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Optimization Scheduling Strategies Considering Multiple Stakeholders in V2G Mode

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Abstract. This paper takes the participation of electric vehicles in distribution network dispatching under the Vehicle-to-Grid (V2G) model as the research scenario, and systematically reviews and compares typical domestic and international literature on the core issue of coordinating the interests of multiple stakeholders. First, it starts with the V2G system architecture and dispatching mechanism, summarizing the modeling methods for electric vehicle charging and discharging behavior and their applicable conditions. Second, it summarizes and analyzes common ways of setting objective functions and constraints on the user side, grid side, and aggregator side. Based on this, it compares and evaluates multi-objective processing methods such as linear weighted summation, two-level optimization models, and nested models, and analyzes their differences in effectiveness in load fluctuation suppression, user economic improvement, and system operation safety based on simulation results. The study shows that a reasonable multi-objective modeling and dispatching strategy can achieve a synergistic improvement in grid operation performance and multi-party economic benefits while ensuring user travel needs. The conclusions of this review can provide a reference for the subsequent design and engineering application of V2G optimized dispatching models.

Keywords: V2G, electric vehicles, multi-objective optimization

1. Introduction

In recent years, China's electric vehicle industry has entered a period of rapid development. By the end of 2024, China's new energy vehicle ownership had reached 31.4 million vehicles, of which 22.09 million were pure electric vehicles, accounting for about 8.9% of the total number of vehicles in the country and more than 70% of the total number of new energy vehicles [1]. As an important strategic emerging industry in China, the new energy vehicle industry is not only in line with the concept of green development, but also helps the green development transformation of the economy and society, and is an inevitable choice for the high-quality development of the automotive industry [2].

With the energy structure shifting towards clean and low-carbon, smart grids have become the core of power system development, and the rapid popularization of electric vehicles has brought huge challenges to the power grid. Vehicle-to-grid (V2G) technology transforms electric vehicles

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into "mobile energy storage units" by realizing bidirectional energy flow between electric vehicles and the power grid. Li Xiaoxian et al. pointed out that in the event of a sudden power outage or load shortage, electric vehicles can be used as an important emergency backup power source through V2G mode, which can effectively improve the emergency protection capability of the power system [3]. Hu Siyang et al. further used urban distribution networks as the research object and constructed a power supply restoration strategy based on V2G technology. Their research results showed that introducing electric vehicles to participate in dispatching during the fault recovery process can shorten the power supply restoration time and improve the power supply reliability of critical loads [4].

Xu Jingwen et al.'s research pointed out that as more and more electric vehicles are connected to the grid and participate in V2G interaction, their charging and discharging behavior exhibits significant randomness and time-varying characteristics, making the orderly scheduling of electric vehicle groups more complicated [5]. At the same time, the grid side expects to reduce load fluctuations and improve operating economy, while the user side pays more attention to charging costs and battery life, and aggregators need to seek profit maximization among multiple interests. This conflict between the goals of multiple subjects has made the scheduling problem under the V2G mode gradually evolve into a complex optimization problem with multiple objectives, multiple constraints, and nonlinear characteristics, which urgently needs to be coordinated and balanced through scientific scheduling strategies and optimization algorithms.

To balance the goals of the power grid with the needs of users, this paper takes the participation of electric vehicles in distribution network scheduling under the V2G model as the research scenario. It aims to systematically review and compare the application effects of various typical optimization algorithms in multi-stakeholder collaborative scheduling, and to find a scheduling strategy that can balance the interests of multiple stakeholders, thereby providing a reference for constructing an optimized scheduling strategy that takes into account the interests of the power grid, users, and aggregators.

2. Basic concepts and principles of V2G

2.1. Basic concepts and principles of V2G

Vehicle-to-grid (V2G) technology is a novel energy management model that enables electric vehicles to release (discharge) energy to the grid or draw (charge) energy from the grid via dedicated charging and discharging interfaces, bidirectional charging stations, and intelligent dispatch systems. This technology allows the battery capacity of electric vehicles to be utilized as a grid resource during periods of idleness, thereby improving energy asset utilization efficiency and bringing greater benefits to electric vehicle users.

In terms of operation, based on its behavioral characteristics and goal orientation, V2G energy interaction can be divided into three main modes. One is disordered charging, based on user convenience, such as charging when returning home. It is concentrated at the peak load and exacerbates the peak-valley difference of the power grid. The other is orderly charging, based on guaranteeing demand. It guides charging to the low load or the period of abundant renewable energy through time-of-use pricing or dispatch signals to achieve valley filling, but it is limited to unidirectional energy input. The third is the bidirectional charging and discharging of the V2G core, which enables vehicles to be charged or to feed back as distributed power sources and actively participate in system regulation. This paradigm shift of bidirectional energy flow makes electric

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vehicles a dynamic response resource with flexible power generation and load shifting capabilities [5].

2.2. V2G system architecture and scheduling mechanism

A typical V2G system consists of a power grid, electric vehicles, charging and discharging facilities, aggregators, and a dispatch control center. In this system, electric vehicles are distributed mobile energy storage units and are connected to the power grid through charging and discharging facilities (such as bidirectional charging piles). Aggregators act as core coordinators, collecting real-time status of electric vehicles and user intentions, and communicating bidirectionally with the dispatch control center. The dispatch control center generates optimized dispatch instructions based on power grid demand, load forecasts, and electricity price signals. Aggregators receive instructions and decompose them to each charging and discharging facility, controlling the charging and discharging behavior of the electric vehicle group, thereby realizing peak shaving, valley filling, peak regulation, and backup support of the power grid [6]. The whole process, while meeting the user's travel needs, collaboratively improves the safety and economy of power grid operation. Figure 1 shows a typical V2G system consisting of a power grid, electric vehicles, charging and discharging facilities, aggregators, and a dispatch control center.

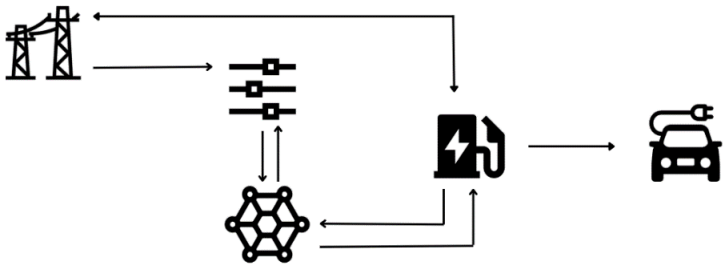

Figure 1. Typical V2G system (original)

3. Selection of electric vehicle charging and discharging model

3.1. Selection of electric vehicle charging and discharging model

To optimize scheduling strategies, it is first necessary to analyze the travel patterns of electric vehicles, namely charging and discharging times. Currently, most studies use traditional probability models.

The most common method for analyzing the characteristics of car travel is to fit the vehicle travel statistics of the 2009 National Household Travel Survey (NHTS2009) of the National Highway Traffic Safety Administration in the United States to establish a probability distribution model, and then use the Monte Carlo sampling method to conduct a survey of electric vehicles in a specified area, so as to model the charging load of electric vehicles and optimize the parameters [7,8]. The data selected by Chen Jianghong and Pan Hua was updated, and the data of the National Household Travel Survey conducted in the United States in 2017 was used as the research data source [9]. The latter method is more accurate, using six-peak (R-squared = 0.9646, RMSE = 0.005986, SSE = 0.0005375) and three-peak (R-squared = 0.9972, RMSE = 0.127, SSE = 0.09679) Gaussian functions to describe travel distance and then inversely deduce the probability of stopping [10]. In comparison, this result is more reliable and has a higher reference value.

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As can be seen from the above literature, the current research generally uses the Monte Carlo sampling method, which makes the source of the survey data and the survey time particularly important. Moreover, this method is only applicable to the case of regular electric vehicle travel time, while the travel time and mileage of the EV cluster conform to a normal distribution, so this method is still applicable [8].

3.2. Selection of objective function

Existing research methods involve setting objective functions for different stakeholders, then defining constraints to ensure the results align with reality, optimizing the interests of multiple parties without violating actual conditions. This allows different objectives to be quantified, compared, and weighed using mathematical formulas. Although the research methods are similar, each paper emphasizes different aspects when selecting specific objectives.

3.2.1. Establishment of user-side objective function

On the user side, all of them have basically considered the user cost issue, but there are obvious differences in the focus.

Most articles follow the approach of charging expenditure plus battery loss minus discharge revenue. First, the charging expenditure is quantified by a weighted summation of charging power and time-of-use electricity price at each moment. Then, the battery loss is quantified by the battery charging and discharging energy throughput and its efficiency characteristics. Finally, the power of electric vehicles discharging to the grid when participating in V2G is statistically analyzed, and the user's economic benefits are calculated in combination with the electricity sales price [11]. Xiao Li and Chen Jianghong also considered the responsiveness of the area under the jurisdiction of the agent, which improved the application value of the model. Liu Yang did not take user-side discharge revenue into account. Pan Hua considered only cost-related factors, calculating the minimum electricity cost based on charging costs and discharging revenue, and established a price-guided economic model with the pricing mechanism as its core.

It can be seen that the above-mentioned papers generally suffer from the problem of relatively idealized behavioral models. However, when the models closely resemble the actual market structure, their complexity is high and the solution is difficult, how to establish a suitable model remains the focus of future research.

3.2.2. Establishment of the objective function on the power grid side

Electric vehicles can also help to regulate grid load fluctuations. Through intelligent and orderly charging control strategies, the fluctuations due to disordered charging of electric vehicles can be transformed into a flexible frequency regulation resource. When the grid frequency is larger than the rated frequency, the system automatically reduces the vehicle charging power; when the grid frequency is lower than the rated value, it can select to discharge energy storage or increase charging demand, achieving deep coupling between dynamic load-side regulation and grid frequency [12].

For grid-side demand, most papers seek to reduce the change of load by minimizing load variance (that is, the square root of deviation between actual net load and average load of the distribution network. Actual net load = original load − output of distributed generation power + charging power of electric vehicles − discharging power of electric vehicles − average load. Average net load is the average of the electric vehicle load after considering distributed generation and EV

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charging/discharge behavior. More, minimizing the total active power loss of distribution network itself can also enhance the completeness of the model [11].

Load variance presents the level of a grid load fluctuation. Minimizing the load variance is the simplest and intuitive strategy to level load distribution, avoiding excessive large peak load and excessive small load bottom. However, in extreme load variance and high system complexity, load variance alone cannot reflect the actual operational characteristics of power grids.

3.2.3. Selection of constraints

Analysis to ensure optimization results follow physical law, limits of equipment performance, users' requirements, and system safety requirements, some constraints have to be added to the model. These constraints make it practical and achievable good performance under typical operating conditions. The grid-side constraints differ across studies. The user-side constraints are mostly based on the state of charge (SOC). Grid-side constraints focus primarily on controlling load variations and decreasing network losses. Taking into consideration electric vehicle owner benefits, reasonable scheduling and control methods may be adopted to alleviate load variations and power losses.However, different scholars emphasize different points, such as power flow balance constraint, voltage constraint, node power constraint, the peak–valley difference constraint [11].

On the user side, SOC is widely adopted as a key constraint, SOC constraints are essential for ensuring normal vehicle operation and extending battery life. Restricting the remaining charge ratio of batteries in electric vehicles also avoids overcharging and over-discharging. Some set the lower limit and upper limit of SOC to 20% and 90%, respectively [10]. Other studies consider SOC as a dynamic state variable varying with time and describe it through recursive equations and hence treat SOC as the core scheduling variable [13].

Most studies of SOS optimization concern themselves with three aspects: load fluctuation elimination, network loss mitigation, and state of charge constraint. On practical issues, considering all kinds of constraints comprehensively but maintaining low computational complexity is helpful for optimizing the coordinated scheduling of electric vehicles and the power grid.

3.3. Processing of the objective function and model solution

Assessing the objective function for processing involves a challenge in trade-offs of interests of different stakeholders.

One commonly used approach is the linear weighted summation method, which turns a multi-objective optimization problem into a single-objective problem. By adjusting weighting coefficient α_1, α_2 and α_3, the model can have different preferences on economic efficiency and stable operation of the grid. Regarding the weight coefficients of the various operating costs, they can often be obtained from the analytic hierarchy process (AHP), such as the importance of each cost proposed by experts. Other studies quantitatively capture subjective judgments and also allow rational trade-off between user costs and grid requirements [13]. Chen also uses a linear weighted method to normalize the objective function, but its weighting strategy is simpler, giving weight of one-third to each objective [14].

The second approach is to perform a two-level optimization of the objective function. The implementation result of the upper-level strategy not only affects the initial state of the lower-level strategy but also changes the relevant conditions of its constraints. The implementation result of the lower-level strategy will be fed back to the upper level in the form of input and the two sides will iterate through feedback. This model does not use a weighted method, but simulates the real

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allocation of scheduling power through a game structure, which is closer to the actual power market operation mechanism, but has a higher complexity [7].

The third type is the nested model. The interests of different subjects are allocated to different levels of the model, which reflects a clear priority order and system synergy. In addition, EV grouping is introduced to reduce the dimensionality of variables. Combined with the power flow calculation of the IEEE 33-node system, the algorithm structure clearly considers the influence of the power grid topology. However, due to the high complexity of the model and the large amount of computation, the solution process is complicated [11].

Each of the three methods has its own focus and is applicable to different scenarios. If the focus is on rapid solution and engineering implementation, the linear weighted method is more advantageous; if the emphasis is on multi-agent game and scheduling power allocation, the two-layer optimization is more reasonable; if the focus is on power grid safe operation and topology impact, the nested model is more advantageous in terms of theoretical and engineering integrity.

3.4. Comparison of simulation results

Table 1 compares the simulation results of each study from both the grid side and the user side, and analyzes the applicable scenarios and characteristics.

Table 1. Comparison and analysis of simulation results

References	Simulation Scenario Setting	Main Evaluation Indicators	Grid-Side Effects	User-Side Effects	Conclusions and Characteristics
[7]	Base load / disordered charging / V2G optimized scheduling	Peak-to-valley load difference, load curve shape, and average monthly charging cost	Peak-to-valley difference: 289.62 kW → 87.63 kW (↓69.7%). Peak load shifted from periods 10–12 and 18–22.	The average monthly charging cost has decreased significantly, with the cost in Region 5 decreasing by 96 yuan (↓35.16%).	V2G significantly smooths out peak traffic and fills in valleys; the higher the regional responsiveness, the greater the user benefits.
[14]	Disorderly charging/V2G (5 communities)	Peak load, load variance; EV cost, EVA benefit	Peak load: 1088.18 kW → 973.09 kW (↓10.58%) Load curve variance ↓ 57.07%	EV battery degradation: 71.67 → 77.01 yuan V2G revenue: 47.69 yuan/month (positive net revenue)	Simultaneous improvement of grid stability, EV economy, and EVA benefits
[10]	Wind power + EV / Multi-time pricing / Large EV scale	Total load variance; Total user revenue	Total load variance: Multi-objective 1.11×10^7 MW² ↑1.85% compared to the minimum single-objective load.	Total user earnings: Multi-objective earnings of 7.58 x 10^4 yuan, down 23.2% from maximum earnings.	Achieving a power grid-user trade-off through fuzzy optimization
[11]	Disordered EV / Disordered EV+DG / Ordered EV / V2G+DG	Load mean square error, peak-to-valley difference, network loss, voltage; charging costs	When electric vehicles are used in conjunction with distributed energy sources (Scenario 4), network loss is minimized and voltage does not exceed limits.	The cost is lowest when electric vehicles are combined with distributed energy resources (1815 yuan), which is 28420 yuan less than when they are connected without proper coordination.	System-level Optimization under Time, Space, and Physical Constraints
[13]	Building + Solar + EV + Energy Storage; No V2G/Economy Priority/Response Priority	Standard deviation of purchased power; SOC, battery degradation cost	Standard deviation of purchased power: None V2G 30.71 kW (Economy Priority) 19.94 kW (Response Priority) 17.15 kW	Total economic cost: Economic priority: 3108.5 yuan (lowest); Response priority: 3220.0 yuan	The weights are adjustable, and there is a trade-off between economic efficiency and load stability.

4. Conclusion

This paper focuses on the problem of electric vehicles participating in distribution network dispatch under the V2G model. It systematically reviews and compares various typical optimization

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strategies, providing valuable reference for researchers and engineers engaged in smart grid planning, electric vehicle dispatch management, and energy internet construction. It can be seen that multi-objective optimization models are more advantageous than single-objective dispatch strategies in balancing grid stability and user economics. However, a mature and reasonable benefit-sharing mechanism has not yet been established, and the division of benefits and costs among electric vehicle users, aggregators, and grid companies is not clear enough. In the future, with the continuous advancement of smart grid and energy internet construction, V2G technology will play an increasingly important role in promoting energy structure transformation, improving power system flexibility, and building a green and low-carbon society.

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