Electric Vehicles Charging Management Based on Flexible Load Aggregation

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Abstract. As the scale of electric vehicles grows year by year, disorderly charging of EVs brings great challenges to the safe operation of the power grid and charging management of EV charging service providers. The charging service providers play the role of EV aggregators and aggregate the flexible load of EVs through centralized scheduling strategy. Take profit of EV aggregators and variance of power grid as objectives. Based on the direct scheduling pattern, a multi-objective optimal scheduling model was established and solved by Genetic Algorithm (GA). The results show that under the centralized scheduling strategy of EV aggregators, the difference between peak and valley load of electric power system is reduced, the variance of the grid is lower, the benefits of the aggregator are increased and the EV charging costs are reduced.

Keywords: Electric Vehicles, Charging Load Aggregation, Centralized Scheduling Strategy

1. Introduction

New energy vehicles, especially electric vehicles (EVs), have been developed rapidly in recent years. According to statistics from the Ministry of Public Security, as of the end of 2019, the number of new energy vehicles in the country has reached 3.81 million, of which 3.1 million is the ownership number of pure EVs, accounting for 81.19% of the total number of new EVs. Currently, there are about 400,000 EVs in Beijing, Tianjin, and northern Hebei. With the growth rate of EVs ownership increasing year by year, large integration of EVs may bring significant challenges to the safe operation of power grid [1]. As a new comprehensive energy service, EVs charging scheduling service will dominate a large share of the market. The service provider is called EVs Load Aggregator [2]. Considering that electric taxis and private EVs have large randomness and occupy a high proportion in the number of EVs, this paper mainly takes electric taxis and private EVs as the main research objects.

In previous studies of scheduling EV charging behaviors, there are two typical research directions: one is to guide EV users to orderly charging through offering different charging tariffs for EV users, that is, price incentive strategy [3, 4, 5]. The other is to schedule the charging behavior of EVs through
direct dispatching by aggregators. A potential drawback of the price incentive strategy is that most EV users will choose to charge in the period with the lowest price, which may result in the second unanticipated peak. Moreover, there is a great deal of uncertainty in the behavior of EV users, so more consideration should be given to users’ responsive potential and credibility [2, 6, 7]. The direct scheduling strategy of the aggregators can effectively address this problem. Aggregators offer the scheduled EV users a lower price than normal in order to entice the users to transfer their rights of charging freely. This way can effectively reduce the peak and valley difference, increase the income of the aggregator and decrease costs of users. As for the direct scheduling strategy, studies have demonstrated that rational participation of large-scale EVs in power grid peak load regulation will bring huge benefits to both the grid and aggregators through the analysis of load characteristics, controllable capacity, optimal control strategy, and comprehensive benefits of EVs cluster [8]. Considering the charging schedule of a single EV, there are two modes have been proposed under direct dispatching of the aggregators: the automatic on-off charging mode and the smooth regulated charging mode. Both of these two orderly charging modes can improve the satisfaction of the power grid and EV users [9]. In addition, the charging agents are taken as the middleman. The superior-grid provides charging guidance curve according to daily load information. According to the guidance curve, the agents schedule the charging behaviors of its subordinate EV users, so that the charging load can meet the requirements of the power grid [10]. A fuzzy control algorithm is proposed to optimize the scheduling strategy of EVs charging to meet EVs charging demand and realize peak loads shaving of the grid. This method utilizes real-time data such as grid load state and EVs charging demand [11]. All of the above models are optimized by taking into consideration both of the reduction of peak and valley difference of the power grid and the minimum cost for EV users. However, cost and benefits of aggregators are often ignored.

An improvement on the EVs charging aggregation model is proposed in this paper by studying the cooperative relationship between the aggregators, EV users and the power grid. The improved model takes grid load variance and the benefits of the aggregator as objective functions, which not only realizes peak load cutting, but also ensures the interests of EV users and aggregators.

2. The Business Model of EVs Charging Load Aggregation

The participants of EVs charging load aggregation include the aggregators, EV users and the power grid. Aggregators offer EV users more favorable charging prices, attracting users to accept aggregators scheduling and optimize the EVs charging behaviors according to instructions given by the grid. The grid compensates the aggregators because the aggregators help to reduce the peak and trough of the grid by scheduling the charging of EVs. EV users can choose whether to sign an agreement with the aggregators when charging.

1) Do not accept aggregators’ scheduling, and charge freely with the normal charging prices.
2) Accept the aggregators’ scheduling. EV users join the aggregators’ schedule to charge at a lower price.

When the users who choose to accept the dispatching approach the charging piles for charging, their EVs’ information including the initial State of Charge (SOC), total battery capacity, departure time and expected SOC shall be uploaded through the APP or battery management system developed by the aggregators. Meanwhile, the power grid sends the demands of the time period and adjustable capacity which are obtained by daily load prediction to the aggregators. According to EVs charging information and the grid demand, the aggregators manage the EVs charging starting time through intelligent algorithm to dispatch the EVs charging behavior, transferring the charging load from the peak period to the valley period and reducing the peak and valley differences. The power grid compensates users and aggregators for their contributions.

In order to make users obey the agreement better, users who accept the dispatch and have a good history credit will be given some economic rewards, and others who violate the agreement will be punished to a certain extent.
3. The Optimization Model of EVs Charging Scheduling

Take the profits of EV aggregators and the load variance of power grid as objectives. Based on the direct scheduling pattern, a multi-objective optimal scheduling model was established and solved by Genetic Algorithm (GA).

(1) Minimize the load variance of grid

The greater load variance, the greater fluctuation of the grid and the greater the power loss. In order to mitigate the volatility result from the integration of EVs to the power system, the objective function with the minimum load variance is established from the consideration of the security of the power system.

\[
\min x = \frac{1}{24} \sum_{t=1}^{24} \frac{\left[ \left( \sum_{e} P_{e,t} + P_{e,t} \right)^2 \right]}{24}
\]

Where \(t\) denotes certain period of a typical day, a total of 24 periods; \(P_{e,t}\) is the charging power of EVs in time period \(t\) after participating in aggregation; \(P_{0,t}\) is other load power except EVs.

Since the total amount of EVs charging is fixed in a day, the part of formula (1),

\[
\left( \sum_{t=1}^{24} \left( P_{0,t} + P_{e,t} \right)^2 \right)
\]

is a fixed value. Therefore, the formula (1) can be simplified as:

\[
\min x = \sum_{t=1}^{24} \left( P_{0,t} + P_{e,t} \right)^2
\]

(2) Maximize the benefits of aggregators

\[
\max y = \sum_{i=1}^{24} \rho_{e,i} Q_{e,i} + \sum_{i=1}^{24} \rho_{f} Q_{f} - \frac{1}{3650} C \cdot \max \{m_i\} - \sum_{i=1}^{24} \rho_{f} Q_{e,i}
\]

\[
Q_{e,i} = \int_{t}^{24} P_{e,t} dt
\]

Where \(Q_{e,i}, Q_{f}\) are respectively the charging amount of EVs at time \(t\) after aggregation and the total Peak Load Regulation of Electric Power; \(\rho_{e,i}, \rho_{f}\) are respectively the charging price of scheduled EVs, the power purchase price of aggregators, and the compensation price of peak shaving service; The \(m_i\) is the number of EVs charged at time \(t\), and \(C\) is the single cost of charging pile.

Since the units of the two objective functions are different, it is necessary to dimensionless the objective functions.

\[
\min F = \alpha \frac{x}{x_0} + (1-\alpha) \frac{y_0}{y}, 0 < \alpha < 1
\]

Where \(x_0, y_0\) are respectively the grid load variance and the aggregators’ profit before aggregation, and \(\alpha\) is the weight of the objective function.

4. Case Study

Electric taxis and private EVs have the distinct characteristics of parking for a long time and charging slowly which make EVs considered to have great convergence potential. The main charging
equipment of EVs is the charging piles installed in the parking lots of residential quarters and entertainment venues. Monte Carlo Simulation is used to get the EVs charging power curve of the day. In this paper, the number of EVs subject to aggregation scheduling is set to 5000, the slow charging power of EVs to 7kW, and the electric power consumption of EVs to 30kWh per 100km. The last return time of the users, that is, the start time of EVs charging, follows the normal distribution of \((18,3.14^2)\), daily driving mileage follows normal distribution of \((32.9,0.88^2)\). Taking into account the lifestyle habits of EV users, the first trip time is uniformly set to 6 am. Using the load data of the December 2019 dispatch information monthly report of a regional power grid as the basic data for simulation, the typical daily load except the charging load of EVs is obtained as shown in Table 1.

| Time | Load Power(MW) | Time | Load Power(MW) | Time | Load Power(MW) |
|------|----------------|------|----------------|------|----------------|
| 1    | 177.075        | 9    | 124.251        | 17   | 203.256        |
| 2    | 137.346        | 10   | 152.148        | 18   | 198.621        |
| 3    | 117.543        | 11   | 219.546        | 19   | 240.396        |
| 4    | 111.996        | 12   | 225.06         | 20   | 273.447        |
| 5    | 105.36         | 13   | 229.719        | 21   | 264.567        |
| 6    | 106.419        | 14   | 230.775        | 22   | 246.783        |
| 7    | 100.221        | 15   | 202.83         | 23   | 243.483        |
| 8    | 105.087        | 16   | 200.586        | 24/0 | 211.62         |

In the absence of aggregators’ scheduling, the daily load curve formed when the disordered charging power of EVs is integrated into the grid is shown in Figure 1. It can be seen from Figure 1 that the peak and valley of EVs’ disordered charging load obtained by Monte Carlo Simulation almost coincides with the peak and valley of the power grid, which to some extent increases the risk of grid operation.

The objective functions are optimized by The GA. The compensation standard for aggregators’ peak regulation is set as 0.426 yuan/kWh, in which 30% for the aggregators and 70% for EV users. According to the bidding price of national grid charging piles, the charging pile is set to 18,000 yuan per pile. The electricity purchasing of aggregators and EVs’ charging prices are shown in Table 2.
Table 2. The electricity purchasing of aggregators and EVs’ charging prices

| Time                      | Electricity purchase price yuan/kWh | Charging price yuan/kWh | Disordered charge | Ordered charge |
|---------------------------|-----------------------------------|-------------------------|-------------------|---------------|
| Peak (8:00-12:00,17:00-21:00) | 0.869                             | 1.2                     |                   |               |
| Flat (12:00-17:00,21:00-24:00) | 0.687                             | 1.2                     | 0.9               |               |
| Valley(0:00-8:00)         | 0.365                             |                         | 0.6               |               |

The optimization results of EVs charging load are shown in Figure 2. After optimization, the charging load of EVs is concentrated in the valley of electricity consumption to achieve peak clipping and valley filling. Other parameter values are shown in Table 3. Before and after optimization, the profit of aggregators increases and the cost of EV users decreases.

Figure 2. Daily load after aggregation

Table 3. Parameter changes before and after aggregation

|                        | The maximum load/MW | The minimum load/MW | Load variance    | Aggregator profit/10^4 yuan | EV user charging cost/10^4 yuan |
|------------------------|---------------------|---------------------|------------------|-----------------------------|---------------------------------|
| Before aggregation     | 285.2534            | 100.2769            | 3618.7129        | 5.052                       | 14.426                          |
| After aggregation      | 273.4470            | 112.9410            | 2572.6534        | 6.018                       | 10.199                          |

5. Conclusion
A large number of unordered charging load of EVs brings great challenges to the safe operation of power grid. Aggregators offer EVs charging load management services. A multi-objective optimal scheduling model is established in this paper to optimize the charging load curve of EVs, in which the objectives are respectively variance minimization of the grid and profit maximization of aggregators. The Genetic Algorithm was used to solve the problem.

Ultimately, the example results showed that the grid load variance decreased from 3618.7129 to 2572.6534; Aggregators’ profits increased from 50520 yuan to 60180 yuan; The charging cost of users...
decreased from 144260 yuan to 101990 yuan. All of the above show that the direct scheduling mode of orderly charging of EVs by aggregators can be very good to realize the mutual benefit and win-win situation of power grid, EV users and aggregators.

Acknowledgments
This research was funded by the Science and Technology Project of the State Grid Corporation of China. The name of the project is the research of market integration transaction and typical business production simulation and benefit evaluation method of the integrated energy service system in Xiongan New District.

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