Orderly grid-connected cooperative scheduling control strategy based on distributed energy storage for electric vehicles

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Abstract. Aiming at the problem that large-scale disorderly grid connection of electric vehicles negatively affects grid operation and causes a large amount of abandoned wind and abandoned light, an orderly grid connection cooperative scheduling control strategy based on distributed energy storage of electric vehicles is proposed. The strategy takes the charging and discharging price as the lever to guide the users to charge and discharge in an orderly manner, takes the optimal economics on the user side and the optimal cost of power generation on the grid side as the objective function, and uses linear weighting normalization to convert the multi-objective function into a single objective function for simulation solution. The simulation results show that the effect of peak shaving and valley filling can be achieved on the basis of satisfying users' demand, and renewable energy can be effectively consumed.

1. Introduction
With the increasing proportion of renewable energy in the power grid, the disadvantages of renewable energy such as discontinuous power generation and large randomness[1], present new challenges to the stable operation of the power system. With the rapid development of the electric vehicle industry, the large-scale disorderly grid connection of a large number of electric vehicles will lead to increased load fluctuations in the grid and intensify the negative impact on the stable operation of the grid. Studies have shown that 90% of electric vehicles are offline during the day[2]. Therefore, it is important to study the orderly grid connection of electric vehicles as distributed energy storage units to participate in grid regulation for the stable operation of the grid.

Many scholars have carried out research on the orderly grid-connection control of electric vehicles. Yang Bing[3] constructed a distribution grid system containing electric vehicles, wind power and photovoltaic from the perspective of collaborative planning of electric vehicles and each distributed power source, but did not fully consider the economics of the user side. Qian Kejun[4] studied the charging and discharging problem of electric buses in charging stations participating in the vehicle network. Hu Biao[5] studied the impact of time-sharing tariff on users' electricity consumption behavior, and constructed a multi-objective system model with the optimization objectives of maximizing the lifetime of energy storage system and maximizing users' benefits in microgrid. Many scholars have proposed various tariff mechanisms based on economic principles, such as graded...
linkage tariffs on both sides of supply and consumption[6] and electricity consumption elasticity
matrix tariffs[7]. Zeng Zheng[8] gave the use of tariff regulation to guide electric vehicle users to
reasonably arrange charging time, but did not consider the actual load profile in a variety of load
contexts, including those involving electric vehicle load. Sun Xiaoming[9] differed from the
conventional peak, valley, and flat time-sharing tariff time division, carried out research on charging
time-sharing tariff time division for regional load fluctuations, but did not propose a specific division
method in conjunction with the actual situation.

It can be seen that the existing researches do not sufficiently consider the user's willingness to
participate in grid dispatch. For this reason, this paper proposes a cooperative control strategy for grid-
connected EVs, which fully considers users' demands, takes charging and discharging prices as levers
to guide users to charge and discharge in an orderly manner, takes grid-side and user-side economics
as the objective function, selects the optimal weighting coefficients, and the multiple objectives are
converted into single objectives and solved by genetic algorithm. Under the premise of satisfying the
user-side demand, the renewable energy is effectively consumed and the grid peak reduction and
valley filling is realized.

2. Electric vehicle disorderly charging analysis

Under the guidance of strategies such as time-sharing tariff without consideration, EVs are connected
to the grid in a disorderly manner, and the charging behavior is completely determined by the
respective travel requirements and demands of vehicle owners, and the charging behavior of EV
owners is stochastic. A Monte Carlo method is used to simulate the disorderly charging behavior of
users, and probabilistic models of charging start time $t_0$, charging power SOC and charging power P
are established, and corresponding random data are generated according to the established
probabilistic models.

For verification purposes, the following settings are made.

- Using one day as a scheduling cycle and 15min as a time interval, we divide a cycle into 96
time slots.
- The starting time $t_0$ of electric vehicle charging uses data from the National Highway Traffic
Safety Administration (NHTS), and the starting time $t_0$ of electric vehicle charging satisfies a
normal distribution $N(70.4,13.6)$.
- 1,000 electric vehicles were selected and their charging power data were statistically analyzed,
and their charging power SOC was found to satisfy a normal distribution $N(12.94,11.8)$.
- Electric vehicle charging power is usually taken in three ways: AC level 1, AC level 2 and DC
charging, and the ratio of the three charging powers is set at 10%, 40% and 50%.
Monte Carlo simulation was carried out with a sample of 10,000 EVs to obtain the load curve of EV disorderly charging and discharging. The simulation results in Figure 1 show that the charging behavior in the case of EV disorderly charging is not regulated and depends entirely on the behavior habits of vehicle owners, and the charging behavior of EVs generally starts immediately at the end of the owner’s trip, and reaches 18:00 in the evening peak.

Figure 2 shows the daily load curve of a region in summer, Pload1 is the daily load curve of the region, and Pload2 is the daily load curve after superimposing the disorderly charging behavior of electric vehicles. It can be seen that there are two peak periods of electricity consumption in the area, among which 18:00-23:00 is the maximum peak period of the day, and it is the peak period of disorderly charging of electric vehicles.

3. Constraints for grid-connected cooperative control of electric vehicles

It is necessary to consider the system power conservation constraint, renewable energy output constraint, in-transit energy storage system constraint, electric vehicle capacity, charging and discharging power constraint and other conditions to make the model construction more realistic and reasonable.

3.1. Equation constraints for the conservation of supply and demand power

The electric vehicle grid-connected cooperative control model needs to comply with the equation constraint of conservation of supply and demand power, satisfying the power provided by energy storage devices, renewable energy sources and the grid to be equal to the power consumed by the load.

\[ P_{\text{load}}(t) = P_{\text{WT}}(t) + P_{\text{PV}}(t) + P_{\text{c}}(t) + P_{\text{bat}}(t) + P_{\text{EV}}(t) \]  

\[ (1) \]

To exchange power between the grid and the microgrid, the grid can both supply power to the microgrid system and recover power from the microgrid system at a lower price than the current time-of-use tariff, meet:

\[ P_{\text{c}}(t) = \lambda P_{\text{WT}}(t) - \mu P_{\text{PV}}(t) \]  

\[ (2) \]

\( \lambda, \mu \) is the grid exchange power factor, when \( \lambda = 1 \) the grid provides power to the microgrid system \( P_{\text{WT}}(t) \), when \( \mu = 1 \) power is purchased from the microgrid system \( P_{\text{PV}}(t) \).

3.2. Energy storage system capacity and power constraints

In order to avoid overcharge and overdischarge, the upper and lower limits of the charge state and charge/discharge power of the energy storage system should be set, the SOC and \( P_{\text{bat}} \) should meet:

\[ SOC_{\text{min}} \leq SOC(t) \leq SOC_{\text{max}} \]  

\[ (3) \]

\[ P_{\text{bat, min}} \leq P_{\text{bat}}(t) \leq P_{\text{bat, max}} \]  

\[ (4) \]

3.3. Renewable Energy Capacity Constraints

The actual output of wind power and photovoltaic should be within a certain range if abandoned wind and light are allowed.

\[ P_{\text{WT, min}} \leq P_{\text{WT}}(t) \leq P_{\text{WT, max}} \]  

\[ (5) \]

\[ P_{\text{PV, min}} \leq P_{\text{PV}}(t) \leq P_{\text{PV, max}} \]  

\[ (6) \]

3.4. Electric vehicle constraints

As a distributed energy storage device, the electric vehicle has two working states, charging and discharging, which can be used as a load to obtain power from the grid for charging, and as a power source to discharge to the grid during peak load periods.

\[ P_{\text{EV}}(t) = \alpha P_{\text{dis}}(t) - \beta P_{\text{cha}}(t) \]  

\[ (7) \]
\( \alpha, \beta \) is the electric vehicle operating state parameter. At any moment, the energy storage system works in only three ways: charging, discharging, and idle, and the operating state parameters and power corresponding to various operating states are shown in Table 1.

| Table 1. Parameters in different operating conditions |
|-------------------------------------------|
| Charging | Discharge | Free |
| \( \alpha \) | 0 | 1 | 0 |
| \( \beta \) | 1 | 0 | 0 |
| \( P_{cha} \) | \( P_{cha} > 0 \) | \( P_{cha} = 0 \) | \( P_{cha} = 0 \) |
| \( P_{dis} \) | \( P_{dis} = 0 \) | \( P_{dis} > 0 \) | \( P_{dis} = 0 \) |

Thus the working state constraint is satisfied:

\[
P_{cha} \cdot P_{dis} = 0 \tag{8}
\]

Without considering the self-discharge of electric vehicle battery, the electric vehicle power and its power meet:

\[
SOC_{EV}(t) = SOC_{EV}(t - 1) + \frac{P_{cha} \Delta \eta - P_{dis} \Delta \eta}{E_{N}}
\tag{9}
\]

\( \eta \) is the charging and discharging efficiency of the battery, and \( E_{N} \) is the rated capacity of the battery.

In order to avoid overcharging and overdischarging of electric vehicles that affect their service life and cause safety hazards, it is necessary to meet the inequality limits of battery capacity and charging and discharging power as follows:

\[
SOC_{EV,min} \leq SOC_{EV}(t) \leq SOC_{EV,max}
\tag{10}
\]

\[
P_{EV,min} \leq P_{EV}(t) \leq P_{EV,max}
\tag{11}
\]

### 4. Consider the objective function of the optimal economy on the grid side and the customer side

In order to achieve the optimal overall benefit, it is necessary to take into account both the interests of the user side and the economics of the grid side. A day is used as a dispatching cycle, 15min is a time interval and the cycle is divided into 96 time periods.

#### 4.1. Optimal objective function of user-side economy

Considering at the customer level, it is desired that the total cost of its electricity consumption is the lowest. The sources of power obtained by the load are mainly the grid and renewable energy sources. The load obtains power from the main grid with a time-of-use tariff billing, and the power exchange cost of the load from the renewable energy side depends on the generation cost of wind PV.

\[
f_1 = \min \ C_{sum} = \sum_{t=1}^{96} (P_{WT}(t)C_{WT} + P_{PV}(t)C_{PV} + C_{bat}(t) + C_x(t) + C_{EV}(t))
\tag{12}
\]

\[
C_x(t) = \lambda P_{1}(t)C_1(t) - \mu P_{2}(t)C_2(t)
\tag{13}
\]

\[
C_{EV}(t) = \alpha P_{dis}(t)C_4(t) - \beta P_{cha}(t)C_2(t)
\tag{14}
\]

\( C_1 \) are the time-of-use tariffs issued by the grid. \( C_2 \) is the tariff for electricity sold to the grid.

#### 4.2. Grid-side generation cost optimal objective function

Considering the generation efficiency and cost of the new energy side, the system's ability to consume new energy should be improved to reduce the abandoned wind and light as much as possible. The power of wind and light abandonment at a certain moment can be expressed as:

\[
X(t) = P_{WT,max} - P_{WT}(t)
\tag{15}
\]

\[
Y(t) = P_{PV,max} - P_{PV}(t)
\tag{16}
\]
Measured by grid-side economic indicators, it can be seen as the least loss of wind and light abandonment.

\[
\min C_{re} = C_{WT} \sum_{t=1}^{24} \left( P_{WT,\text{max}} - P_{WT}(t) \right) + C_{PV} \sum_{t=1}^{24} \left( P_{PV,\text{max}} - P_{PV}(t) \right)
\]  

(17)

5. Simulation analysis of electric vehicle orderly grid-connected cooperative control strategy

The linear weighting method is used to process the objective function and convert the multi-objective function into a single objective function.

\[
F = \phi f_1 + \psi f_2
\]  

(18)

Weighting factor \( \phi, \psi \) meet: \( \phi + \psi = 1 \), the weights of the two objective functions are different and the weighting coefficients are set differently according to the different demands of optimal scheduling. If in the promotion stage of EV on-grid operation mode, in order to motivate users to participate in EV on-grid optimal dispatching, it is necessary to increase the revenue of users' participation in EV charging and discharging and increase \( f_1 \). In the long term, grid-side economy is the main objective, so this paper focuses on grid-side economy with the weighting coefficients set to \( \phi = 0.3 \) and \( \psi = 0.7 \). The results of the daily load curve comparison before and after optimization are shown in Figure 3.

![Figure 3. Daily load curve before and after optimization](image)

The cooperative control strategy of electric vehicle orderly grid connection studied in this paper can realize load leveling, which has a certain effect of peak-shaving and valley-filling for the grid.

Figure 4 and 5 show the wind power before and after optimization. Before optimization, the renewable energy cannot be consumed and the wind and light abandonment rate is high, especially during the 0:00-7:00 hours, when the load of the grid is low, the cost of power purchased from the grid is low, and the main source of power consumed by the load is the grid exchange, so it will cause the wind power cannot be consumed. When the grid-side economics are taken into account to optimize the regulation of the system, the abandoned wind and light rate is significantly reduced, effectively improving the utilization rate of wind power and photovoltaic.
6. Conclusion

In this paper, we construct a model with the optimal economics on the user side and the optimal cost of power generation on the grid side as the objective function, select the optimal weighting coefficients, and use linear weighting normalization to convert the multi-objective function into a single objective function for simulation solution.

- An orderly grid-connected cooperative scheduling control strategy based on distributed energy storage for electric vehicles is proposed, which takes into account the willingness of users to participate in grid scheduling and satisfies the needs of users to the greatest extent.
- The charging and discharging price is used as a lever to guide users to orderly charging and discharging, so that users can stagger their electricity consumption and achieve load leveling.
- The optimal weighting coefficients are selected according to the demand of optimal scheduling, and the linear weighting method is used to transform the complex multi-objective function into a single objective function.

This strategy can significantly reduce the rate of abandoned wind and light, which provides an idea for the research of orderly grid integration of electric vehicles as distributed energy storage units.

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