Distributed Charging and Discharging Strategy for Electric Vehicle Considering Three-Phase Load Balance for Incremental distribution network

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Abstract. The unbalanced three-phase may occur in distributed network with large-scale uncontrolled charging loads of electric vehicles plugged in, at present, most of the researches on the coordinated electric vehicles charging and discharging strategies are based on the assumption of single-phase power networks, the load balancing constraints of three-phase are not considered. In this paper, a centralized charging and discharging optimization model for electric vehicles is established aiming to achieve a valley-filling concept, it can allocate electric vehicles demand during valley hours. Based on this, a distributed charging and discharging optimization method for electric vehicles considering three-phase load balancing constraints is proposed, and then the centralized optimization problem is decomposed into multiple sub-optimization problems, and a penalty term is added to the single electric vehicle charging and discharging optimization objective function. Solve the three-phase load imbalance problem in distribution network operation, and use CPLEX solver to solve the optimization model in MATLAB. Combining with information interaction mechanism, through the method of iteratively correcting the virtual electricity price, the orderly intelligent charging and discharging of electric vehicles can be realized. The IEEE 33-node distribution system is used for simulation analysis to verify the characteristics and effectiveness of the proposed method.

Keywords: Unbalanced Three-Phase, Electric Vehicle, Centralized Charging, Centralized Optimization

1. Introduction
In recent years, the excessive consumption of fossil energy leads to serious environmental pollution. Due to the characteristics of energy saving, emission reduction and green cleanliness, electric vehicles (EVs) have been widely promoted by governments as a substitute for fossil fuels. In China, the annual production of EVs and plug-in hybrid EVs will be huge by 2020, and the cumulative production and sales will reach about 5 million [1], at a moderate rate of development, the proportion of EVs in total vehicles will account for 35%, 51%, and 62%, respectively by 2020, 2030, and 2050 in the United States [2]. Obviously, the promotion and application of EVs has become inevitable. At the same time,
a lot of EVs are connected to the distribution network for uncontrolled charging, if the charging load is concentrated during the peak load, and it could coincide with the peak value of the base load of the system, and further exacerbating the difference between the peak and the valley load [3], moreover, the randomness of charging behavior in time and space has an important influence on the balance of three-phase load, the quality of power and the planning and operation of the distribution network [4-6]. Depending on the technology of EVs-to-grid (V2G) [7], an orderly EV charging and discharging strategy can be developed, which can smooth system load, improve voltage quality and solve the problem of three-phase load unbalance [8, 9].

Scholars around the word have conducted extensive research on the orderly charging and discharging strategy of the EVs, the existing charging/discharging optimization scheduling strategies mainly include centralized and distributed control methods. Several studies pursue centralized approach to control vehicle charge rates, it uses full network state information and all constraints of EVs. The advantage of this method is that it can solve the global optimal solution. The main disadvantage is that as the scale of EVs gradually increases, the calculation time of this method is too long, because centralized management needs to record the EV charging data, plug-in time, and departure time, charging mode preference, battery capacity / SOC, charger efficiency, etc. [10-11]. Reference [12] proposes a multi-time scale, rolling optimization method, which can make its optimization goal to make the total charging cost of EVs the lowest under certain network constraints. Another method proposed by [13] to control EVs charging loads in response to time-of-use (TOU) price in a regulated market, the model is formulated to minimize the charging cost. Results show that the optimized charging pattern could flatten the load curve and reduce the charging cost. Reference [14] proposed a global optimal scheduling scheme and a local optimal scheduling scheme for EV charging and discharging. However, a global optimal scheduling scheme is impractical because it assumes that the arrival time and daytime base load of all EVs are known in advance. This method is very suitable for EV charging and discharging systems with a large population and dynamic arrival [15, 16].

Aiming at the unbalanced problem of the three-phase in distributed network, this paper proposes an improved distributed charging and discharging strategy for EVs considering three-phase load balancing. The optimization model is based on valley filling. Through the information interaction mechanism, a three-phase load imbalance penalty term is added to the single-user charge cost function to reduce the three-phase imbalance of the system and improve the reliability of distribution network operation.

2. Problem Formulation

2.1. Centralized Charging and Discharging Optimization Model

2.1.1. Objective Function

Adjustable EVs in the region receive unified dispatching of the control center after they are access to the grid. The basic parameters such as the initial state of charge, the travel energy requirements and off-grid time are all obtained by the regional control center, the optimization model of centralized charging and discharging control mode with valley-filling can be formulated as:

$$\min f = \sum_{i=1}^{T} U \left[ \sum_{j=1}^{N} \left( p_{\text{ch},j}(t) - p_{\text{d},j}(t) \right) + D(t) \right] = \sum_{i=1}^{T} \left[ \frac{1}{2} \left( \sum_{j=1}^{N} \left( p_{\text{ch},j}(t) - p_{\text{d},j}(t) \right) + D(t) \right) \right]^2$$

(1)

Where $T$ is the total number of hours in the study period, $N$ is the number of EVs, $p_{\text{ch},j}(t)$, $p_{\text{d},j}(t)$ is the charging and discharging power of the $i$th EV at time $t$, $D(t)$ is the base load of the distribution network at time $t$.

2.1.2. Constraints
1. Charging and discharging of EV

\[
0 \leq P_{e,i}(t) \leq P_{plug}
\]  

(2)

\[
0 \leq P_{d,i}(t) \leq P_{plug}
\]  

(3)

\[
\sum_{i=1}^{T} \left( P_{e,i}(t) \eta_i - \frac{P_{d,i}(t)}{\eta_i} \right) - P_{vip,i} \geq 0
\]  

(4)

\[
P_{e,i}(t) \cdot P_{d,i}(t) = 0
\]  

(5)

\[
\sum_{i=1}^{T} \frac{P_{e,i}(t)}{\eta_i} - \rho_i \cdot C_{bat,i} \leq 0
\]  

(6)

\[
SOC_i(t) + \frac{P_{e,i}(t)}{C_{bat,i}} - 1 \leq 0
\]  

(7)

\[
\lambda_i - SOC_i(t) + \frac{P_{d,i}(t)}{\eta_i \cdot C_{bat,i}} \leq 0
\]  

(8)

Where \( P_{plug} \) is the capacity of the charging device, \( \eta_i \) is the charge-discharge efficiency of the \( i \)th EV, \( P_{vip,i} \) is the energy demand of the \( i \)th EV, \( \rho_i \) is the percentage of battery capacity that can be used by the user \( i \) defined V2G service, \( C_{bat,i} \) is the batteries capacity of the \( i \)th EV, \( SOC_i(t) \) is the state of charge of the \( i \)th EV at time \( t \), \( \lambda_i \) is an state of charge threshold for safe battery operation.

Due to the need for energy mobility and the purpose of battery degradation[17, 18], EV owners have defined the percentage of battery capacity available for V2G services, as shown by inequality (6), which must not exceed this percentage. Constraint condition (7) indicates that the EV can only be charged under the rated charging state. The constraint (8) restricts the discharging of EVs to ensure the battery must not be lower than the minimum state of charge during the plug-in period.

2. Three-phase load balance

Three-phase unbalance may have negative effects on electrical equipment, such as overheating of motors, higher current in neutral and voltage drop [26], therefore it is necessary to take measures to improve it. However, in order to keep the constraint linear, the three-phase imbalance is defined as the average value of each phase load and three-phase load, and the specific expression is as follows.

\[
\left| \frac{P_{A}(t) - \frac{1}{3}(P_{A}(t) + P_{B}(t) + P_{C}(t))}{\frac{1}{3}(P_{A}(t) + P_{B}(t) + P_{C}(t))} \right| \leq \zeta
\]  

(9)

\[
P_{A}(t) = D_{A}(t) + P_{eA}(t) - P_{dA}(t)
\]  

(10)

Where \( \zeta \) is unbalance degree, \( \phi \in \{A, B, C\} \), \( D_{\phi}(t) \) is a single-phase base load at time \( t \), \( P_{e\phi}(t) \) is the charging load of EVs in phase \( \phi \) at time \( t \), \( P_{d\phi}(t) \) is the discharging load of EVs in phase \( \phi \) at time \( t \).

2.1.3. Nonlinear Constraint Linearization

The equation (5) is a nonlinear constraint, to simplify the calculation, it needs to be linearized.
\[ u_i(t) + v_i(t) \leq 1 \]  

(11)

Combined with constraints (2) and (3), the following inequalities can be obtained:

\[ 0 \leq P_{\text{ch}}(t) \leq P_{\text{plug}} \cdot u_i(t) \]  

(12)

\[ 0 \leq P_{\text{dis}}(t) \leq P_{\text{plug}} \cdot v_i(t) \]  

(13)

Where \( u_i(t) \) and \( v_i(t) \) are 0-1 variables, when \( u_i(t) = 1 \), it indicates the \( i \)th EV is charging at time \( t \), when \( v_i(t) = 1 \), it indicates the \( i \)th EV is discharging at time \( t \).

2.2. Distributed Charging and Discharging Optimization

Distributed charge-discharge of EVs management control structure. Aggregators can integrate decentralized controlled loads to make more flexible scheduling. The proposed EV controlled by a grid distributed management control center, EVs and EVs coordination polymerization, particularly the structure shown in Figure 1.

![Figure 1. The structure block diagram of distributed management control](image1)

In Fig.1, the aggregators need to obtain the system base load data from the grid dispatch center, and set up control signals to arrange the charging and discharging of EVs. The schematic diagram of the EV aggregator control unit is shown in Figure 2.

In Figure 2, the aggregator sets the price control signal, according to the base load of distributed grid, and the charge-discharge power of all EVs that can be scheduled and calculates the three-phase unbalanced degree, then broadcast the information to EVs. The EV optimizes its own electricity consumption based on the instructions issued by the aggregator and reports the charging and discharging profiles to the EV aggregator. Through the information transmission between the aggregator and EVs, the centralized optimization problem can be transformed into the optimization problem of single consumers' own electricity consumption.

![Figure 2. The management control unit of the EV (EV) aggregator](image2)
3. Algorithm Flow
The above optimization, the problem could be quickly solved by CPLEX solver in MATLAB [11]. The specific procedures are as follows:
(I) Pick a parameter $\gamma$ satisfying $0 < \gamma < 1/(N\beta)$, initialize the charging and discharging profiles

$$p_{c,i,0}(t) = p_{d,i,0}(t) = [0, 0, \cdots, 0]_{1 x T}.$$ 

(II) The aggregator calculates the control signals $p^k(t)$ and $\sigma^k(t)$ by the formula (14) and (16), and broadcasts the control signals to all EVs.
(III) Each EV calculates a new charging and discharging profiles by solving the formula (17) and reports the profiles to the aggregator.
(IV) set $k = k + 1$, and go to step (II).

4. Numerical Results and Discussion
In this section, the IEEE 33-node distribution network system shown in Fig.3 is used to evaluate the presented charging and discharging dispatch strategy of EVs. We assume that the total system load is at peak time, the power base is 10MVA, the voltage base is 12.66kV, and node 0 is used as a reference node to access the main network. A total of 300 EVs at each node and each stage are relatively evenly distributed. The EV dispatch cycle is 24 hours, the battery capacity is 21kWh, the charger efficiency is 0.85, the minimum battery charge state is 0.2, and the user-defined V2G service's available battery capacity percentage is 0.1, the initial charging state is a continuous random number between 0.2–0.6, and the travel energy consumption requirements are set according to user needs.

Figure 3. The topology of the IEEE33-node system

4.1. Analysis of the Change of Charging and Discharging Power Profiles
Using the distributed optimization method of EV proposed in this paper to control EVs charge and discharge behavior, the power profiles obtained are shown in Fig.4.

Figure 4. The load profiles of EVs (EV) and base load

Figure 5. The total load of each phase profiles
As shown in Fig.4, the charging behavior of EVs will be concentrated in the off-peak period when the optimization model aims at valley-filling as the target, and EVs supply power to distributed network through V2G services during peak hours, to realize peak-shaving and valley-filling and suppress load fluctuation. After the EV load is connected to the system, the load profiles superimposed with the base load is shown in Fig.5. From the Figure 5, through the three-phase load balance constraint, after the overlap of each phase and the EV power, the difference between the total load of each phase decreases. From 21:00 to 03:00, the total load of the ABC phase is the same, and the unbalance amount It is zero, which shows that by optimizing the load of the EV, the three-phase load imbalance can be reduced. The total load profiles of the system after the load of the EVs plug in grid is shown in Fig.6.

![Figure 6. The total load of three-phase profiles](image)

As shown in Fig.6, the charging period of EVs is guided to the valley period after the charge-discharge power of EVs is optimized, and discharge at the morning peak 07:00 to the power grid to realize flexible dispatching of controllable load, avoid coincidence with the peak of basic load and improve reliability of distribution network operation.

5. Conclusion

Based on the working conditions of electric vehicles, an improved distributed charge-discharge optimization strategy for EVs considering three-phase load balance is proposed. A charge-discharge optimization model for EVs with valley filling as the goal is established. Three-phase load balancing constraints. Iteratively modify the virtual electricity price method to achieve intelligent charge-discharge of EVs. Finally, the following conclusions can be obtained by the example analysis: the charging load of EV can be guided to the valley period by the charge-discharge optimization method proposed in this paper, and discharge to system through V2G service during peak period to achieve peak-shaving. The centrally optimized three-phase load balance coupling constraint is converted into a weak coupling constraint. By adding the three-phase load imbalance penalty to the single-user billing cost function, the system's three-phase load imbalance can be effectively reduced. Compared with centralized optimization, distributed optimization can reduce calculation time, improve charge and discharge scheduling efficiency, and has practical application value.

Acknowledgments

This work was financially supported in part by the National Natural Science Foundation of China is Research on Evaluation Method of SG-DR Collaboration Benefit Based on Multi-Agent Model (51307019) and in part by the Provincial Industrial Innovation Project in Jilin Province is Research on Control Strategy of Home Temperature Control Load Participating in Frequency Modulation of Power System(2018C034-7).and State Grid Xinjiang Electric power Co., Ltd., Science & Technology Project (SGXJJY00GHJS1900038).
References

[1] YU Na, FEI Xuan, FENG Zhongbao. Multi State Reliability Evaluation of Distributed Photovoltaic Power Generation System with Time Varying Illumination and Component Failure[J]. Journal of Northeast Electrical Power University, 2019, 39(03): 8-14.

[2] LI Guoqing, YANG Yang, WANG He, et al. Overview of Topology Structure and Power Flow Control of DC Grid[J]. Journal of Northeast Electrical Power University, 2019, 39(02): 1-9.

[3] Fu Gui, Wang Zihang, Li Jiang, et al. Additional Power Change Control for Modular Multilevel Converter Based on Flexible HVDC Systems[J]. Journal of Northeast Electrical Power University, 2018, 38 (05): 16-22.

[4] LIN Chiqiao, TONG Hui, YU Wenfang, et al. Distribution Grid Intelligent State Monitoring and Fault Handling Platform Based on Ubiquitous Power Internet of Things[J]. Journal of Northeast Electrical Power University, 2019, 39(04): 1-4.

[5] YANG Mao, WANG Jinxin, DU Jian. The Complement of The Missing Data Based on The Extreme Learning Machine and Granger Test in Wind Power[J]. Journal of Northeast Electrical Power University, 2019, 39(05): 9-16.

[6] ZU Xiangdong, ZHANG Yuhui, NIU Guojun, et al. Supply-demand Coordination Optimal Dispatch of Active Distribution Network With Electric Vehicle Group Flexible Charging/discharging Response[J]. Journal of Northeast Electrical Power University, 2019, 39(03): 29-37.

[7] Zhang, H., Hu, Z., Xu Z., et al. Evaluation of achievable vehicle-to-grid capacity using aggregate PEV model[J]. IEEE Trans. Power Syst. 2017, 32, 784-794.

[8] WANG Rutian, HAN Xu, WEN Xiangyun, et al. The Optimization of Novel Control Strategy on Cascaded Modular Multilevel Matrix Converter[J]. Journal of Northeast Electrical Power University, 2019, 39(03): 59-66.

[9] WANG Rutian, SHI Ziming, WEN Xiangyun. MPPT Algorithm Based On Constant Voltage Estimation and Disturbance Observation[J]. Journal of Northeast Electrical Power University, 2019, 39(06): 24-29.

[10] Karfopoulos E.L.; Hatziargyriou, N.D. A multi-agent system for controlled charging of a large population of electric vehicles[J]. IEEE Trans. Power Syst. 2013, 28, 1196-1204.

[11] Sortomme, E.; Hindi, M.M.; James Macpherson, S.D.; Venkata, S.S. Coordinated charging of plug-in hybrid electric vehicles to minimize distribution system losses[J]. IEEE Trans. Smart Grid. 2011, 2, 198-205.

[12] O’Connell, A.; Flynn, D.; Keane, A. Rolling multi-period optimization to control electric vehicle charging in distribution networks[J]. IEEE Trans. Power Syst. 2014, 29, 340-348.

[13] Cao, Y.; Tang, S.; Li, C.; Zhang, P.; Tan, Y.; Zhang, Z.; Li, J. An optimized EV charging model considering TOU price and SOC cure[J]. IEEE Trans. Smart Grid. 2012, 3, 388-393.

[14] He, Y.; Venkatesh, B.; Guan, L. Optimal scheduling for charging and discharging of electric vehicles[J]. IEEE Trans. Smart Grid. 2012, 3, 1095-1105.

[15] LIU Hongbo, DI Qiu. Design of VSC-HVDC System Controller Based on Clark Transform and PI Parameter Tuning[J]. Journal of Northeast Electrical Power University, 2019, 39(01): 22-28.

[16] Yang Mao, Yang Chunlin. Research of Wind Power Prediction Considering Wind Direction Journal of Northeast Electric Power University[J]. 2018, 38(05): 9-15.

[17] YANG Zhenda, LI Jiaxun, XIANG Jixiang, et al. Influence and Analysis of Impact Load in Microgrid[J]. Journal of Northeast Electrical Power University, 2019, 39(05): 59-64.

[18] YANG Dongfeng, MA Qunkai, WANG Yong, et al. Optimal Configuration of Stand—Alone Microgrid Capacity Considering Volatility of Photovoltaic Output[J]. Journal of Northeast Electrical Power University, 2019, 39(04): 19-26.