Research on Optimal Design of Plug-in Hybrid Electric Vehicle Charging Based on Smart Grid

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Abstract. Plug-in hybrid vehicle charging piles are an important part of the smart grid, and electric vehicles are also an important means of alleviating energy shortages and environmental degradation. This article analyzes the influencing factors from three factors that determine the charging power. Finally, the charging power, charging demand and charging time are determined one by one to model the charging load of the electric vehicle. For the working frequency range of different equivalent resistances, wireless charging PID controller, battery charging state analysis, the equivalent resistances of different stages of the battery are studied, and the transmission efficiency of wireless charging technology is optimized, so that the transmitting mutual inductance coil is opposite to the receiving coil The offset is minimized to maximize the charging efficiency and simulations are performed. Simulation results from the final wireless charging technology of the car show that the wireless charging technology has a better effect.

1. Introduction
With the gradual popularization of electric vehicles, especially plug-in hybrid electric vehicles (PHEVs) under the incentive policies of relevant countries, a certain market size has begun. It becomes more obvious [1]. Different from other electric vehicles, as the name suggests, PHEVs are both electric vehicles and ordinary fuel vehicles. At the same time, they need to be directly connected to the power grid through a dedicated charging pile (general electric vehicles may require a power adapter to indirectly connect to the power grid). It brings many challenges and opportunities to the power grid. The access of a large number of electric vehicles charging loads has increased the pressure during the peak load period of the distribution network. Establishing an electric vehicle charging load model to formulate measures to guide users to take orderly charging is of great significance to the optimal operation of the distribution network.

At present, most of the modelling of electric vehicle charging load does not distinguish the type of electric vehicle. Even if there is a distinction, the various influencing factors of the charging load are not fully considered in detail. This article starts with the influencing factors of electric vehicle charging load, explains in detail the modelling methods of different types of electric vehicles under different influencing factors, summarizes the charging behaviour characteristics of various types of electric vehicles, and establishes a charging load prediction model [2].
2. Charge and discharge control strategy
At the beginning of each time interval, the following three control rules are adopted in order to determine the controlled state of the electric vehicle, the charge and discharge state of the V2G service, and the size of the charge and discharge current.

Rule 1: Determine if pure electric private cars are controlled.
When electric vehicles are in an uncontrolled state, they cannot participate in charging and discharging services. The controlled signal CS is 1 to indicate that the car is controlled, and 0 to indicate that the car is not controlled. The driving state of the electric vehicle is determined according to the parking probability of the electric vehicle in each time period. If the electric vehicle is in the driving process, the electric vehicle is uncontrolled, and the electric vehicle is controlled when the electric vehicle is in the parked state.

Table 1. Time-of-use electricity price for charging and discharging of electric vehicles

| Time  | Charge Price (British) | Discharge Price (British) | Time  | Charge Price (British) | Discharge Price (British) |
|-------|------------------------|---------------------------|-------|------------------------|---------------------------|
| 7:30  | 0.173                  | 0.225                     | 19:30 | 0.191                  | 0.211                     |
| 8:00  | 0.173                  | 0.198                     | 20:00 | 0.19                    | 0.197                     |
| 8:30  | 0.173                  | 0.192                     | 20:30 | 0.189                  | 0.189                     |
| 9:00  | 0.173                  | 0.179                     | 21:00 | 0.185                  | 0.177                     |
| 9:30  | 0.173                  | 0.221                     | 21:30 | 0.18                    | 0.173                     |
| 10:00 | 0.174                  | 0.245                     | 22:00 | 0.179                  | 0.173                     |
| 10:30 | 0.174                  | 0.238                     | 22:30 | 0.176                  | 0.164                     |
| 11:00 | 0.174                  | 0.221                     | 23:00 | 0.17                    | 0.15                      |
| 11:30 | 0.18                   | 0.198                     | 23:30 | 0.169                  | 0.146                     |
| 12:00 | 0.183                  | 0.186                     | 0:00  | 0.169                  | 0.146                     |
| 12:30 | 0.17                   | 0.16                      | 0:30  | 0.174                  | 0.158                     |
| 13:00 | 0.182                  | 0.186                     | 1:00  | 0.173                  | 0.156                     |
| 13:30 | 0.176                  | 0.193                     | 1:30  | 0.174                  | 0.154                     |
| 14:00 | 0.176                  | 0.183                     | 2:00  | 0.174                  | 0.154                     |
| 14:30 | 0.176                  | 0.184                     | 2:30  | 0.174                  | 0.152                     |
| 15:00 | 0.17                   | 0.15                      | 3:00  | 0.173                  | 0.153                     |
| 15:30 | 0.169                  | 0.154                     | 3:30  | 0.172                  | 0.153                     |
| 16:00 | 0.169                  | 0.154                     | 4:00  | 0.172                  | 0.153                     |
| 16:30 | 0.17                   | 0.155                     | 4:30  | 0.171                  | 0.153                     |
| 17:00 | 0.17                   | 0.156                     | 5:00  | 0.171                  | 0.154                     |
| 17:30 | 0.171                  | 0.157                     | 5:30  | 0.171                  | 0.154                     |
| 18:00 | 0.189                  | 0.202                     | 6:00  | 0.171                  | 0.154                     |
| 18:30 | 0.191                  | 0.212                     | 6:30  | 0.174                  | 0.154                     |
| 19:00 | 0.191                  | 0.203                     | 7:00  | 0.169                  | 0.149                     |

3. System overall design description and technical index analysis
Firstly, the overall structure model of a large-scale air pollution remote alarm system is constructed. The air pollution alarm system uses a distributed control system (DCS) to implement remote control and alarm trigger design. ADSP-BF53 is selected as the ARM embedded microprocessor chip for the air pollution remote alarm system. The main control module is mainly composed of a processor, an integrated operational amplifier control module, a pollution information acquisition module, a data storage module and a bus driver module. The system uses ISA bus control technology for processor / memory connection, and has developed a VL bus specification for multi-channel Reuse bus design, using ARM Cortex-M0 processor core to realize the computer network development and design of large-scale air pollution remote alarm system, according to the overall design and development environment
description above, the overall design architecture of large-scale air pollution remote alarm system based on computer network is obtained. The system is shown in Figure 1 [3].

Rule 2: Determine the charging and discharging role \( R \) of the electric vehicle participating in the V2G service.

1) If the pure electric private car is controlled, if the state of charge of the power battery is greater than 0.75, it indicates that the power is sufficient and can be discharged to the grid as a distributed power source. \( R \) is -1 and \( i \) is less than 0 at this time;

2) If the state of charge of the electric battery is less than 0.5, it indicates that the battery is insufficient and can be charged by the power grid as a load. \( R \) is 1, and \( i \) is greater than 0 at this time;

3) When the state of charge is between the two, \( R \) is 2 and the charge and discharge state of the electric vehicle is determined by the next rule.

Rule 3: Determine the charge and discharge current.

The charge-discharge current of the electric vehicle is determined by the time-of-use electricity price in the V2G mode and the load characteristics of the urban grid. According to the charging current ratios set above 0.1C / 5 (2A), 0.5C / 5 (10A), 1.5C / 5 (30A), they are respectively expressed by \( I_L, I_M, I_H \); for electric vehicle owners, \( hcp \) represents the lower limit of the high charge price, and \( hdp \) represents the lower limit of the high charge price. The charge-discharge time-of-use electricity price adopted by the charge-discharge control strategy is shown in Table 1 [4]. The control flowchart is shown in Figure 1.

![Flowchart of charging control strategy for electric vehicle](image)

**Figure 1.** Flow chart of charging control strategy for electric vehicle.

During the day (7:30-23:00):

When \( R = 1 \), if \( cp < hcp \), then:

\[
  i(t) = \begin{cases} 
  I_M, & 7.5 \leq t < 15 \\
  I_H, & 15 \leq t < 23 \\
  I_M, & 15 \leq t < 17.5 
  \end{cases}
\]

When \( R = 1 \), if \( cp \geq hcp \), then:
\[ i(t) = I_L, 7.5 \leq t < 23 \]  

(2)

When \( R = -1 \), if \( dp > hdp \), then:

\[ i(t) = \begin{cases} 
0 & \text{, } 7.5 \leq t < 8.5 \\
-I_L, & 8.5 \leq t < 14 \\
-I_M, & 14 \leq t < 23 
\end{cases} \]  

(3)

When \( R = -1 \), if \( dp \leq hdp \), then:

\[ i(t) = \begin{cases} 
0 & ,7.5 \leq t < 11 \text{ or } 13 \leq t < 15 \\
-I_L, & 11 \leq t < 12.5 \text{ or } 15 \leq t < 23 
\end{cases} \]  

(4)

When \( R = 2 \), if \( dp \geq hdp \), then:

\[ i(t) = \begin{cases} 
0 & ,7.5 \leq t < 11 \\
-I_L, & 12.5 \leq t < 15 \text{ or } 18.5 \leq t < 20 \\
-I_M, & 11 \leq t < 13 \text{ or } 15 \leq t < 18.5 \text{ or } 20.5 \leq t < 23 
\end{cases} \]  

(5)

When \( R = 2 \), if \( dp < hdp \) and \( cp < hcp \), then:

\[ i(t) = \begin{cases} 
I_H, & 7.5 \leq t < 15 \text{ or } 17.5 \leq t < 23 \\
I_M, & 15 \leq t < 17.5 
\end{cases} \]  

(6)

When \( R = -1 \), if \( dp < hdp \) and \( cp > hcp \), then:

\[ i(t) = I_L, 7.5 \leq t < 23 \]  

(7)

During evening hours (23: 00-7: 30)

When \( \text{SoC} < 0.8 \) and \( CS = 1 \), then:

\[ i(t) = \begin{cases} 
I_L, & t < 2.5, 23 \leq t < 24 \\
I_M, & 2.5 \leq t < 6 
\end{cases} \]  

(8)

When \( 6 \leq t < 7.5 \), and \( CS = 1 \), then:

\[ i(t) = \begin{cases} 
I_M, & \text{SoC} > 0.68 \\
I_H, & \text{SoC} \leq 0.68 
\end{cases} \]  

(9)

4. Battery characteristics modelling

For a constant discharge current, the state of charge (SoC) of a battery according to its battery capacity can be obtained from the formula:

\[ s(t) = 1 - \frac{i_d t}{C_a} \]  

(10)
Where: \(i_d\) is the discharge current, A; \(C_a\) is the effective capacity, Ah; \(t\) is the time, h.

According to Peaker’s formula [5], the effective capacity \(C_a\) of the battery can be expressed as:

\[
C_a = \frac{(T)^{i+1}C_N}{(i_d)^{t+1}}
\]

(11)

Where: \(C_N\) is the rated capacity, Ah; \(T\) is the rated discharge duration (h); \(k\) is the Peukert index, the typical value is 1.1-1.3.

This article uses lead-acid batteries to model the characteristics of electric vehicle batteries. The Peukert index \(k\) of this type of battery is 1.2, the rated capacity is 100 Ah, and the rated discharge time is 5 h. When the discharge current is increased from 0.1C / 5 (5A) to 2C / 5 (40A), the effective capacity decreases from 158.5Ah to 87.1Ah. When this type of battery is connected to the grid for charging or participating in V2G services, the charging and discharging current is three discharge rates of 0.1C / 5 (2A), 0.5C / 5 (10A), and 1.5C / 5 (30A). The effective battery capacity is 158.5Ah, 114.87Ah, 92.21Ah.

### Table 2. Correspondence between power battery terminal voltage and discharge capacity

| Charge and discharge current (A) | Voltage (V) / Released Capacity (Ah) |
|---------------------------------|--------------------------------------|
| 2                               | 259.4/0 244.6/20 ... 237.5/60 ... 225.4/80 |
| 10                              | 258.9/0 244.2/20 ... 237/60 ... 224.9/80  |
| 30                              | 257.7/0 243/20 ... 235.8/20 ... 223.7/80 |

At a constant charge-discharge current rate \(i\), the relationship between the terminal voltage \(U\) of the battery and the discharged capacity \(C_i\) of the battery is shown in Table 1. According to the selected charge and discharge current \(i\), determine the effective capacity \(C_a\) of the battery, and then determine the battery release capacity \(C_i\) from the state of charge \(S\) at the beginning of the assumed time interval \(t\). By looking at Table 1 and linearizing the \(U\) and \(C\) at the beginning of the time interval can be obtained. Assuming that the terminal voltage of the power battery is constant within a specified time interval, \(i\) and \(U\) can be used to determine the charge and discharge power of the power battery during this time interval.

Since excessive charging and discharging will affect the service life of power batteries, the state of charge of batteries is generally maintained between 0.2-0.8. This article sets the upper limit value \(S_{\text{max}}\) of the state of charge to 0.8, and the lower limit of the state of charge \(S_{\text{min}}\) needs to be set so that the electric car has enough energy to complete the next journey. In the interval of \([S_{\text{max}}, S_{\text{min}}]\), the battery terminal voltage \(U\) of the private car and the released capacity \(C_i\) basically maintain a linear relationship, so the relationship between the two is expressed as follows:

\[
U = \begin{cases} 
307.1 - 3.125C_i, & i = \pm 2A \\
306.38 - 3.109C_i, & i = \pm 10A \\
305.18 - 3.109C_i, & i = \pm 30A 
\end{cases}
\]

(12)

### 5. Numerical simulation

#### 5.1. Mathematical Model of Electric Vehicle
This section will give detailed examples of some of the mainstream PHEVs on the market and their parameters, show the relationship between the type value and some of these parameters, and the
relationship between the user benefit function and the type value. In order to highlight the focus of the discussion, only one battery material, LiFeP04, is used in the simulation, which is also the most widely used lithium iron battery material in PHEVs.

![Charging power curves of different k values.](image1)

**Figure 2.** Charging power curves of different k values.

Battery pack tolerance degradation is not only related to the battery's chemical structure, but also to the actual temperature and impulse discharge depth of the battery pack. Due to the memory characteristics of lithium iron compounds, repeated charge and discharge will lead to battery pack tolerance degradation. The degree of degradation depends on the depth of charge and discharge and the use temperature.

![Modeling and analysis of electric vehicle batteries during charging and discharging.](image2)

**Figure 3.** Modeling and analysis of electric vehicle batteries during charging and discharging.
Here, a degradation coefficient is used to describe this relationship. The influence of the material also includes the characteristics of the LiFeP04 material itself. Considering that the temperature difference in an electric power jurisdiction is almost negligible and most PHEV manufacturers use LiFeP04 as the battery pack material, it is advisable to use a uniform degradation factor $\delta = -0.001$. It is also the chemical characteristics of the lithium iron battery. The battery pack has a certain energy loss during charge and discharge, such as the loss of thermal energy. According to the experimental results of the lithium iron battery, it generally meets $\eta \in [0.8, 0.9]$. According to the results of multiple linear regression, for a battery pack of LiFeP04 material, its linear regression coefficient $\alpha = 0.8$. The simulation diagram is shown in Figure 2.

![Figure 4](image.png)

**Figure 4.** Optimal contract design for each type of user under complete information.

5.2. **Optimal contract with complete information**

In this case, because the power sector fully knows the type value of the PHEV user, the power sector can provide targeted contracts, so IC conditions need not be considered here. At the same time, the power department also knows the specific number of users of each type.

![Figure 5](image.png)

**Figure 5.** Modeling and analysis of charge and discharge based on matlab.
It is assumed that the number of users $N_k$ of each type meets a certain condition (the expected value is 125). First, we give the relationship between the power sector benefits and the different types of user power distribution without considering the actual situation, that is, Figure 3. Obviously, if the user type value $\tau_k$ is less than the real-time market electricity price $p_r$, it will not bring any benefit to the power sector, otherwise, the benefit brought by the unit power depends on the size of the type value and the actual number of users.

6. Conclusion
This paper studies the coordination charging problem of plug-in hybrid vehicles in a distributed grid architecture. First, the charging coordination problem of electric vehicles is described as a convex optimization problem with multiple constraints. Based on this, this paper proposes a two-layer optimal charging strategy to solve the optimization problem. In the proposed optimal strategy, the upper layer uses a scheduling algorithm based on demand side management to solve, and based on this, the lower layer applies a consistent iterative optimization algorithm to solve. Finally, numerical simulations verify the effectiveness of the proposed algorithm. The proposed optimal charging strategy not only keeps the fluctuation of the power supply load curve of the power grid transformer to a minimum, but also achieves the minimum charging cost of each electric vehicle user, while meeting the user's charging needs. Future research directions will consider large-scale electric vehicle charging scenarios, that is, randomly connecting electric vehicles to the grid for charging according to user behaviours and habits, and the start and end times of user charging are different. The proposed optimal control strategy is combined with the rolling domain optimization method to solve it.

References
[1] J Gu, Y Yin, & J Zhu. Su-f-t-331: the effect of optimization grid size on helical tomotherapy for nasopharyngeal carcinoma. Medical Physics, 43(6) (2016) 3539-3539.
[2] Imran Rahman, Pandian M. Vasant, Balbir Singh Mahinder Singh, & M. Abdullah-Al-Wadud. On the performance of accelerated particle swarm optimization for charging plug-in hybrid electric vehicles. Alexandria Engineering Journal, 55(1) (2016) 419–426.
[3] Pedro J. Ramirez, Dimitrios Papadaskalopoulos, & Goran Strbac. Co-optimization of generation expansion planning and electric vehicles flexibility. IEEE Transactions on Smart Grid, 7(3) (2015)1-11.
[4] Mushfiqur R. Sarker, Daniel Julius Olsen, & Miguel A. Ortega-Vazquez. Co-optimization of distribution transformer aging and energy arbitrage using electric vehicles. IEEE Transactions on Smart Grid, 8(6) (2016)1-11.
[5] Deuster, P. A., O’Connor, F. G., Henry, K. A., Martindale, V. E., Talbot, L., & Jonas, W., et al. Human performance optimization: an evolving charge to the department of defense., 172(11) (2015)1133-7.
[6] Baseem Khan, & Pawan Singh. Selecting a meta-heuristic technique for smart micro-grid optimization problem: a comprehensive analysis. IEEE Access, 5(99) (2017) 13951-13977.