Phases-Controlled Coordinated Charging Method for Electric Vehicles

Chenglin Liao, Bing Yang

Abstract—When private electric vehicles (EVs), which will be the main part of the EVs’ cluster in the future, are plugged in power system by single phase power line, can result to three-phase unbalance problem of distribution network. In this work, a phases-controlled coordinated charging method was put forward to solve this problem. Firstly, the impacts of charging load to distribution network was analyzed based on the equivalent circuit; and then an architecture of the control method and its corresponding optimal control model were introduced. The optimal model is a multi-objective optimization model, which includes minimizing load variance of each phase and minimizing the power asymmetrical degree of three-phase load; lastly, three scenarios considering balance and unbalance cases were envisioned to verify the reasonableness of this control method based on IEEE-37 distribution network. Results show that the phases-controlled coordinated charging method can minimize the load variance as well as the negative sequence current.

Index Terms—Electric Vehicles (EVs), load variance, negative sequence current Percentage, power asymmetrical degree.

I. INTRODUCTION

DEPLETION of fossil energy, impacts of global warming and haze weather to human life have result in an increasing popularity for electric vehicles (EVs) in many countries over the last few years. With the advantages of low energy consumption and zero emissions, EVs will certainly be applied in large scale in the near future. However, the large-scale applied EVs must result in a large power energy demand [1-3], and then lead to non-ignored effects to power system [4]. So, it is necessary to research the influence of charging EVs to power system and its corresponding solving methods before large-scale EVs being applied.

Recent studies about the impacts of charging EVs might to power system under uncoordinated conditions can be summarized as the following aspects [5-9]: increased system peak load, losses and voltage deviation; harmonic pollution result from EVs’ charger; three-phase voltage unbalance problem and so forth. In literature [8], the unbalance current in distribution system result from charging EVs was researched under the assumption that charging EVs accessed to power system uniformly, the results show that charging EVs might lead to unbalance current and with the increase of charging EVs’ number the percentage of unbalance current decreased. In literature [9] the voltage unbalance problem resulted in different EVs penetration connected to power system was studied taking a real distribution feeder in Dublin city as example, it is assumed that charging EVs were distributed in each phase, and the results show that the three-phase voltage unbalance can be caused even if the original load of each phase is nearly balance.

Coordinated charging models have been explored to mitigate the impacts caused by charging EVs [10-13]. The dominant ideology is to control EVs’ charging time and charging power to optimize the objective functions, which include load factor, load variance, load peak valley difference or feeder loss of power system, under the prerequisite that EVs’ charging demand must be fulfilled. Minimizing feeder losses and load variance were respectively as the objective function in [10] and [11] to regulate EVs’ charging taking the acceptance capacity, voltage of the load bus as constraint conditions. In [12], the relationship among the coordinated charging methods, which include minimizing losses, minimizing load variance, and maximizing the load factor, were investigated and the results show that the three methods are equivalent under a certain condition. A coordinated charging model based on time sequence was proposed in [13] to modify EVs’ total charging demand by scheduling EV charging times and it can be used to real-time charging system. The off-peak charging method is proposed in [14] to realize the optimal charging taking EVs’ received power energy as objective function and EVs’ charging power as control variable, meanwhile considering the constraints that charging power limit, voltage limit and thermal limit of power transformer. In [15], a coordinated charging method considered three-phase load balance is put forward to control charging power and power system loss. In [16] a real-time control method is discussed to optimize three-phase power via controlling EVs charging sequence. But both methods in [15] and [16] are hard to realize.

In the near future, private EVs as the mainly constituent part of EVs cluster will access to power grid via single phase power line, which might result to unbalance operation of distribution network; and the problem has really occurred in a normal EVs’ operation community, where the original power load in each phase is almost symmetrical. Nevertheless, how to reduce or eliminate the three-phase unbalance problem caused by charging EVs has not been discussed in the existed coordinated charging control methods, so it is necessary to explore the
corresponding solution.
In view of the deficiencies in the existed studies, the three-phase unbalance problem was investigated theoretically in Section II of this work; and a phase-controlled coordinated charging control method was proposed to solve the three-phase unbalance problem in Section III; Section IV described the test network, EVs’ accessed modes and the calculation of charging demand. Results and discussion for the superiority of the phase-controlled method were presented in Section V; and conclusions were presented in Section VI.

II. THEORETICAL ANALYSIS OF CHARGING LOAD TO THREE PHASES UNBALANCE

The three-phase unbalance degree of distribution network can be interpreted with the negative sequence current percentage (NSP), which can be calculated by the equation (1) [17]. So, the three-phase unbalance impact of the charging EVs to distribution network can also be described by NSP.

\[
NSP = \frac{NSC}{PSC} \times 100\%
\]

(1)
Where, NSC and PSC represent negative sequence current and positive sequence current, respectively.

According to the conductive interface standard of electric vehicle, private EVs can plug in distribution network via single-phase line. So the three-phase unbalances problem might be induced if EVs’ number or plug-in time is different. Here, the three-phase unbalance problem of distribution network caused by charging EVs is analyzed by the equivalent circuit as shown in Fig.1. Where, \(Z_{11}, Z_{12}, Z_{13}\) describe the equivalent impedance of the original load of the distribution network; and \(Z_{21}, Z_{22}, Z_{23}\) represent the load impedance caused by charging EVs.

\[I_{a}\]
\[I_{b}\]
\[I_{c}\]
\[u_{a}\]
\[u_{b}\]
\[u_{c}\]
\[i_{a}\]
\[i_{b}\]
\[i_{c}\]
\[Z_{11}\]
\[Z_{12}\]
\[Z_{13}\]
\[Z_{21}\]
\[Z_{22}\]
\[Z_{23}\]
Fig.1. Three-phase four line equivalent circuit of distribution network.

According to equivalent circuit in Fig.1, the currents in each phase can be calculated by equation (2) as follow [17].

\[
\begin{align*}
I_a &= \frac{\bar{U}_a}{Z_1 + Z_{11} + Z_{21}} \quad I_b &= \frac{\bar{U}_b}{Z_1 + Z_{12} + Z_{22}} \quad I_c &= \frac{\bar{U}_c}{Z_1 + Z_{13} + Z_{23}} \\
I_{a1} &= \frac{1}{3} (I_a + I_b + I_c) \\
I_{a2} &= \frac{1}{3} (\alpha \cdot I_a + \alpha^2 \cdot I_b + \alpha \cdot I_c) \\
I_{a0} &= \frac{1}{3} (\bar{U}_a + \bar{U}_b + \bar{U}_c)
\end{align*}
\]

(2)
Where, \(I_a, I_b, I_c\) mean the effective current of \(a, b, c\) phase; \(\bar{U}_a, \bar{U}_b, \bar{U}_c\) express the effective value of three-phase symmetrical alternating current power source; and \(Z_1\) represents equivalent impedance of power line.

Assume that the original distribution load is three-phase symmetrical, that is \(Z_{11}=Z_{12}=Z_{13}=Z\); the charging EVs’ load impedance are respectively \(Z_{21}, Z_{22}, Z_{23}\); if the number or time of EVs plug in each phase is different, which means \(Z_{22} \neq Z_{22} \neq Z_{23}\) can be caused, and then the unbalance current can be induced, namely negative sequence current (NSC) and zero sequence current (ZSC) can be raised in the distribution power line. The following is the derivation of the positive, negative and zero sequence current in phase \(a\).

\[
\begin{align*}
I_{a1} &= \frac{1}{3} \left( \bar{U}_a + \frac{1}{Z_{11}} \bar{U}_a + \frac{1}{Z_{21}} \bar{U}_a \right) \\
I_{a2} &= \frac{1}{3} \left( \alpha \cdot \bar{U}_a + \alpha^2 \cdot \bar{U}_b + \alpha \cdot \bar{U}_c \right) \\
I_{a0} &= \frac{1}{3} \left( \bar{U}_a + \bar{U}_b + \bar{U}_c \right)
\end{align*}
\]

(3)
Similarly, the follow equations can be derived:

\[
\begin{align*}
\bar{I}_{a2} &= \frac{1}{3} \left( \bar{U}_a + \frac{1}{Z_{12}} \bar{U}_a + \frac{1}{Z_{22}} \bar{U}_a \right) \\
\bar{I}_{a0} &= \frac{1}{3} \left( \bar{U}_a + \bar{U}_b + \bar{U}_c \right)
\end{align*}
\]

(4)
Where, \(I_{a1}, I_{a2}, I_{a0}\) represent positive, negative and zero sequence current in phase \(a\), respectively; \(\alpha=e^{j120°}\), and the \(Z_1\) is neglected because it is far less than the load impedance.

Seen from equations (5) and (6), if \(Z_{12}=Z_{22}=Z_{23}\), the NSC and ZSC will equal to zero; if \(Z_{12} \neq Z_{22} \neq Z_{23}\), the NSC and ZSC will not equal to zero, and the more obvious different among \(Z_{12}, Z_{22}\) and \(Z_{23}\), the greater NSC and ZSC will be.

If the original distribution load is asymmetrical, the NSC and ZSC in phase \(a\) can be calculated by equations (7) and (8). Seen from the equations, the result can be got if the charging load can be regulated to \((1/Z_{11}+1/Z_{12})=(1/Z_{21}+1/Z_{22})=(1/Z_{21}+1/Z_{23})\), and the NSC and ZSC can be decreased in EVs’ charging duration.

\[
\begin{align*}
\bar{I}_{a2} &= \frac{1}{3} \bar{U}_a + \frac{1}{Z_{12}} \bar{U}_a + \frac{1}{Z_{22}} \bar{U}_a \\
\bar{I}_{a0} &= \frac{1}{3} \bar{U}_a + \frac{1}{Z_{12}} \bar{U}_a + \frac{1}{Z_{22}} \bar{U}_a
\end{align*}
\]

(7)
\[
\begin{align*}
\bar{I}_{a2} &= \frac{1}{3} \bar{U}_a + \frac{1}{Z_{12}} \bar{U}_a + \frac{1}{Z_{22}} \bar{U}_a \\
\bar{I}_{a0} &= \frac{1}{3} \bar{U}_a + \frac{1}{Z_{12}} \bar{U}_a + \frac{1}{Z_{22}} \bar{U}_a
\end{align*}
\]

(8)
III. METHODOLOGY OF COORDINATED CHARGING CONTROL
A. Architecture of coordinated charging model
Based on the analysis in above section, three-phase unbalance problem might be caused by the charging EVs accessed by single-phase power line; meanwhile the load peak valley difference of distribution network can also be increased [8]- [10]. So a phase-controlled coordinated charging method for large-scale charging EVs was put forward, and its basic
architecture as shown in Fig.2. The basic power load of each phase, the plug-in and pull-off time, charging energy demand of EVs are firstly obtained by EVs’ regulation center(ERC), and then the charging start time plan are formulated to reduce the effects caused by charging EVs’ under the condition that EVs’ charging energy demand can be guaranteed.

![Diagram of phase-controlled coordinated charging model for large-scale electric vehicles.](image)

**Fig.2.** Diagram of the phase-controlled coordinated charging model for large-scale electric vehicles.

It must be accurate to each EV when the coordinated charging control strategy is carried out. So it is necessary to get each EV’s detail plug-in time and the charging energy demand. For the i-th charging EV, the coordinated charging steps can be interpreted by Fig.3. When the EV-i plugs-in distribution network, the first step is to interact its charging demand, which include charging time and charging energy demand with ERC; and then the local charging controller upload its charging demand to ERC; optimal charging scheme for EV-i is then worked out by ERC according to the forecasted power load and the plugged EVs’ charging plan and be returned to the local charging controller; and last local charging controller implement the charging plan.

![Schematic diagram of phase-controlled coordinated charging process for the i-th EV.](image)

**Fig.3.** Schematic diagram of phase-controlled coordinated charging process for the i-th EV.

### B. Objective function

The goal of the phase-controlled coordinated charging model is to minimize the load variance (LV) and minimize the NSP at the same time, so the optimization problem can be written as follows:

\[
\min \ LV(t_{c,i}) = 1 \frac{1}{T} \sum_{t=1}^{T} \left( [P_{ev,j}(t) + P_{ev,i}(t_{c,i}, t)] - P_{av,j} \right)^2 \tag{9}
\]

\[
\min \ NSP(t_{c,i}) = 1 \frac{1}{T} \sum_{t=1}^{T} PSC(t_{c,i}, t) \tag{10}
\]

Where, \( LV_j \) means the load variance of phase \( j, j=\alpha, \beta, \gamma \); \( t_{c,i} \) represents the charging start time of the \( i \)-th EV connected to phase \( j \); \( T \) is the regulation period, which was set as 96 in the following simulation; \( P_{ev,j} \) means the whole power load of phase \( j \) at time \( t \) taking into account the original load and plugged EVs’ scheme charging load; \( P_{ev,i} \) expresses the \( i \)-th EV’s charging load of phase \( j \); \( P_{av,j} \) represents the average load of phase \( j \) and can be calculated by equations (11); \( NSP \) means the average NSP when the \( i \)-th EV’s charging start time is \( t_{c,i} \).

\[
P_{av,j} = \frac{1}{T} \sum_{t=1}^{T} [P_{ev,j}(t) + P_{ev,i}(t_{c,i}, t)] \tag{11}
\]

To search the minimum NSP, 96 times power flow must be performed in each optimal step and a long computing time must be wasted, it is hard to meet the real-time demand of the coordinated control. So, the objective function (10) can be rewrite as follow:

\[
\min \ LP(t_{c,i}) = \frac{1}{T} \sum_{t=1}^{T} \left[ P_{ev,j}(t) - P_{ev,j}^{}(t) \right]^2 \tag{12}
\]

Where , \( LP \) expresses the power asymmetrical degree of three-phase load, and the smaller \( LP \) is, the higher balance of the power system will be; \( P_{ev,j} \) means the total load value of phase \( j \) considering the basic load and EVs’ charging load; \( P_{ev,j} \) represents average value of three-phase load. The corresponding calculate equations are shown as equations (13).

\[
\begin{align*}
P_{ev,j}(t_{c,i}, t) &= P_{ev,j}(t_{c,i}, t) + P_{ev,i}(t_{c,i}, t) \\
P_{ev,j}(t_{c,i}, t) &= \frac{1}{3} \sum_{j=\alpha, \beta, \gamma} P_{ev,j}(t_{c,i}, t)
\end{align*} \tag{13}
\]

### C. Constraint conditions

The prerequisite of coordinated charging control is to satisfy EVs’ charging demand, namely the remaining charging time can absorb enough power energy to full charged EVs’ power battery. Therefore, the following equality constraints must be satisfied by the optimal calculation.

\[
\sum_{i=1}^{N} P_{ev,j}(t_{c,i}, t) = E_i \tag{14}
\]

\[
0 \leq t_{c,i} \leq t_{end,j} - t_{start,j} - t_{ev,j} \tag{15}
\]

Where, \( E_i \) represents charging energy demand of \( i \)-th EV; \( t_{end,j} \) and \( t_{start,j} \) express the \( i \)-th EVs’ driving end time and the next driving start time, respectively. In the operation of distribution network, the voltage of each bus must meet the requirements of power quality. Researches in [8] and [14] have found that three-phase voltage might be impacted by charging EVs, so the voltage constraint must be considered, as expression (16).

\[
V_{min} \leq V_{i} \leq V_{max} \tag{16}
\]

Where, \( V_i \) means the amplitude of voltage on bus \( i \); \( V_{max} \) and \( V_{min} \) represent the maximum and the minimum limits of bus.
voltage, and ±7% of the rated voltage is set as normal.

IV. TEST MODEL AND CALCULATION METHOD

A. Parameters of distribution network

In this paper, the IEEE-37 distribution system shown in Fig. 4 was used to analyze the impacts of EVs’ charging load to power system and to verify the control effect of the coordinated charging control method. The parameters of each power line, load value of each phase can be obtained from reference [18].

Balance and unbalance operating states of distribution network were considered. The maximum power load of each load bus for unbalance operation was set as the given value of the standard IEEE-37 distribution network, and for balance operation was set as the given value of phase a.

The daily base load profile starting at midnight for each load bus is based on what shown in Fig. 5 [19]. This is an hourly load profile. From this profile, two other profiles are generated by time shifting ±2h. Each load bus is then randomly assigned one of these three load profiles, and multiplies to the maximum load value for their base load. The curves shown in Fig. 6 and Fig. 7 are, respectively, total daily load profiles of distribution network operating at balance and unbalance states.

![Fig. 4. Single line diagram of IEEE37 distribution network.](image)

![Fig. 5. Idealized daily load curve of residential, which can available from literature.](image)

B. Access methods of EVs to distribution network

The number and position of EVs’ charging infrastructures in each phase are relevant to the users’ living location and construction method of distribution network. In this work, three construction methods for EVs’ charging infrastructures were considered: the first one is that charging facilities accessed to each load bus uniformly; the second one is to construct charging facilities in each load bus in proportion to the value of basic power load; and the third one is to decrease the three-phase unbalance degree by accessing more charging facilities in the phase where its basic load is small as far as possible.

![Fig. 6. Three phase daily load curve under balance operating condition.](image)

![Fig. 7. Three phase daily load curve under unbalance operating condition.](image)

Define the number of charging EVs as \( N_{ev} \), the bus number of the distribution network as \( N_{node} \), the maximum load in bus \( i \) as \( P_{node,i} \) (\( i=1,2...N_{node} \)), the peak load in phase \( j \) as \( P_{ph,j} \) (\( j=a, b, c \)) and the peak load of the total distribution network as \( P_{max} \). So, the number \( N_{ev,i} \) of EVs’ charging facilities in bus \( i \) under three methods can be calculated as follow. Where, the express \([g]\) means rounding up.

**Method one:**

\[
N_{ev,i} = \left[ \frac{N_{ev}}{N_{node}} \right] \quad (17)
\]

**Method two:**

\[
N_{ev,i} = \left[ \frac{N_{ev}}{P_{node,i}} \right] \quad (18)
\]

**Method three:** Assume that \( P_{ph,c} = \max \{ P_{ph,a}, P_{ph,b}, P_{ph,c} \} \), the rated charging power of the charging facilities is \( P_{c} \), so the acceptance number \( N_{c} \) by the load margin between phase a, phase b and phase c can be calculated as follow.

\[
N_{ch} = \left[ \frac{(P_{ph,c} - P_{ph,a}) + (P_{ph,c} - P_{ph,b})}{P_{c}} \right]
\]

If \( N_{ch} > N_{ev} \), there is no charging facilities accessed to phase c. the number of charging facilities accessed to phase a and b can be calculated in proportion, and set \( N' = 0 \); if \( N_{ch} \leq N_{ev} \),
If the total number of EVs is 300 and the rated charging power is 3.3kW, the number of the charging facilities accessed to each phase can be calculated according to the three methods shown in Table I.

### TABLE I

<table>
<thead>
<tr>
<th>NUMBER OF CHARGING FACILITIES ACCESSED TO THE PHASES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Access method</strong></td>
</tr>
<tr>
<td>Method 1</td>
</tr>
<tr>
<td>Method 2</td>
</tr>
<tr>
<td>Method 3</td>
</tr>
</tbody>
</table>

### C. Calculating method of EVs’ charging load

Because there is no large-scale private EVs operating in residential areas nowadays, EVs’ charging load demand and their charging time are not available, so it is assumed that the driving behavior of the drivers remain largely unaffected by electrification of their vehicles. To estimate the charging load by imitating EVs’ driving and charging behaviors according to the driving time and daily driving mileage of fuel vehicles and EVs’ charge and discharge property, five kinds of EVs were taken into account in the simulation. Parameters about driving and EVs are shown in Table II and Table III.

### TABLE II

<table>
<thead>
<tr>
<th>PARAMETERS OF THE USERS’ DRIVE HABITS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driving data</strong></td>
</tr>
<tr>
<td>Driving start time</td>
</tr>
<tr>
<td>Driving end time</td>
</tr>
<tr>
<td>Daily mileage</td>
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</table>

### TABLE III

<table>
<thead>
<tr>
<th>PARAMETERS OF FIVE KINDS CLASSICAL EVs</th>
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<tbody>
<tr>
<td><strong>EV type</strong></td>
</tr>
<tr>
<td>BJI-E150</td>
</tr>
<tr>
<td>Nissan Altra</td>
</tr>
<tr>
<td>Nissan Leaf</td>
</tr>
<tr>
<td>Foton-MIDI</td>
</tr>
<tr>
<td>BYD-6</td>
</tr>
</tbody>
</table>

The charging load for an arbitrary load bus can be calculated by the following steps.

**Step 1:** According to the probability distribution of fuel vehicles’ driving rules, a set of random number sequences, which include EVs’ daily driving mileage, charging start time, and charging end time limit were sampled using Monte Carlo simulation technology.

**Step 2:** EV’s driving simulation. The state of charge (SOC) of EVs’ power battery after driving can be calculated by equation (20).

\[
N^* = N_{ev} - N_{ch}; \text{ So, the number of charging facilities accessed to each phase can be computed by equation group (19)}.
\]

\[
N_{a-ev} = \left[ \frac{N_{ev} \cdot (P_{ph-c} - P_{ph-a}) + N^*}{(P_{ph-c} - P_{ph-a})} \right] + \left[ \frac{N_{ev} \cdot (P_{ph-c} - P_{ph-a}) + N^*}{3} \right]
\]

\[
N_{b-ev} = \left[ \frac{N_{ev} \cdot (P_{ph-c} - P_{ph-b}) + N^*}{(P_{ph-c} - P_{ph-b})} \right] + \left[ \frac{N_{ev} \cdot (P_{ph-c} - P_{ph-b}) + N^*}{3} \right]
\]

\[
N_{c-ev} = \left[ \frac{N_{ev} \cdot (P_{ph-c} - P_{ph-b}) + N^*}{3} \right]
\]  

Where, \(N_{ev}\) means the number of EVs, \(N_{ch}\) represents the number of plugged in EVs on bus \(N\), and \(N^*\) represents the number of EVs that are able to be charged.

**Step 3:** Calculating the charging energy demand and the charging time, which can be calculated by equation (21) and equation (22), respectively.

\[
E_i = [1 - SOC_i(t_{n-1})] \cdot C_i
\]

\[
t_{len} = E_i / c
\]

**Step 4:** Estimating EV’s charging and obtaining its charging power at every time. The \(t\)-th EV’s charging power can be expressed as equation (23), and the SOC can be renewed by equation (24). Generally, EV is charged by “constant current or constant voltage” method, however, the constant current charging time is overwhelm longer and the voltage between two electrodes of power battery changed slightly in the charging duration, so the charging property can be seen as constant power charging, approximately.

\[
p_i(t) = \begin{cases} 
C_{t_{en}} \leq t \leq t_{en+1} & \text{1, others} \\
0, & \text{otherwise}
\end{cases}
\]

\[
SoC_i(t_{n-1}) = SoC_i(t_{n-2}) + c \cdot t_{len} / C_i
\]

Where, \(p_i(t)\) means the charging power of \(i\)-th EV at time \(t\), \(t_{en}\) and \(t_{en+1}\) represent the charging start time and charging end time, respectively, and \(t_{len} = t_{en+1} - t_{en}\) if \(t_{en} \geq t_{end}, t_{en+1} \leq t_{end}\).

**Step 5:** Calculating the charging load by accumulating the total EVs’ charging power accessed on one certain load bus according to equation (25).

\[
P_{ev-j}(t) = \sum_{i=1}^{N_j} p_i(t)
\]

Where, \(P_{ev-j}\) means the active charging load on bus \(j\) at time \(t\), and \(N_j\) represents the number of plugged in EVs on bus \(j\).

The reactive charging power can be determined by the power factor of the charging facilities, so the reactive charging load can be calculated by equation (26).

\[
Q_{ev-j}(t) = P_{ev-j}(t) \frac{1 - \lambda^2}{\lambda^2}
\]

Where, \(Q_{ev-j}(t)\) means reactive charging load on node \(j\) at time \(t\), \(\lambda\) means the power factor of charging facilities, in this research \(\lambda\) was set as 1.

### D. Solution of the optimal model

There are many ways to solve the multi-objective optimal model. In this research, the widely used non-dominated sorting genetic algorithm II (NSGA-II) was selected to solve this optimization problem. The detail algorithm and its solving steps can be seen in [20], here, only the steps how to deal with the constraint conditions and objective function are discussed.

1) **Processing of control variable and constraint conditions**

Before solving the optimal model, the samples of the driving
data must be obtained at first, which can be sampled by the Monte Carlo simulation technology according to the statistical results in TABLE II, including EVs’ driving end time vector $T_{end}$, driving start time vector $T_{start}$ and the daily mileage vector $D$, and then to calculate the charging length vector $T_{len}$ by equations (20) (21) and (22). Based on these vectors mentioned above, the vector of charging start deadline $T_{dline}$ can be calculated by the equation as follow.

$$T_{dline} = T_{start} + 24 - T_{end} - T_{len}$$  (27)

In this work, it is assumed that the charging power is constant, so the charging energy constraint condition can be fulfilled if the charging time condition can be satisfied. Since the optimal equation (10) is replaced by (12), there is no need to calculate the three-phase power flow during the solution process; it is difficult to obtain the voltage on each load bus, so the constraint condition (16) is only taken as a standard to test the reasonableness of the optimal solution.

2) Processing of objective function

To achieve an optimal solution, three-phase load variance and its balance degree must be calculated in each iterative step of the optimal model. The calculation steps in each iteration for $i$-th EV as follows.

Step 1: Inputting its charging time information including $t_{start,i}$, $t_{end,i}$, and $t_{len,i}$.

Step 2: Simulating EV’s charging behavior, and computing plugged EVs’ charging load on each load bus and in each phase at every time when the $i$-th EV’s charging start time $t_i$ is equal to a certain value.

Step 3: To calculate the three-phase load variance $LV_{j}$, $j=a, b, c$; and the balance degree $LP$ of distribution network.

Step 4: Judging whether the calculated solution $(LV_j, LP)$ is a non-inferiority solution or not. If yes, output the calculation result; or return to step 2.

V. SIMULATION RESULTS AND DISCUSSION

A. Impacts of EVs’ different access methods to distribution network

In this work, three charging scenarios were constructed to study the influence of charging EVs’ to power grid and to verify the validity of the coordinated charging control method. The first one is to access EVs to symmetrical network by method 1 named case 1; the second and the third one is to access EVs to asymmetrical system by method 2 and 3, respectively, and named case 2 and 3. Then EVs’ charging simulations were implemented according to the driving data and EVs’ parameters under the assumption that EVs only be charged after the last driving. The charging load profiles were achieved by averaging 1000 times simulation results, as shown in Fig.8, of which the black curves express the basic load of each phase, and the red curves are load profiles added by EVs’ charging load demand. The data shown in Table IV is $LV$ and average NSP before and after EVs’ accessed in three scenarios.

It can be seen that the load peak valley difference was increased and the average NSP was influenced in every scenario, so the coordinated charging control must be carried out to mitigate the negative impacts; the impact of average NSP in case 1 is relatively small, in case 2 is badly, and in case 3 is positive, although the load various in case 2 and 3 is almost the same after charging EVs were accessed. So the best accessed method for EVs must be explored in asymmetrical distribution network.

Fig.8. Three phases load curves of distribution network before coordinated charging control. Where, black profiles mean the basic load curves, and red profiles represent load curves added EVs’ charging load.

<table>
<thead>
<tr>
<th>Table IV</th>
<th>AVERAGE NSP (%) AND LV IN EACH SCENARIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>NSP</td>
</tr>
<tr>
<td>Case 1 No EV</td>
<td>2.24</td>
</tr>
<tr>
<td>Case 1 With EV</td>
<td>2.27</td>
</tr>
<tr>
<td>Case 2 No EV</td>
<td>18.42</td>
</tr>
<tr>
<td>Case 2 With EV</td>
<td>18.86</td>
</tr>
<tr>
<td>Case 3 No EV</td>
<td>14.10</td>
</tr>
<tr>
<td>Case 3 With EV</td>
<td>14.32</td>
</tr>
</tbody>
</table>

B. Analysis of the solution for the multi-object optimal

Phase-controlled coordinated charging method is a multi-objective optimization problem. When an EV accessed to distribution network, non-inferiority solutions of charging start time are needed to be solved by ERC. In this section, the case 1 and 3 were taken as examples to demonstrate the solving process. What shown in Fig.9 is the non-inferiority solutions of one certain EV accessed to phase $a$ in these two scenarios. As can be seen from the graph, decisions for each EV’s charging start time are various, each one has its advantage to a certain
extent, and the most suitable one can be adopted in accordance with the demand of actual control. In this work, the adiaphorous solution was employed in each simulation.

Fig.8. Distribution of non-inferior solutions for coordinated charging control.

C. Coordinated charging control for balance system

The traditional coordinated charging method named coordinated 1 and the phase-controlled coordinated charging method named coordinated 2 were used to control the charging load in case 1, where the traditional coordinated charging method is the optimal model to minimize the total load variance of distribution network only, and the load profiles after control is shown in Fig.10. As can be seen from the graph, the total load curves of two control methods is nearly the same; three-phase load curves controlled by coordinated 2 are smoother and more balanced than controlled by coordinated 1.

Profiles shown in Fig.11 are the NSP at each period before and after coordinated charging, and the statistical histograms shown in Fig.12 are average NSP simulated by 1000 times. Comparative results show that, the phase-controlled coordinated charging method can decrease the unbalance degree for three-phase symmetrical network effectively, but cannot impact the whole load variance.

Fig.10. Load curves after coordinated charging control in case 1, of which (a) are the whole load curves, (b) is controlled by the traditional method and (c) is controlled by the phase-controlled method. Charging energy demand in each phase is, respectively, 0.045, 0.048 and 0.044 MWh.

Fig.11. The NSP in distribution network before and after coordinated charging control.

D. Coordinated charging control of unbalance system

In distribution network, the three-phase load is more likely at unbalance states due to unbalance load increased in one certain phase by people’s random life behavior. So the unbalance operating modes were considered such as case 2 and 3. Since it might aggravate the unbalance degree of the distribution
network and very hard to mitigate by case 2, it is seldom to put this scenario into effect. For the simulation of unbalance system, only case 3 was carried out.

Profiles given in Fig. 13 are controlled load curves in case 3. Similar to symmetrical system, a good three-phase balance effect can also be achieved by the phase-controlled method. However, the total load variance object is increased, as shown in Fig.13(c), the load variance are 0.1022 and 0.1087, 5.47% of the superiority is cut down.

Fig.13. Load curves after coordinated charging control in case 3, of which (a) is controlled by the traditional method, (b) is controlled by the phase-controlled method and (c) is the whole load curves. Charging energy demand in each phase is, respectively, 0.0557, 0.0836 and 0.0095MWh.

Fig. 14. NSP of different coordinated charging methods, of which (a) is access mode 2, and (b) is access mode 3. The first average value is 14.48, and the second value is 12.78.

Profiles in Fig.14 are NSP curves at different periods and the statistical histogram of average NSP after coordinated charging control by two methods, respectively. It can be seen that, coordinated 2 can mitigate NSC better. For the statistical data, the average NSP of coordinated 2 is 14.48%, but for coordinated 2 is 12.78%, 11.74% is decreased. So the validity of the method in this paper was further proved.

E. Study of the best access method

It can be found from the latest section that the two objects load variance and average NSP cannot be controlled to the most optimal at the same time for the reason that the charging energy demand connected to each phase is mismatch with the basic load. Here, a further explore was did to find a better match method under the assumption that the total number of charging EVs is still 300, that is $N_{a,c}+N_{b,c}+N_{c,c}=300$, and the basic load curves is shown in Fig.6.

After iteration calculating, the best arrange for the accessed number in abc-phase is 121, 141 and 38, under which the probability of load variance and average NPS can synchronously be reached to optimization. As shown in Fig.15 are the controlled load curves in one certain charging simulation; and the statistical histogram of average NSP by 1000 simulation is shown in Fig.16.

Fig. 14. Load curves of one certain coordinated charging imitating under the best access mode.
VI. CONCLUSION

The phase-controlled coordinated charging method and its corresponding optimal model were proposed in this work, based on the theoretical analysis of equivalent circuit of distribution network. Most three-phase coordinated charging methods for EVs were cumbersome, complex and hard to realize. The proposed phased-controlled coordinated charging method was simple and practical. We did not directly control the phase sequence, but control the nocturnal charging time of EVs on per phase according to the degree of unbalanced phases. The objective function of the coordinated model is composed of minimizing three-phase load variance and minimizing the asymmetrical degree. Taken the IEEE-37 distribution network as example, the charging load on different accessed modes were imitated, the impacts of charging load to distribution network were analyzed, and the phase-controlled coordinated method was verified. The results show that the phase-controlled coordinated charging method can inhibit or reduce the negative sequence current in distribution network. This research can be used as the theoretical basis for the construction of EVs’ charging facilities and the EVs’ charging operation.

REFERENCES


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