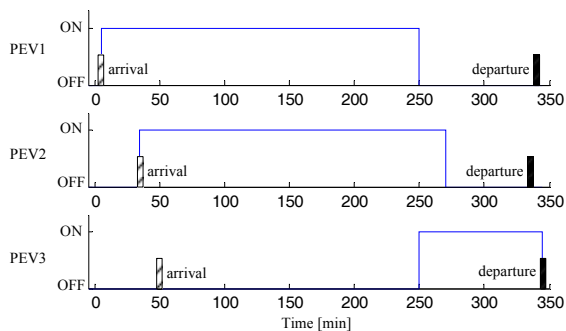


Fig. 3. ON/OFF status of three PEVs for FCFS method

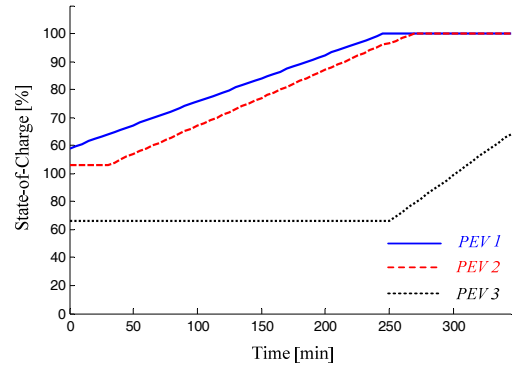


Fig. 4. SOC status of FCFS case for three PEVs

While the CSO provides the charging service to PEV1 and PEV2, PEV3, which arrived late, has to wait until PEV1 or PEV2 finishes the charging operation. In this example, PEV3 can start being charged only after the charging operation for PEV1 is completed, as described in Fig. 3.

Consequently, as shown in Fig. 4, PEV3 is not sufficiently charged at departure time when compared with PEV1 and PEV2. This example demonstrates that limited power is unlikely to be fairly distributed among all PEVs in the FCFS method. The FCFS method will be used in the simulation for comparison with the proposed approach.

4. Proposed Method using Priority Index

4.1 Requirement for proposed method

As demonstrated by the simple example, the FCFS algorithm cannot provide fair charging service to PEVs. In addition, the most serious disadvantages of the mathematical approach are that it requires future information to be available and consumes a long computation time, which make it impractical. Thus, these advantages naturally give rise to the following requirements in devising a method for fair distribution.

Requirement 1

The method should be capable of fairly distributing the restricted power to each PEV in terms of the fairness index in (3).

Requirement 2

The method should be capable of finding a solution without pre-knowledge of future information.

Requirement 3

The method should be capable of finding a solution within a short or reasonable time.

A trade-off must exist between the short computation time in Requirement 3 and the guarantee of the global optimality. Thus, a heuristic method can be considered as a method for fair distribution that satisfies three requirements.

	10min	40min	200min	300min	350min
Slot1	Rank 1	Rank 3	Rank 10	Rank 7	Rank 5
Slot2	Rank 2	Rank 4	Rank 8	Leave	Leave
Slot3	Null	Rank 2	Rank 9	Rank 5	Leave
Slot4	Null	Rank 1	Rank 2	Rank 8	Rank 3
Slot5	Null	Null	Rank 5	Rank 3	Rank 2
Slot6	Null	Null	Rank 3	Rank 1	Leave
Slot7	Null	Null	Rank 7	Rank 9	Leave
Slot8	Null	Null	Rank 1	Rank 4	Rank 4
Slot9	Null	Null	Rank 4	Rank 6	Rank 1
Slot10	Null	Null	Rank 6	Rank 2	Leave

Fig. 5. Exemplary process of proposed method.

Although the heuristic method cannot find the optimal solution for (5)(8), this method should be qualified to find a solution that is as close to the optimal one as possible. In other words, the heuristic method should find a solution within an admissible error from the optimal value within a sufficiently short time to be considered a practical charging method for the CSO.

4.2 Description of proposed method

A heuristic charging method proposed in this study is the priority index method (PIM), which distributes restricted power to PEVs by using only past and current information given the constraints on N_{max} . Using a PI, the PIM ranks the slots and chooses N_{max} slots as the top priority. The chosen slots are charged during the specified time step, and this process is repeated from the arrival time of the first PEV to the departure time of the last PEV.

One exemplary process of the PIM is shown in Fig. 5. Ten slots are present, and N_{max} is 6 throughout the time range in this example. At each time step, the CSO calculates the ranks of PEVs in a descending order of the PI and chooses six slots for providing charging services.

The specific procedures of the PIM are given below.

Description of the Proposed Priority Index Method	
1:	$N_{max}[j]$ is set by the CSO at the time step j .
2:	if $N[j] \leq N_{max}$
3:	Charge all slots $N[j]$ at the rated power P .
4:	else
5:	Calculate the <i>priority index</i> of each slot.
6:	Rank all slots in a descending order of the priority index and store the rank of the j -th slot as $Rank_i[j]$.
7:	for $i=1: N[j]$
8:	if $Rank_i[j] \leq N_{max}[j]$ Charge this slot.
	else Let this slot uncharged.
	end if
9:	end for
10:	end if

The most important factor in PIM is to develop a

Table 2. Three priority indexes of the PIM.

Types	Index
PI-1	PI = 1/Remaining Time (%)
PI-2	PI = Required Energy (%)
PI-3	PI = Required Energy (%) / Rest time (%)

suitable PI for ranking PEVs. Three types of PIs are proposed in this study, as listed in Table 2.

In PI-1, the remaining time (%) to departure of PEVs is considered. A PEV that has low remaining time to departure is assigned a higher priority in PI-1. In PI-2, the CSO ranks PEVs according to the required energy (%) for being fully charged. A PEV that has the least SOC or the largest required energy has the highest priority ranking in PI-2.

In some cases, however, a PIM using these two PIs may have a problem despite being better than the FCFS. For PI-1, each priority ranking of PEVs will not suitably change because the order of the remaining time of PEVs will be fixed over time. Thus, PEVs that have more remaining time upon arrival might not be sufficiently charged in the PIM with PI-1. In the case of PI-2, the CSO cannot primarily provide charging service to PEV A, which departs earlier than PEV B, which has the same energy as PEV A. Therefore, the PIM with PI-2 is likely to fail in distributing the restricted charging power fairly. Considering the disadvantages of PI-1 and PI-2, PI-3 is suggested as an alternative PI and is a combination of PI-1 and PI-2. With PI-3, both the remaining time and the required energy are considered in determining the priority of PEVs. In other words, the required energy is normalized with respect to the remaining time. For example, if PEV A and PEV B have the same required energy, the one that departs earlier is assigned a higher priority in PI-3. The most desirable attribute of PI-3 is that it can simultaneously consider the fairness in the aspects of remaining time and required energy and can also find a solution that is closer to the optimum of (5)-(8) when compared with other methods using PI-1 or PI-2.

5. Illustrated Example

5.1 Simulation setting

An illustrated example is presented to verify the performance and advantage of the proposed heuristic charging method using the PI through a comparison with the FCFS method and the optimal case. Simulation is performed during typical office hours from 10:00 to 18:00. Ten PEVs are used for intuitively verifying the performance of the proposed method, although more than 10 PEVs may be used in practice.

The values of initial SOC, battery capacity, arrival time, and departure time for 10 PEVs are randomly generated, as

Table 3. Parameters for ten PEVs in the simulation.

Parameters	Initial SOC [%]	Battery capacity [kWh]	Arrival Time [min]	Departure Time [min]
PEV1	22.1	10	5	360
PEV2	33.4	20	10	300
PEV3	25.6	15	20	345
PEV4	18.9	19	35	390
PEV5	44.2	31	45	380
PEV6	61.2	24	70	320
PEV7	22.4	10	90	335
PEV8	26.9	17	110	420
PEV9	48	26	115	370
PEV10	43.2	15	130	320

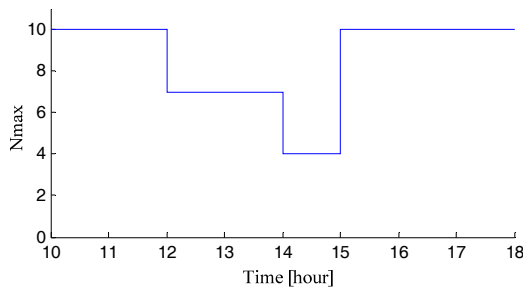


Fig. 6. N_{max} used in the simulation

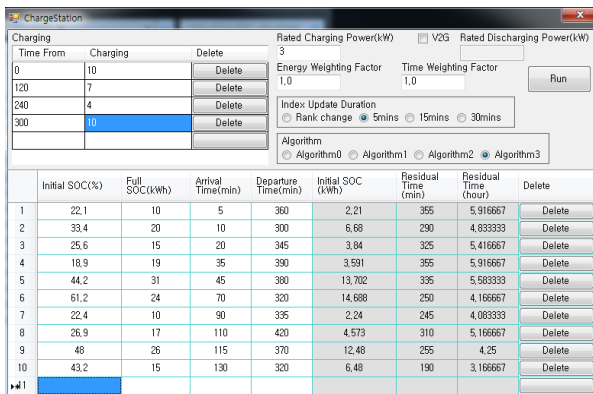


Fig. 7. GUI of the developed simulator for the PIM.

listed in Table 3. The constraint on N_{max} is set for the period of 10:00 to 18:00, as described in Fig. 6.

A commercial laptop with Intel i5 2.3 GHz CPU, 8 G RAM is used in the simulation. To obtain the optimal solution of (5)-(8) assuming future information is available, the Matlab/Opti toolbox is used [23]. Additionally, a simulator for charging PEVs with the proposed PIM has been developed by the authors using the JAVA language to perform the simulation easily for the FCFS case and the proposed method. The graphic user interface (GUI) of the simulator is shown in Fig. 7.

5.2 Simulation Results

The final SOC of 10 PEVs and the performance in terms of the fairness index and the execution time for each

Table 4. Final SOC (%) of 10 PEVs for each method.

Method	FCFS	PI-1	PI-2	PI-3	Ideal case
PEV1	100	100	100	100	100
PEV2	100	100	82.2	98.4	95.9
PEV3	100	100	97.3	100	97.3
PEV4	100	100	100	100	96.5
PEV5	98.2	97.3	95.0	90.2	94.2
PEV6	100	100	86.2	95.6	95.6
PEV7	100	100	99.9	100	97.4
PEV8	98.1	65.1	100	100	96.0
PEV9	66.9	69.7	95.1	86.5	95.1
PEV10	49.9	89.9	88.2	94.9	96.5

Table 5. Performance of Charging Methods.

	FCFS	PI-1	PI-2	PI-3	Ideal case
Fairness Index	60.16	47.34	26.54	18.12	12.17
Execution Time	Null	<<1 s	<<1 s	<<1 s	>>24h

charging method are given in Tables 4 and 5, respectively. The variations of the SOC of each PEV with respect to time for each method are shown in Fig. 8. The ideal case means the simulation using the mathematical approach in Section 3 with perfectly forecasted information on initial SOC, battery capacity, arrival time, and departure time of each EV. However, it is very hard to obtain such information in practical case. Therefore, the ideal case is only considered as the case for comparison.

As shown in Table 4, some PEVs have markedly less SOC values than other PEVs in the cases of the FCFS and the PIM with PI-1. Meanwhile, the restricted charging power is distributed quite well in the cases of PI-2 and PI-3 compared with FCFS and PI-1. The results in Table 4 can be quantified through the fairness index in Table 5.

The level of dispersion of the SOC at the final time can be clearly seen from Fig. 8. Some PEVs have significantly less SOC at the final time in the case of the FCFS and PI-1. Meanwhile, the values of the SOC are concentrated in PI-2, PI-3, and the ideal case. For a more detailed analysis, on/off states of some selected PEVs are represented in Fig. 9. In the FCFS case, PEV9 and PEV10, which came later than the others, should be under the off-state for a considerable time until other PEVs finish their charging. As a result, their SOC values at the departure time are significantly less than that of other PEVs in the FCFS case. These SOC values which correspond to the green and red lines at the final time in Fig. 8(a). In the case of the PI-1, PEV8 and PEV9 are pushed back in the priority ranking after the arrival of PEV10 because only the remaining time (%) is considered for ranking PEVs in the PIM with PI-1 and the remaining time (%) of PEV10 is significantly smaller. Therefore, PEV8 and PEV9 should be under the off-state for most of the latter part of the simulation time. Consequently, PEV 8 and PEV9, which respectively correspond to the green and blue lines at the final time in Fig. 8(b), have large SOC deviation from other PEVs.

In the case of PI-2, the fairness index is significantly far

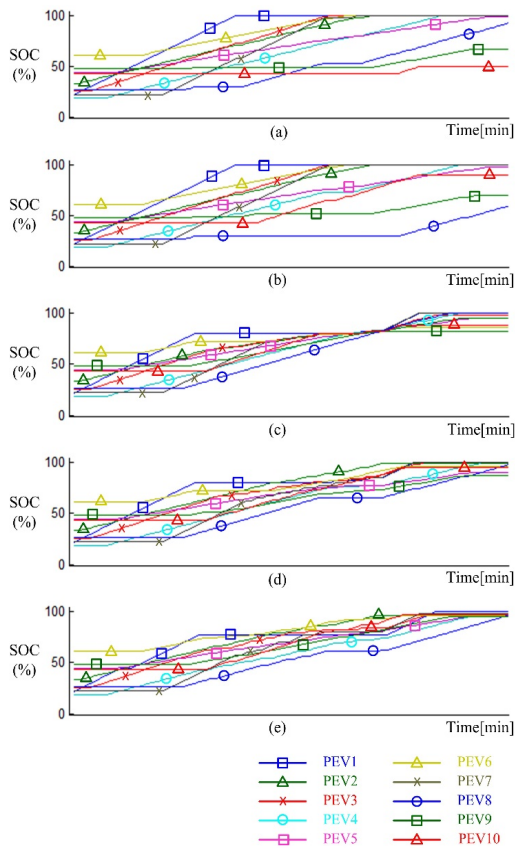


Fig. 8. SOC (%) of each PEV; (a) FCFS (b) PI-1 (c) PI-2 (d) PI-3 (e) Ideal case.

from that of the ideal case as seen in Table 4 because PI-2 uses only the required energy (%) of each PEV as the PI. In this situation, the SOC values of all the PEVs converge to the highest SOC value at the beginning time of power restriction, which is why a cross point of SOC values appears in Fig. 8(c). This condition is different from that of other methods. Owing to this phenomenon, even some PEVs with less remaining time cannot be sufficiently assigned for charging. In other words, PI-2 only pursues equal distribution of charging power without considering the departure time. This condition implies that equal distribution in terms of the required energy (%) does not always result in fair distribution.

The SOC graph of PI-3 in Fig. 8(d) is similar to that of the ideal case in Fig. 8(e). Except for the ideal case, PI-3 actually has the best fairness index among the charging methods. According to Table 4, however, PEV9 does not reach 90% SOC value in this case because PI-3 does not perfectly reflect the condition in which the battery capacity of PEV9 is relatively larger than that of others. Thus, the fairness index of PI-3 is slightly worse than that of the ideal case, which shows the limitation of a heuristic method.

Despite this limitation, PIM with PI-3 has a practical advantage over the ideal case. According to the results of the execution time in Table 5, more than 24 hours are

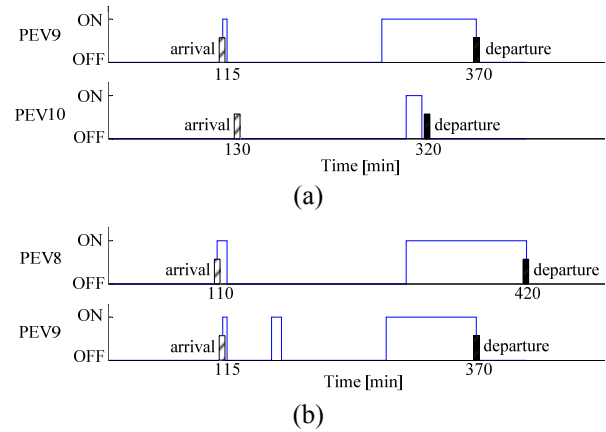


Fig. 9. ON/OFF status of Selected PEVs for (a) FCFS and (b) PI-1.

required to obtain the optimal solution in the ideal case. This duration is beyond the level of comparison with the PIM with PI-3 in a practical sense. Moreover, the optimal solution can be obtained in the ideal case only under the assumption that the future information is perfectly known in advance. By contrast, the proposed PIM with PI-3 requires shorter execution time than the ideal case and even requires future information availability. In other words, although the ideal case determines a charging schedule during the whole time range while considering all possible cases, PIM with PI-3 assigns PEVs for charging at each time step on the basis of the current situation. Consequently, the proposed method with PI-3 could be an efficient and practical charging method for the CSO. This method requires a relatively short execution time and guarantees the fairness index within an acceptable range.

6. Conclusion

The voltage problem caused by the electrical load of a PEV charging station in a distribution network can be mitigated by the constrained consumption order from the DNO. Under this situation, the CSO needs an algorithm for appropriately distributing the restricted charging power among PEVs. If the CSO perfectly know the information, such as initial SOC, battery capacity, arrival time, and departure time of each EV, in advance, the mathematical approach in Section 3 can be a good solution to fairly distribute the restricted power in the charging station. However, it is just an ideal approach which has limitations for being implemented in practical cases, because it is very hard for CSO to perfectly forecast the required information. Therefore, this study suggests a heuristic method for fairly charging PEVs on the basis of three kinds of PIs. The proposed method can rank PEVs using the PI, which only reflects available information at the current time, to distribute the constrained power among all PEVs. Illustrated examples show that the proposed method is

efficient in terms of execution time and simple structure. Despite the fairness index of the proposed method is slightly worse than the ideal case, the performance is within an acceptable range and thus can be a practical charging method of the CSO under constraints on the power consumption.

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