Influence of electric vehicle distributed energy storage access on safety and stability of distribution network

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Abstract—This paper proposes a distributed energy storage control strategy for electric vehicles to improve the security and stability of distribution network when electric vehicles are connected. Firstly, the load characteristics of electric vehicles are investigated, and the optimal power flow model including energy storage power station, electric vehicle charging station considering V2G and distribution network is established. The objective function is established to minimize network loss, voltage deviation and load peak to peak. The problem is transformed into a mixed integer second-order cone optimization problem for solution, and based on the analysis of distributed energy storage model and constraints, the distributed energy storage control strategy of electric vehicle is established. Through the solution analysis in IEEE33 node system, it can be concluded that using this strategy can improve the power quality of distribution network and effectively improve the security and stability of distribution network.

1. Introduction

In recent years, electric vehicles have been vigorously developed by various countries because of their advantages of environmental protection and energy saving. At the same time, with the continuous increase of the number of electric vehicles, the impact of electric vehicle charging load on the planning and operation of power grid is becoming greater and greater.

As a flexible regulation resource of power grid, energy storage has a good effect in cutting peak and filling valley, absorbing new energy, reducing network loss and delaying the transformation and expansion of distribution network. V2G technology of electric vehicle is a distributed energy storage technology. It takes the electric vehicle connected to the power grid as a decentralized energy storage unit, releases electric energy when the power grid load is heavy, and absorbs electric energy when the power grid load is light, which can improve power quality, cut peak and fill valley and balance the power grid.

Domestic and foreign scholars have done some research on the impact and strategy of distributed energy storage access to distribution network. Reference [1] proposes a charging and discharging control model of electric vehicle in V2G mode. Taking the minimum charging cost of electric vehicle users and the variance of power grid load as the objective function, the optimization effect of the model is verified by Lingo simulation. Reference [2] establishes the V2G response model of electric vehicle and formulates the corresponding V2G strategy. Taking the residential area as an example, this paper analyzes the economy and load peak valley difference of distribution network under disordered charging and V2G mode. Reference [3] establishes a dynamic optimal power flow model framework based on second-order cone programming (SOCP), and transforms the relaxation of the original nonlinear programming model into SOCP for solution. Finally, the relaxation accuracy and effectiveness of the optimal power flow model are analyzed and verified. Reference [4] introduces the parametric model of
distributed energy storage in active distribution network. The clustering method is used to generate the data of load demand, wind output and photovoltaic output. Finally, the model is transformed into a mixed integer second-order cone model, and the economic benefits, security and stability brought by distributed energy storage access to distribution network are calculated and analyzed.

This paper investigates the load characteristics of electric vehicles, establishes the mathematical model of optimal power flow of electric vehicle charging station, energy storage station and distribution network considering V2G, puts forward the distributed energy storage control strategy of electric vehicles, simulates the model in the example of IEEE33 node, and compares and analyzes the safety and stability of distribution network before and after distributed energy storage access.

2. Constraints and objective function of distribution network model with distributed energy storage

2.1 electric vehicle load model

Based on the U.S. Department of transportation's survey of vehicles in the United States in 2017 and 2018, by normalizing and analyzing the time of private cars leaving home and returning home, it is obtained that the probability density function of electric vehicles returning home meets:

\[
f_i(x_i) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma_s} \exp \left( -\frac{(x_i + 24 - \mu_s)^2}{2\sigma_s^2} \right) & 0 \leq x_i < \mu_s - 12 \\ \frac{1}{\sqrt{2\pi}\sigma_s} \exp \left( -\frac{(x_i - \mu_s)^2}{2\sigma_s^2} \right) & \mu_s - 12 \leq x_i < 24 \end{cases}
\]

where \( \mu_s = 17.9, \sigma_s = 3.4 \).

The probability density at the time of leaving home meets:

\[
f_e(x_e) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma_e} \exp \left( -\frac{(x_e - \mu_e)^2}{2\sigma_e^2} \right) & 0 \leq x_e < \mu_e + 12 \\ \frac{1}{\sqrt{2\pi}\sigma_e} \exp \left( -\frac{(x_e - 24 - \mu_e)^2}{2\sigma_e^2} \right) & \mu_e + 12 \leq x_e < 24 \end{cases}
\]

where \( \mu_e = 9.24, \sigma_e = 3.16 \).

The probability density function of user's daily mileage meets the following requirements:

\[
f_D(d) = \frac{1}{\sqrt{2\pi}d\sigma_d} \exp \left( -\frac{(Ind - \mu_d)^2}{2\sigma_d^2} \right)
\]

where \( D \) is the daily mileage of the vehicle, \( \mu_D = 8.92, \sigma_D = 0.88 \).

2.2 distributed energy storage model

2.2.1 energy storage model

Generally, there are three states when energy storage works: charging state, discharging state and non charging and non discharging state. The constraints include state constraints, power constraints and capacity constraints.

1. State constraints

\[
u^{dch}_{j,t} + u^{dsh}_{j,t} \leq 1 \quad \forall j \in B, \forall t \in T
\]

2. Power constraints
3. Capacity constraints

\[
\begin{align*}
\begin{cases}
    u_{j,t}^{dch} & \leq P_{j,t}^{dch} & \leq u_{j,t}^{dch,max} \\
    u_{j,t}^{ch} & \leq P_{j,t}^{ch} & \leq u_{j,t}^{ch,max}
\end{cases} \\
\forall j \in B, \forall t \in T
\end{align*}
\]

(5)

where \( B \) is the collection of nodes connected to energy storage, and \( T \) is the collection of divided time periods. \( u_{j,t}^{dch} \) and \( u_{j,t}^{ch} \) respectively represent the charge and discharge state of the energy storage device during the time period \( t \), and the value is 0 or 1. \( P_{j,t}^{dch,min} \), \( P_{j,t}^{dch,max} \), \( P_{j,t}^{ch,min} \), and \( P_{j,t}^{ch,max} \) respectively represent the upper and lower limits of energy storage charge and discharge power. \( P_{j,t}^{dch} \) and \( P_{j,t}^{ch} \) are the charge and discharge power of energy storage in \( t \) period. \( E_{j,t}^{ESS} \) is the quantity of stored energy in \( t \) period.

2.2.2 Electric vehicle charging station model considering V2G

The working state and constraints of the electric vehicle charging station considered V2G are roughly the same as those of the energy storage device, except that the charging power of the charging station shall reach the determined amount in a certain period of time, so as to ensure that the SOC of the electric vehicle can reach the expected SOC.

1. State constraints

\[
\begin{align*}
\beta_{i,t}^{dch} + \beta_{i,t}^{ch} & \leq 1 \\
\forall i \in C, \forall t \in T
\end{align*}
\]

(7)

2. Power constraints

\[
\begin{align*}
\begin{cases}
    \beta_{i,t}^{dch} & \leq P_{i,t}^{dch} & \leq \beta_{i,t}^{dch,max} \\
    \beta_{i,t}^{ch} & \leq P_{i,t}^{ch} & \leq \beta_{i,t}^{ch,max}
\end{cases} \\
\forall i \in C, \forall t \in T
\end{align*}
\]

(8)

3. Capacity constraints

\[
\begin{align*}
\begin{cases}
    E_{i,t+1}^{v2g} & = E_{i,t}^{v2g} + \alpha_{i,t}^{ch} P_{i,t}^{ch} - \alpha_{i,t}^{dch} P_{i,t}^{dch} \\
    E_{i,t}^{v2g,min} & \leq E_{i,t}^{v2g} & \leq E_{i,t}^{v2g,max}
\end{cases} \\
\forall i \in C, \forall t \in T
\end{align*}
\]

(9)

where \( C \) is the collection of nodes connected to the electric vehicle charging station considering V2G, and \( T \) is the collection of divided time periods. \( \beta_{i,t}^{dch} \) and \( \beta_{i,t}^{ch} \) respectively represent the charge and discharge state of the electric vehicle charging station during period \( t \), and the value is 0 or 1. \( P_{i,t}^{dch,min} \), \( P_{i,t}^{dch,max} \), \( P_{i,t}^{ch,min} \), and \( P_{i,t}^{ch,max} \) respectively represent the upper and lower limits of charging and discharging power of the charging station. \( P_{i,t}^{ch} \) and \( P_{i,t}^{dch} \) are the charge and discharge power of energy storage in \( t \) period. \( E_{i,t}^{v2g} \) is the total charging capacity of the charging station in \( t \) period. \( \alpha_{i,t}^{ch} \) and \( \alpha_{i,t}^{dch} \) are the charge discharge efficiency coefficients of the charging station, which are greater than 0 and less than 1. \( E_{i,t}^{v2g,min} \) and \( E_{i,t}^{v2g,max} \) represent the minimum and maximum values of the charging power required by the charging station in the \( t \) period.
2.3 optimal power flow model of distribution network

2.3.1 Operational constraints

\[
\begin{align*}
\sum_{kj \in D(j)} P_{kj,t} &= P^\text{gen}_j - P^\text{load}_j + \sum_{i \in \delta(j)} \left( P_{ij,t} - I_{ij,t} r_{ij} \right) \quad \forall j \in D, \forall t \in T \\
\sum_{kj \in D(j)} Q_{kj,t} &= Q^\text{gen}_j - Q^\text{load}_j + \sum_{i \in \pi(j)} \left( Q_{ij,t} - I_{ij,t} x_{ij} \right) \quad \forall j \in D, \forall t \in T \\
\tilde{V}_{ij,t} &= \tilde{V}_{ij} - 2 \left( P_{ij,t} r_{ij} Q_{ij,t} x_{ij} \right) + \tilde{I}_{ij,t} \left( r_{ij}^2 + x_{ij}^2 \right) \quad \forall ij \in E, \forall t \in T
\end{align*}
\]  

(10)

where \( D \) represents the collection of all nodes in the network. \( E \) represents the collection of all branches in the network. \( T \) represents the collection of divided time periods. \( ij \) represents the branch whose positive direction of power flow is from node \( i \) to node \( j \). \( \delta(j) \) is the set of branch end nodes headed by \( j \), and \( \pi(j) \) is the set of branch end nodes headed by \( j \). \( P^\text{gen}_j \) and \( Q^\text{gen}_j \) respectively represent the active and reactive power injected into the node by the power supply connected to node \( j \). \( P^\text{load}_j \) and \( Q^\text{load}_j \) represent the active and reactive loads connected to node \( j \) respectively. \( P_{ij,t} \) and \( Q_{ij,t} \) are the active and reactive power flowing through the branch \( ij \) respectively. \( r_{ij} \) and \( x_{ij} \) are the resistance and reactance of branch \( ij \).

2.3.2 Safety constraints

\[
\begin{align*}
0 &\leq \tilde{I}_{ij,t} \leq I^\text{max}_{ij} \quad \forall ij \in E, \forall t \in T \\
\tilde{V}_{ij}^\text{min} &\leq \tilde{V}_{ij,t} \leq \tilde{V}_{ij}^\text{max} \quad \forall ij \in B, \forall t \in T \\
0 &\leq s^\text{gen}_j \leq P^\text{max}_j + Q^\text{max}_j \quad \forall j \in G, \forall t \in T
\end{align*}
\]  

(11)

where \( G \) represents the collection of nodes connected to the power supply. \( I^\text{max}_{ij} \) represents the maximum allowable current of branch \( ij \). \( V^\text{min}_j \) and \( V^\text{max}_j \) respectively represent the maximum and minimum allowable values of node \( j \) voltage. \( P^\text{max}_j \) and \( Q^\text{max}_j \) respectively represent the maximum active and reactive power that can be output by the power supply connected to node \( j \).

2.4 Objective function

The objective function takes into account the economy of distributed energy storage and the safety and stability of distribution network, and sets the objective function \( F \) as:

\[
\min F = \mu_1 f_1 + \mu_2 f_2 + \mu_3 f_3
\]  

(12)

where \( f_1, f_2 \) and \( f_3 \) are line loss, voltage deviation and load peak valley difference respectively. \( \mu_1, \mu_2 \) and \( \mu_3 \) are weight coefficients respectively, and their sum is 1.

1. Line loss \( f_1 \)

\[
f_1 = \sum_{i=1}^{24} \sum_{j=1}^{b} P^\text{line}_{j,t}
\]  

(13)

where \( b \) is the total number of branches of the distribution network and \( P^\text{line}_{j,t} \) is the line loss of branch \( j \) in the period \( t \).
2. Voltage deviation $f_2$

$$f_2 = \sum_{i=1}^{n} \sum_{t=1}^{24} \left| \frac{U_{i,t} - U_N}{U_N} \right|$$  \hspace{1cm} (14)

where $n$ is the number of distribution network nodes, $U_{i,t}$ is the voltage of node $i$ in $t$ period and $U_N$ is the rated voltage of distribution network.

3. Load peak valley difference $f_3$

$$f_3 = \max P_{\text{sum},t} - \min P_{\text{sum},t}$$  \hspace{1cm} (15)

where $P_{\text{sum},t}$ is the total load power in period $t$.

In the above model, the last expression of constraint (10) is a nonlinear equation, which is relaxed as:

$$\tilde{T}_{ij,t} \geq \frac{P_{ij,t}^2 + Q_{ij,t}^2}{V_{ij,t}} \hspace{1cm} \forall ij \in E$$  \hspace{1cm} (16)

This formula can be transformed into standard second-order cone form. At this time, the original optimization problem is transformed into mixed integer second-order cone model (MISOCP), which can be programmed by MATLAB and solved by CPLEX.

3. Distributed energy storage control strategy

Based on the analysis of electric vehicle distributed energy storage model and constraints, a distributed energy storage control strategy is established, and its control topology is shown in the figure below:

For electric vehicles waiting for dispatching, the control center of electric vehicle charging station will collect the basic information of each electric vehicle, including initial SOC, electric vehicle charge and discharge power, battery capacity and user's charging expectation. According to the collected information and the statistical information on the historical driving data of electric vehicles, calculate the maximum charge and discharge power of each node of the electric vehicle charging station, and report the statistics to the distribution network dispatching center. According to its own needs and the information reported by the energy storage control center and electric vehicle charge and discharge control center, the distribution network dispatching center formulates the optimal charge and discharge power curve of the energy storage station and electric vehicle charging station under the condition of meeting the power flow constraints and safety constraints of the distribution network, and sends it to the control center and energy storage station of each electric vehicle charging station. According to the issued charging and discharging power curve and the collected basic information of electric vehicles,
the control center of electric vehicle charging station formulates the charging and discharging plan for each electric vehicle in the station to perform the charging and discharging tasks for the electric vehicles that meet the charging and discharging requirements. This control method is based on the real-time electric vehicle participation V2G information, which greatly reduces the uncertainty of electric vehicle driving behavior and improves the accuracy of control results.

4. Example analysis
In this paper, the feasibility of the proposed distributed energy storage control model is tested by an IEEE 33 bus distribution system. The distribution network model includes 32 branches in total. Node 1 is the reference node, and the other nodes are PQ nodes. The distribution network reference voltage is 12.66kv. The total active power at peak load is 3715kw and the total reactive power is 1799kvar.

4.1 parameter setting
The electric vehicle charging station is set with five groups, which are respectively connected to nodes 4, 8, 15, 20 and 30, and the energy storage system is set with two groups, which are respectively connected to nodes 17 and 32. The electricity price ladder diagram and daily load curve are shown in the figure.

The charging and discharging power of the two groups of energy storage is 200kW, the capacity is 1mwh, and the charging and discharging efficiency is 0.9.

Under V2G mode, the number of electric vehicles is set as 300, and the start charging time, departure time and initial state of charge obey the probability distribution mentioned in Section 2. Three types of electric vehicles are selected, with the proportion of 50%, 30% and 20%, the charging power of P1 = 2.4kW, P2 = 4kW and P3 = 8.8kW, and the battery capacity of B1 = 13.9kWh, B2 = 23.6kWh and B3 = 64.8kWh respectively. The charging and discharging efficiency of electric vehicles is 0.9, and electric vehicles are evenly distributed in 5 charging stations.

4.2 simulation results and analysis
According to the mathematical model established in Section 2, taking the charge and discharge power of electric vehicle and energy storage in each period as the optimization variable, the second-order cone
The model is optimized and solved to obtain the charge and discharge power of electric vehicle and energy storage in each period, node voltage and line flow power in each period. This paper sets up two scenarios. Scenario 1 does not use the distributed energy storage strategy, and scenario 2 uses the distributed energy storage strategy.

1. Load peak valley difference

![Fig.4 24h load power curve](image)

It can be seen from the figure that after the electric vehicle is connected to the power grid, the load peak value of the power grid will further increase, affecting the safe operation of the power grid. After using the distributed energy storage strategy, the peak-to-peak load are significantly reduced. The distributed energy storage equipment shifts the power consumption at the peak load to the time when the load is small in the early morning. The peak-to-peak load are 27.4% lower than that in scenario 1, which has a good effect of peak shaving and valley filling.

2. Static voltage stability index

The static voltage stability index is used to characterize the adjacent voltage collapse and voltage stability margin. It is defined by power flow calculation according to the existing solution of power flow calculation. The static voltage stability index of distribution network is defined as:

\[
L_{ij} = 4 \left( \left( X_{ij} - R_{ij} \right)^2 + \left( R_{ij} + X_{ij} \right) U_i^2 \right) / U_i^4
\]  

(17)

The greater the value of \( L_{ij} \), the worse the branch stability. The voltage collapse of distribution network generally starts from the place with the weakest stability. For the nth branch of the distribution network, the static voltage stability index of the branch in each period is calculated, and its maximum value is selected as the voltage stability index of the branch in one day.

The voltage stability indexes of each branch in 24h under the two scenarios are shown in the figure:

![Fig.5 The voltage stability indexes of each branch in 24h](image)
It can be seen from the figure that after using the distributed energy storage strategy, the static voltage stability index of each branch is reduced. For the 2 and 5 branches with the highest L value, the static voltage stability index is reduced by 16.6% and 10.1% respectively, and the stability margin of the line is significantly improved.

3. Voltage deviation during peak load period

The figure shows the voltage unit value of each node in the period with the highest load of the day. It can be seen from the figure that after using the distributed energy storage strategy, the voltage level of each node can be greatly improved and the voltage stability of the distribution network can be improved.

5. Conclusion
This paper investigates the load characteristics of electric vehicles, establishes the models of energy storage power station, electric vehicle charging station considering V2G and optimal power flow distribution network, and establishes the objective function aiming at the economy, safety and stability of distribution network. The original problem is transformed into a mixed integer second-order cone optimization problem, which is solved by CPLEX, and a distributed energy storage control strategy is proposed. The optimization solution is carried out in the example of IEEE33 node distribution system. The results show that the application of distributed energy storage strategy can greatly improve the power quality of distribution network. Compared with not using distributed energy storage strategy, the load peak valley difference, static voltage stability index and voltage deviation during load peak period are significantly reduced, which improves the security and stability of distribution network.

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