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A COORDINATED CHARGING SCHEDULING METHOD FOR ELECTRIC VEHICLES CONNECTING TO MICROGRID CONSIDERING EMERGENT CHARGING DEMAND

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ABSTRACT

In this study, a coordinated charging scheduling model for EVs connecting to microgrid is proposed to achieve peak shaving and valley filling. In the model, we develop an EV Charging Emergency Indicator (CEI) that used to measure whether the EVs have emergent charging demand. For the EVs that have emergent charging demand, the emergent charging strategy is employed. Considering the emergent EV charging, the optimal dispatch model including all the EVs (both emergent charging EVs and usual charging EVs) is developed. The objective of the model is to minimize the overall peak-valley load difference. The proposed model considered both the randomness of the EVs connected to the microgrid and the emergent charging demand of some EVs. Finally, the simulation results show the effectiveness of the proposed model.

Keywords: Electric vehicle, microgrid, coordinated charging, optimal load scheduling, emergent charging

NONMENCLATURE

Abbreviations	
EV	Electric Vehicle
CEI	Charging Emergency Indicator
SOC	State of Charge
Symbols	
N	Total number of EVs
i	The i-th EV
j	The *j*-th time slot of the day
t_i^c	Connection time of i-th EV
t_i^{dis}	Disconnection time of i-th EV
ΔT	Length of each time slot
T_i^{Rem}	Number of remaining time periods of the i-th EV
J_i^c	Serial number of the time slot when i-th EV connected to microgrid
J_i^{dis}	The serial number of the time slot when i-th EV disconnected from microgrid
CEI_i	Calculated value of Charging Emergency Indicator for i-th EV
η_{EV}	Charge efficiency of EV
$SOC_i^{\min}$	Lower bound of SOC
$SOC_i^{\max}$	Upper bound of SOC
SOC_i^{con}	SOC of i-th EV when connected into microgrid
SOC_i^{dis}	SOC of i-th EV when disconnected from microgrid
Cap_{EV}^{bat}	EV battery capacity
P_{EV}	Charge power of EV
P_{EV}^{fast}	Charge power of emergent charging EVs
P_{EV}^{usual}	Charging power of usual charging EVs
$x_{i,j}$	Charging state of i-th EV in *j*-th time slot
P_{T-c}^j	Total load at the *j*-th time slot with coordinated method
P_{con}^j	Load providing for conventional electricity power consumption in *j*-th time slot
$P_{T-c}^{\max}$	Peak value of the total load in coordinated charging method
$P_{T-c}^{\min}$	Valley value of the total load in coordinated charging method

$P_{T-uc(\max SOC)}^{\max}$	Maximum value of the uncoordinated total load that satisfies the maximum demand of SOC for EVs

1. INTRODUCTION

EVs provide an alternative option for developing cleaner transportation systems and offer a great potential for sustainable transport development [1]. From the energy consumption and environmental impact perspective, EVs are more eco-friendly and efficient since they consumed cleaner electric power energy and generate near zero emissions on the user side [2, 3]. From the transportation aspect, EVs are more easily to incorporate with intelligent transportation system to enhance smart transportation services [4, 5].

Nevertheless, the development of EVs still faces some challenges. Specially, The management and business issues are critical for the large scale EV penetration in future, particularly their interaction with main power grid or local microgrid [6, 7]. Uncoordinated charging of large scale EVs will bring great pressure on the power supply system, such as the increased load peak, power quality degradation and so on, which influencing the stability and safety of power system operation. It has been presented that uncoordinated charging of large-scale EVs will elevate peak loads of microgrid at rush time, so the scheduling of EV charging should be implied to deal with the passive effect of uncoordinated charging of EVs [8].

Currently, there have been some research efforts on the scheduling of EV charging [9]. To reduce the huge pressure of uncoordinated charging of increasing amount of EVs to microgrid, the optimal load dispatch problem has been considered to support the safe and efficient operation of microgrid [10]. Peak shaving and valley filling can be achieved through coordinated EV charging scheduling, which can reduce the possibility of surge load occurrence. Ultimately, the coordinated charging can improve the operation performance microgrid. But existing studies mainly focused on the supply side to achieve minimizing the power losses [11, 12] or minimizing the power load variance [13, 14]. But owners' specific charging demand are usually not considered. Actually, the charging demand of EV owners are significantly different, especially for the emergent charging demand.

To fill this gap, in this study, an EV Charging Emergency Indicator (CEI) is developed to distinguish whether the EV charging demand is emergent. And then a coordinated charging scheduling method are proposed to achieve peak shaving and valley shaving for total load of microgrid, which consider the emergent charging demand.

2. MODEL

2.1 Input charging related data

In EVs charging scheduling process, the EV aggregator achieve information collection and EV charging scheduling implementation. Before the charging, the EV owners settle the charging information and send to EV aggregator. Therefore, the input charging related data include the connection time and disconnection time, the SOC when EV connected into microgrid, the basic SOC demand and the EV's upper SOC for safety [14, 15].

2.2 Time slot division

In this model, the time of a day is discretized into 96 parts, and each time slot is 15 min [15-17], i.e., ΔT =15min. And the time slot of each EV's connection time and disconnection time to the microgrid are calculated respectively by:

$$J_i^c = \left\lceil \frac{t_i^c}{\Delta T} \right\rceil \tag{1}$$

$$J_i^{dis} = \left\lfloor \frac{t_i^{dis}}{\Delta T} \right\rfloor, \quad i = 1, 2, ..., N \tag{2}$$

where $\left\lceil \frac{t_i^c}{\Delta T} \right\rceil$ is the next integer larger than the results of division operation. $\left\lfloor \frac{t_i^{dis}}{\Delta T} \right\rfloor$ is the previous integer smaller than the results of division operation.

2.3 EV Charging Emergency Indicator

The proposed coordinated charging scheduling method uses an EV CEI to distinguish which the EVs have emergent charging demand, and divides all EVs into two groups: emergent charging EVs and usual charging EVs.

Based on the connection time slot J_i^c and disconnection time slot J_i^{dis} calculated above, the whole time slot that the EV connected into the microgrid T_i^{Rem} can be calculated by:

$$T_i^{\text{Rem}} = J_i^{dis} - J_i^c \tag{3}$$

As shown above, the coordinated scheduling method considers the emergent charging demand of the EV owner. For distinguish the emergent demand, we present the CEI for EV, which can be calculated by:

$$CEI_i = (T_i^{Rem} \cdot \Delta T) P_{EV} \cdot \eta_{EV} - (SOC_i^{\min} - SOC_i^{con}) \cdot Cap_{EV}^{bat} \quad (i = 1, 2, \ldots, N;\ j = 1, 2, \ldots, 96) \tag{4}$$

While $CEI_i < 0$, indicates that the charging demand of $i\text{-}th$ EV is emergent. $CEI_i > 0$ means that the charging demand $i\text{-}th$ EV is not emergent. In the basis of the CEI_i, all EVs are divided into emergent changing EVs and usual charging EVs.

2.4 EV charging power setting

In the coordinated charging scheduling, the emergent charging EVs should be arranged fast charging, and corresponding charging power is P_{EV}^{fast}. And the rest of usual charging EVs are arranged usual charging with usual charging power P_{EV}^{usual}.

$$P_{EV} = \begin{cases} P_{EV}^{fast}, \text{emergent charging EVs} \\ P_{EV}^{usual}, \text{usual charging EVs} \end{cases} \tag{5}$$

2.5 EV charging state

With the preparation for the optimization model, the variable would be established. The state variable $x_{i,j}$ should be defined to reflect the charging state of the $i\text{-}th$ EV in the $j\text{-}th$ time slot. And the $x_{i,j}$ is 0 or 1, $x_{i,j} = 0$ indicates the $i\text{-}th$ EV in the $j\text{-}th$ time slot is not charging. $x_{i,j} = 1$ means the $i\text{-}th$ EV in the $j\text{-}th$ time slot is in charging state as shown in Eq. (6).

$$x_{i,j} = \begin{cases} 1, & \textit{charging state} \\ 0, & \textit{not charging state} \end{cases} \tag{6}$$

2.6 Optimization model

2.6.1 Objective function

The total load of microgrid includes the conventional load and the EV charging load. Furthermore, and the EV charging load consists of the emergent EV charging load and usual EV charging load. And the total load of the coordinated charging model can be calculated by:

$$P_{T-c}^{j} = P_{con}^{j} + \sum_{i=1}^{N} x_{i,j} \cdot P_{EV} \tag{7}$$

where P_{EV} equals to P_{EV}^{fast} when the $i\text{-}th$ EV is emergent charging EV and equals to P_{EV}^{usual} if the $i\text{-}th$ EV is usual charging EV.

The objective of the charging scheduling is reducing the peak-valley load difference of the microgrid calculated by Eq. (7). And the objective of the scheduling plan can be expressed as:

$$\min\left(P_{T-c}^{\max} - P_{T-c}^{\min}\right) \tag{8}$$

2.6.2 Constraint for emergent charging EVs

If the $i\text{-}th$ EV is judged as emergent EV, we define that $x_{i,j}$ is equal to 1 in every connection time slots to assure that the EV can be charged from connected time to disconnected time. And $x_{i,j}$ equal to 0 when the EV disconnected into the microgrid. The constraint that emergent charging EVs should meet can be expressed as:

$$x_{i,j} = \begin{cases} 1, & \textit{if } j = J_i^c, \ldots, J_i^{dis} \\ 0, & \textit{if others} \end{cases} \tag{9}$$

2.6.3 Constraints for usual charging EVs

At first, for usual charging EVs, charging power need for each EV owner should be satisfied while the EV disconnected to the microgrid. Due to the diversity of charging demand for EV owners, and each EV has minimum demand of SOC and maximum demand of SOC. If $i\text{-}th$ EV is usual EV, we ensure the EV lower SOC must be satisfied at the time slot that EV disconnected to the microgrid.

$$SOC_i^{\min} \le SOC_i^{dis} \le SOC_i^{\max} \tag{10}$$

$$SOC_i^{dis} = SOC_i^{con} + \frac{\sum_{j=J_i^c}^{J_i^{dis}} (\Delta T \cdot P_{EV} \cdot x_{i,j} \cdot \eta_{EV})}{Cap_{EV}^{Bat}} \tag{11}$$

where $x_{i,j}$ includes the all usual charging EVs. The $\sum_{j=J_i^c}^{J_i^{dis}} (\Delta T \cdot P_{EV} \cdot x_{i,j} \cdot \eta_{EV})$ represents the power usual EV charged from the microgrid during the connection periods for $i\text{-}th$ EV.

The second constraint for usual charging EVs is related to the control time. Because of the randomness of the EV charging, the connection time and disconnection time to the microgrid are quite different for the EVs. And we can schedule the charging behavior only in the period that the EV connected in the microgrid, and control time constraint represent that when the usual EV is not connected to the microgrid, the charging state $x_{i,j}$ must be equal to 0, $x_{i,j} = 0$ ($i = 1, 2, \ldots, N$, $j = 1, 2, \ldots, J_i^c - 1, J_i^{dis} + 1, \ldots, 96$). Because when the EV disconnected into the microgrid, the scheduling plan cannot be executed then the EV cannot be charged.

2.6.4 Constraint for microgrid

For avoiding the new charging peak load of the microgrid in the coordinated plan, a constraint for microgrid shown in Eq. (12) should be added to restrict the increase of the peak value [16].

$$P_{T-c}^{j} \le P_{T-uc(\max \mathrm{SOC})}^{\max} \tag{12}$$

And such limitation can restrict the peak value of new coordinated total load is lower than the peak value of uncoordinated total load of the microgrid, reducing the load pressure in the rush time and making the microgrid operation safer.

3. PREPARATION OF INPUT DATA

The experiment has been designed to test the effect of peak shaving and valley filling of the optimization model. In solving method aspect, we build environment in MATLAB and use YALMIP and CPLEX software at the same time during the experiment. The model is written with YALMIP language in MATLAB workspace. And the CPLEX solver has been used to solve the optimization model. In data respect, the input data is generated randomly according to probability density function to simulate the real EV charging situations. Nevertheless, some assumptions have to be established for simplicity. Firstly, we select 100 EVs for comparative experiments. And in the simulation, the data can be generated on the basis of the people charging habits desperately as follow:

In EV charging, the EV owners are accustomed to start charging when arriving home after work and end up charging when they get ready to go work. The EV connection time t_c and disconnection time t_{dis} follow normal distribution. Then the probability distribution can be given by Eq. (13) and Eq. (14). And the next step is to generate the stochastic EV connection time and disconnection time according to probability distribution.

$$f(t_c)=\begin{cases}\dfrac{1}{\sqrt{2\pi}\sigma_{t_c}}\exp\left(-\dfrac{\left(t_c+24-\mu_{t_c}\right)^2}{2\sigma_{t_c}{}^2}\right) & 0<t_c\le\mu_{t_c}-12\\ \dfrac{1}{\sqrt{2\pi}\sigma_{t_c}}\exp\left(-\dfrac{\left(t_c-\mu_{t_c}\right)^2}{2\sigma_{t_c}{}^2}\right) & \mu_{t_c}-12<t_c\le 24\end{cases} \tag{13}$$

$$f(t_{dis})=\begin{cases}\dfrac{1}{\sqrt{2\pi}\sigma_{t_{dis}}}\exp\left(-\dfrac{\left(t_{dis}-\mu_{t_{dis}}\right)^2}{2\sigma_{t_{dis}}{}^2}\right) & 0<t_{dis}\le\mu_{t_{dis}}+12\\ \dfrac{1}{\sqrt{2\pi}\sigma_{t_{dis}}}\exp\left(-\dfrac{\left(t_{dis}-24-\mu_{t_{dis}}\right)^2}{2\sigma_{t_{dis}}{}^2}\right) & \mu_{t_{dis}}+12<t_{dis}\le 24\end{cases} \tag{14}$$

where $\mu_{t_c}=18$, $\sigma_{t_c}=3.3$, $\mu_{t_{dis}}=8$, $\sigma_{t_{dis}}=3.24$ [10].

The next step is generating some parameters related to SOC generated randomly. In this experiment, the uniform distribution is adopted to simulate the scenarios of SOC when EV connected to the microgrid, the upper and lower SOC demand. We assumed that the SOC when EVs connected into microgrid follows the continuous uniform distribution between 0.1 and 0.3. Furthermore, the lower SOC demand of EVs is given by a uniform distribution between 0.4 and 0.6, and the upper SOC demand of EVs is given by a uniform distribution between 0.8 and 1.0 by fitting to the existing data [15-17]. Otherwise, some parameters for all EVs are identical, the capacity of battery. The charging power of EVs is settled as 3.5 kW, the fast charging power for emergent charging EVs is 10 kW, and the charging efficiency is defined as 0.9. Besides, the capacity of the onboard battery (in kWh) is set as 30kWh [15].

Finally, the conventional power data has been simulated according to the pattern of electricity use [16]. Fig.1 illustrates the conventional power load profile of the regional microgrid in a day-cycle. The peak hours occur at around 6h, 10h, and 18h. The highest load is 710.62 kW, the lowest load is 445.69 kW, the peak-valley load difference is about 265 kW. The load fluctuation in one-day period is fierce, which is going against the stable operation of the microgrid definitely.

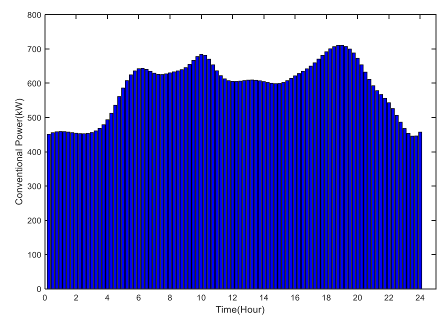

Fig 1 Conventional load profile in one-day cycle.

4. RESULTS

In the experiment, the one-day cycle contained by two half-days is chosen. For presenting the whole scheduling process of the EV charging, the 12h of one day to the 12h of the next day is chosen as the experiment time period, and 15 min defined as one time-slot that divide one-day cycle as 96 parts equally. At the same time, the conventional load should be modified according to the adjustment of the charging time periods.

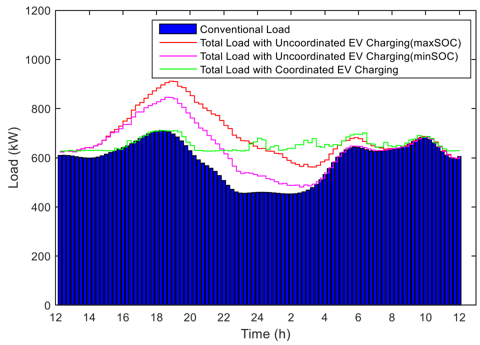

Fig 2 Simulation results with uncoordinated charging and proposed coordinated charging methods in EV charging.

Table 1

Comparison results of three profiles in EV charging.

Peak value (kW)	UC (max SOC)	911.3520
	UC (min SOC)	846.1500
	C	710.9073
Valley value (kW)	UC (max SOC)	562.4223
	UC (min SOC)	480.9941
	C	626.9265
Range (kW)	UC (max SOC)	348.9297
	UC (min SOC)	365.1559
	C	83.9808
Variance	CON	6,588.8
	UC (max SOC)	8,967.7
	UC (min SOC)	9,628.4
	C	690.5747

UC (max SOC) means EV charging scheduling situation with uncoordinated EV charging scheduling method that satisfies the maximum demand of SOC. UC (min SOC) dedicates EV charging scheduling situation with uncoordinated EV charging scheduling method that satisfies the minimum demand of SOC. C is EV charging scheduling situation with coordinated EV charging scheduling method. CON denotes typical conventional power load in one-day cycle.

The simulation results of EV optimal charging scheduling with three different charging methods in EV charging have been shown in Fig.2, in which three different charging scheduling strategies are employed. And for such uncoordinated charging scheduling plans, the EV be charged once the EV connected into the microgrid. The EV stops charging when occurring to two cases: the disconnection time is finished, and the SOC demand of EV owner is satisfied. Because both min SOC and max SOC have been considered in this model, the two kinds of charging SOC should be considered in uncoordinated charging scheduling methods.

In this simplified model, the connection time and disconnection time, the EV's maximum and minimum of the SOC demand and the SOC when EV connected into microgrid are generated randomly according to the Monte Carlo. The uncoordinated scheduling plans cannot distinguish the emergent charging EVs and usual charging EVs, so it ensures all EVs stay charging state until the minimum or maximum of SOC demand satisfied during the time periods that EV connected to microgrid. But parts of EV charging time is too short and the charging power is settled, so the uncoordinated charging strategies cannot ensure minimum SOC demand of EVs can be satisfied in such emergent situation. But in the coordinated charging scheduling strategy, the emergent demand EVs can be separated from all EVs according to the CEI, and then employ emergent scheduling plan. So the emergent charging situation can be handled when adopt coordinated charging scheduling method.

As Table 1 shown, compared to the two uncoordinated charging plans, the coordinated charging scheduling plan can reduce peak value, range and variance of total load, making the total load profile of the microgrid gentler. Table 1 shows that the peak value of uncoordinated charging methods and coordinated charging method are equal to 911.532 kW, 846.15 kW and 710.9073 kW. The coordinated charging scheduling method can reduce the total load of uncoordinated charging methods by 21.99% and 15.98% respectively.

At same time, the total load range of uncoordinated charging methods (max SOC and min SOC) and coordinated charging method are 348.9297 kW, 365.1559 kW and 83.9808 kW. The coordinated charging scheduling method can reduce the total load of uncoordinated methods by 75.93% and 77%. Besides, the coordinated charging scheduling method can reduce the variance of total load that apply uncoordinated charging methods (max SOC and min SOC) by 92.30% and 92.83% respectively.

Apparently, the proposed coordinated charging scheduling method has a significant superiority over the uncoordinated charging method in the regard of relieving the peak load pressure in the microgrid operation, while this superiority of such proposed coordinated method can satisfy emergency charging demand.

5. CONCLUSION

Considering the emergent charging demand of the different EVs and to relieve the load fluctuation, a coordinated charging optimization model is proposed to optimal EV charging scheduling. And EV CEI is defined to reflect the emergency of the EV charging demand. According to the indicator, all EVs are divided into emergent charging EVs that have emergent charging demand and usual charging EVs. Two group constraints are applied to emergent charging EVs and usual charging EVs respectively. And then optimization model is built up with an additional constraint for microgrid. In the experiment, simulation results have shown that the proposed model is more efficient than uncoordinated charging method in terms of achieving peak-shaving and valley-filling of microgrid.

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