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

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<th>Abbreviations</th>
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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., \( T =15 \text{min} \). And the time slot of each EV’s connection time and disconnection time to the microgrid are calculated respectively by:

\[
J_i = \left\lceil \frac{t_i^c}{\Delta T} \right\rceil \quad (1)
\]

\[
J_i^{\text{dis}} = \left\lfloor \frac{t_i^{\text{dis}}}{\Delta T} \right\rfloor , \quad i = 1, 2, \ldots, N \quad (2)
\]

where \( \left\lceil \frac{t_i^c}{\Delta T} \right\rceil \) is the next integer larger than the results of division operation. \( \left\lfloor \frac{t_i^{\text{dis}}}{\Delta T} \right\rfloor \) 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 \( J_i^{\text{dis}} \) calculated above, the whole time slot that the EV connected into the microgrid \( T_i^{\text{conn}} \) can be calculated by:

\[
T_i^{\text{conn}} = J_i^{\text{dis}} - J_i^c \quad (3)
\]

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}^{\text{con}} - T)P_{EV} \cdot \eta_{EV} - (SOC_{i}^{\text{min}} - SOC_{i}^{\text{con}}) \cdot Cap_{EV}^{bat} 
\quad (i = 1, 2, \ldots, N; \ j = 1, 2, \ldots, 96) 

While CEI_i < 0, indicates that the charging demand of i-th EV is emergent. CEI_i > 0 means that the charging demand i-th EV is not emergent. In the basis of the CEI_i, all EVs are divided into emergent charging 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}^{\text{fast}}. And the rest of usual charging EVs are arranged usual charging with usual charging power P_{EV}^{\text{usual}}.

\[ P_{EV} = \begin{cases} P_{EV}^{\text{fast}}, & \text{emergent charging EVs} \\ P_{EV}^{\text{usual}}, & \text{usual charging EVs} \end{cases} \]  
\( (5) \)

### 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-th EV in the j-th time slot. And the x_{i,j} is 0 or 1, x_{i,j} = 0 indicates the i-th EV in the j-th time slot is not charging. x_{i,j} = 1 means the i-th EV in the j-th time slot is in charging state as shown in Eq. (6).

\[ x_{i,j} = \begin{cases} 1, & \text{charging state} \\ 0, & \text{not charging state} \end{cases} \]  
\( (6) \)

### 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:

\[ P_{T-c} = P_{con} + \sum_{i=1}^{N} x_{i,j} \cdot P_{EV} \]  
\( (7) \)

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

\[ \min \left( P_{T-c}^{\text{max}} - P_{T-c}^{\text{min}} \right) \]  
\( (8) \)

#### 2.6.2 Constraint for emergent charging EVs

If the i-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:

\[ x_{i,j} = \begin{cases} 1, & \text{if } j = J_{i}^{c}, \ldots, J_{i}^{dis} \\ 0, & \text{if others} \end{cases} \]  
\( (9) \)

#### 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-th EV is usual EV, we ensure the EV lower SOC must be satisfied at the time slot that EV disconnected to the microgrid.

\[ SOC_{i}^{\text{min}} \leq SOC_{i}^{\text{dis}} \leq SOC_{i}^{\text{max}} \]  
\( (10) \)

\[ SOC_{i}^{\text{dis}} = SOC_{i}^{\text{con}} + \frac{\sum_{j=1}^{J_{i}^{dis}} (\eta_{EV} \cdot P_{EV} \cdot x_{i,j})}{Cap_{EV}^{bat}} \]  
\( (11) \)

where x_{i,j} includes the all usual charging EVs. The \( \sum_{j=1}^{J_{i}^{dis}} (\eta_{EV} \cdot P_{EV} \cdot x_{i,j}) \) represents the power usual EV charged from the microgrid during the connection periods for i-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].

\[ P_{T}^1 \leq P_{I}^{\text{max}} \cdot \text{max(SOC)} \] (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.

\[
f(t_c) = \begin{cases} 
\frac{1}{\sqrt{2\pi}\sigma_{t_c}} \exp \left( -\frac{(t_c + 24 - \mu_{t_c})^2}{2\sigma_{t_c}^2} \right) & 0 < t_c \leq \mu_{t_c} - 12 \\
\frac{1}{\sqrt{2\pi}\sigma_{t_c}} \exp \left( -\frac{(t_c - \mu_{t_c})^2}{2\sigma_{t_c}^2} \right) & \mu_{t_c} - 12 < t_c \leq 24 
\end{cases}
\] (13)

\[
f(t_{dis}) = \begin{cases} 
\frac{1}{\sqrt{2\pi}\sigma_{t_{dis}}} \exp \left( -\frac{(t_{dis} - \mu_{t_{dis}})^2}{2\sigma_{t_{dis}}^2} \right) & 0 < t_{dis} \leq \mu_{t_{dis}} + 12 \\
\frac{1}{\sqrt{2\pi}\sigma_{t_{dis}}} \exp \left( -\frac{(t_{dis} + 24 - \mu_{t_{dis}})^2}{2\sigma_{t_{dis}}^2} \right) & \mu_{t_{dis}} + 12 < t_{dis} \leq 24 
\end{cases}
\] (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.](image)

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.
Table 1 Comparison results of three profiles in EV charging.

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<th>UC (max SOC)</th>
<th>UC (min SOC)</th>
<th>C</th>
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<tr>
<td>Peak value (kW)</td>
<td>911.3520</td>
<td>846.1500</td>
<td>710.9073</td>
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<tr>
<td>Valley value (kW)</td>
<td>562.4223</td>
<td>480.9941</td>
<td>626.9265</td>
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<tr>
<td>Range (kW)</td>
<td>348.9297</td>
<td>365.1559</td>
<td>83.9808</td>
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<td>Variance</td>
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<td>6,588.8</td>
<td>8,967.7</td>
<td>9,628.4</td>
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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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REFERENCES