The Optimal EV Charging Strategy in Smart Grid and Insight into Practical Solutions

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Abstract In recent years, the massive increase in electric vehicles (EV) and renewable energy (RER) has caused serious problems in the power system network. During peak hours of electricity consumption, the soaring demand for electricity from variable renewable energy sources severely undermines the stability and efficiency of the power supply. This article first reviews the infrastructure and charging strategies of electric vehicle batteries. After modeling and analyzing the charging activities, the results show that the charging behavior can transform the charging demand from the peak time period to the off-peak time period, and the online MSS optimization of electric vehicle charging is extracted through the Jacobian matrix. Finally, it provides a practical overview of the existing and future solutions to manage the large-scale integration of EVs into the network.

1. Introduction
Smart grids is an autonomous power and information network, which takes advantages of the information and communication technology (ICT) to achieve smart power distribution, as shown in Fig. 1. By smartly regulating distributed resources (DRs), a smart grids can accommodate a higher penetration of renewable energy, supply reliable electricity to customers, and provide ancillary services to the utility grid [1-5]. Its advantages make it more and more widely used in academia and industry, because the smart grid can make these energy sources well meet the basic power needs of local distribution networks and residential buildings [6, 7].
In the past ten years, through the introduction of electric vehicles (EV) and distributed energy (DER), smart grid technology has been rapidly developed. However, the rapid increase of renewable energy in residential buildings will cause excessive voltage loads in the power distribution system (DG). In [8-11], the authors propose an alternative to balance the DG voltage by connecting electric vehicles through charge-discharge management measures. By applying the technology of charging station vehicles to the power grid (V2G), this management solution enables electric vehicles to store surplus power generated by renewable energy or inject additional power into the power grid to adjust the voltage. However, if the charging method is performed unreasonably, a new peak load may be caused due to a single charging behavior.

This article provides practical insights and reviews on charging strategies for electric vehicles. This article first introduces the basic charging facilities of electric vehicles and the charging strategies currently adopted. Next, by modeling the charging behavior of electric vehicles, the analysis results show that the charging behavior can transform the charging demand from peak hours to off-peak hours, thereby reducing the cost of electricity during different parking periods. Finally, the method of coordinating charges is summarized.

2. EV Battery Charging Strategies and Infrastructure

The way electric vehicles are connected to the grid for charging and the charging infrastructure may vary. Some electric car manufacturers provide convenient sockets for charging their cars, while other manufacturers design electric cars with fast charging capabilities. This can be AC charging or fast DC charging [12–17]. The communication and connection between the EV battery charger and the charging station depends on the EV infrastructure and the type of charger specified by each manufacturer [13]. Currently, the classification of battery chargers and their connectors already exists and has been specified [14]. Generally, there are three important categories of EV charge levels. According to the SAEJ1772 standard, level 1 charging (slow charger), level 2 charging (medium-speed charger) and level 3 charging (fast charger) [15–17]. Table 1 lists the EV's power level, charging level characteristics, and expected charging rate.

| EV Type | Input Voltage | Input Current | Typical Use | Charging Time |
|---------|---------------|---------------|-------------|---------------|
| Level 1-AC | 120 single phase | 15A-1.9kW | House or office | 10-13 h |
| Level 2-AC | 208-240 Three phase | 40A-20kW | Private or Commercial | 1-3 h |
| Level 3-DC | 200-500 Three phase | 80A-40kW | Public | 0.5-1.44 h |

Table 1. EV battery charger characteristics and power level.
3. EV Charging Strategies
Adding renewable energy (RER) or electric vehicles to the grid may have a negative impact on the power performance, quality and efficiency of the grid. Therefore, appropriate investigations and studies on EV control strategies are required. So far, the two most common strategies in electric vehicle charging are coordinated/controlled charging strategies and random/uncontrolled strategies [18, 19].

As we all know, in stochastic strategies, medium and high EV penetration rates may have serious adverse effects on the power quality and performance of the power grid, as well as large voltage changes, especially during peak power consumption. In addition, the latest research shows that the introduction of new controlled solutions/charging strategies can solve the above problems even when the penetration rate of electric vehicles is high [18-21].

The optimal charging target is usually related to battery performance and battery health awareness in terms of temperature rise and aging rate. Therefore, by formulating the best charging strategy to make the battery achieve the best battery performance and charging speed.

4. Charging Behavior Modeling
In the EV charging scheme, EV owners hope to get the electric vehicle from a hungry state to a fully charged state as quickly as possible. This has led to a significant increase in the demand for charging during peak hours of electricity consumption, which will destroy the distribution network, causing serious economic losses to network restoration, industrial development, and quality of life. If the parking time of an electric vehicle in the charging state is longer than its charging time, the electric vehicle can split and rearrange the charging strategy into multiple time slots. When the electricity price provided by the energy market is lower than the peak electricity consumption period, at this time, the electric vehicle will arrange the charging strategy for the off-peak period. Nevertheless, if all electric vehicle owners re-arrange the charging strategy to the lowest electricity price period, the current off-peak period may become a new peak electricity period. At this time, the grid still has the risk of being decomposed by a large amount of charging demand at the same time, and then the energy market may change the real-time electricity price during the new peak period of electricity consumption to reduce the charging demand, until all the charging demand is equally divided in each time slot.

For electric vehicles in a charged state, we assume that all electric vehicle owners hope to charge at the maximum SOC during the ideal parking time, which means that the charging demand of electric vehicle owners must be met. If the parking time is not less than the charging duration, from the SOC when EV is arriving, SOC_{arr} to maximal SOC, SOC_{max}. The charge amount et in each time slot t cannot exceed the upper limit of the energy charging rate between EV and EV charger E. The physical characteristics can be modeled as:

\[ W \sum_{t \in T} e_t = SOC_{\text{max}} - SOC_{\text{arr}} \]  
\[ 0 \leq e_t \leq E_{\text{max}} \]

For each time slot t, the battery SOC should be equaled to the SOC of the last time slot, and SOC_{t-1} increases the amount of charge in the time slot t, \( \omega e_t \), where \( \omega \) is the coefficient that exchange the amount of charge (kWh) into SOC (%). That can be modeled as:

\[ SOC_t = SOC_{t-1} + \omega e_t \]

For electric vehicles that have a charging demand within the parking time range, attention needs to be paid to reducing the monetary cost of the charging strategy. In other words, if there is a large amount of charging demand, although the price will be greatly increased, the driver of the electric vehicle can allocate the charging strategy to the lowest electricity price period. The charging problem can be described as:

\[ \min \, F_r(y) = \sum_{h \in H} \alpha_0 (L_h + \sum_{j \in C} y_{j,h})^2 \]
The goal of the charging problem model is to minimize the total cost of charging each electric vehicle. \( C = \{1, 2, \ldots, M\} \) is the collection of all charging requirements during parking time. \( L_h \) and \( a_h \) are the basic load and the basic load coefficient in time slot \( h \), respectively. \( y_{j, h} \) is the charging volume for \( EV_j \) in time slot \( h \). Constraint (2b) represents the physical characteristics of the battery. Constraint (2c) means that each EV should be fully charged, where SOC\(_{\text{max}}\) is the maximal SOC, \( \sum_{h \in H} y_{j, h} \) is the SOC of \( EV_j \) at its departure time, and SOC\(_{\text{arr}}\) is the initial SOC, when it arrive at the parking lot. Constraint (2d) indicates that the charging capacity of each EV should be positive, and less than the maximal energy charging capacity, indicated by \( E_j,\text{max} \).

Consider the EV charging demand in Fig. 2, the charging situation, and the grid as an energy supplier. It is assumed that the power grid has a limit capacity of energy from the EV charger to the EV in a period of time. The price of electricity is affected by the amount of electricity demand. More electricity demand (Q1) will lead to higher electricity price (P1), and relatively small electricity demand (Q0) will lead to lower electricity consumption. Price (P0). Consider the basic electricity load quantity of the area, and then allocate the charging demand to different time slots, thereby evenly distributing the total energy demand of each time slot. All electric vehicles will change the charging schedule through real-time electricity prices. In other words, the EV charging demand during peak hours can be transferred to off-peak hours. It also reduces the risk of shutting down the distribution network due to excessive load [22].

\[
\begin{align*}
\text{s.t.} \quad & SOC_{j, h} = SOC_{j, h-1} + w y_{j, h}, \quad \forall j \in C \\
& w \sum_{h \in H} y_{j, h} = SOC_{j, \text{max}} - SOC_{j, \text{arr}}, \quad \forall j \in C \\
& 0 \leq y_{j, h} \leq E_j,\text{max}, \quad \forall j \in C \\
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\end{align*}
\]

Fig. 2. The supply curve in charging market.

5. Online MSS Optimization with EV charging

This practical method is an accurate and fast optimization technique, which solves the objective function by calculating the sensitivity of EV charging load at each time interval. This optimization is defined based on the Jacobian matrix using the power mismatch equation [23]. This optimization can be applied in large-scale distribution networks to control reactive power and voltage stability.

The existing solution for online controlled EV charging is the sensitivity of the system losses to the number of EVs that can be extracted from the entries of the Jacobian matrix:

\[
MSS_{t,i} = \frac{\partial P_{t,\text{loss}}}{\partial P_{EV,i}}, i = 1, \ldots, i_m
\]

Among them, MSS\(_{t,i}\) is defined as the sensitivity of power losses to node \( i \) to EV charging at time interval \( t \) and \( i_m \) represents the number of EVs. In the above formula, \( P_{EV,i} \) is the total consumption of
EV connected to node i. The entries of the MSS vector are derived from the Jacobian matrix of decoupled harmonic power flow (DHPF). The DHPF algorithm is usually used in harmonic power flow calculations to model the smart power system under non-sinusoidal operating conditions with nonlinear loads. In this model, the nonlinear loads are modeled as current sources. These current sources inject harmonic current into the system.

6. EV Coordinated Charging Approach
Many studies have investigated the capacity problems and adverse effects of uncoordinated electric vehicle charging on the power distribution system and residential electricity. The main solutions are summarized as follows:

- By introducing infrastructure, such as large rechargeable vehicles, batteries to the grid (V2G) or increasing network capacity.
- Install the charge controller in the car: At present, many electric car manufacturers have developed their own charging control equipment to control the charging behavior of electric vehicles and avoid the use of high electricity prices, such as Nissan Leaf. It is also possible to send a signal to the charging controller to remotely operate the charging device.
- EV coordination plan: Introduce/control different electricity price and billing standards for customers during peak and off-peak hours, and encourage people to charge vehicles according to demand during off-peak hours. This can be done in a dynamic/static combination, or through smart charging, where the active control of electric vehicle charging can be solved by infrastructure or electric vehicle charging providers. Smart charging can be centralized or decentralized.
- EV coordination (load screening integrated with RER) is another possible solution strategy that has been continuously proposed and discussed extensively in recent years. There have been many studies on combining wind power generation or RER's EV control charging strategy.

Currently, there are many different optimization strategies to cover controlled/coordinated EV charging. Its main purpose is to reduce charging costs, electricity loss and electricity bills through different optimization techniques, and to improve customer satisfaction and system stability.

7. Conclusion
This article reviews the battery infrastructure and charging strategies of electric vehicles. As a new generation of transportation tools, electric vehicles have a large number of charging behaviors that play an important role in delivering energy from the main grid. By modeling the charging behavior of electric vehicles, the analysis results show that charging activities can transform the charging demand from peak hours to off-peak hours, and the online MSS optimization of electric vehicle charging is extracted through the Jacobian matrix. Also provided a practical insight into the existing and future solutions to achieve high penetration of EVs into the network.

References
[1] R. H. Lasseter, MicroGrids, In Proceedings of 2002 IEEE Power Engineering Society Winter Meeting, 2002, 305–308.
[2] R. H. Lasseter, Smart distribution: coupled microgrids, Proceedings of the IEEE, 2011, 99, 1074–1082.
[3] N. Hatziargyriou, H. Asano, R. Iravani, C. Marnay, Microgrids, IEEE Power and Energy Magazine, 2007, 5, 78–94.
[4] G. V. Enkataramanan, C. Marnay, A larger role for microgrids, IEEE Power and Energy Magazine, 2008, 6, 78–82.
[5] D. Boroyevich, I. Cvetkovic, R. Burgos, D. Dong, Intergrid: a future electronic energy network? IEEE Journal of Emerging and Selected Topics in Power Electronics, 2013, 1, 127–138.
[6] P. Gope, B. Sikdar, Privacy-Aware Authenticated Key Agreement Scheme for Secure Smart Grid Communication, in IEEE Transactions on Smart Grid, 2019, 10, 3953-3962.
[7] M. I. Milanés-Montero, F. Barrero-González, J. Pando-Acedo, E. González-Romera, E.
Romero-Cadaval, A. Moreno-Munoz, Smart Community Electric Energy Micro-Storage Systems With Active Functions, in IEEE Transactions on Industry Applications, 2018, 54, 1975-1982.

[8] T. S. Ustun, S. M. S. Hussain, H. Kikusato, IEC 61850-Based Communication Modeling of EV Charge-Discharge Management for Maximum PV Generation, in IEEE Access, 2019, 7, 4219-4231.

[9] Y. Shi, H. D. Tuan, A. V. Savkin, T. Q. Duong, H. V. Poor, Model Predictive Control for Smart Grids With Multiple Electric-Vehicle Charging Stations, in IEEE Transactions on Smart Grid, 2019, 10, 2127-2136.

[10] S. Huang, Q. Wu, Dynamic Tariff-Subsidy Method for PV and V2G Congestion Management in Distribution Networks, in IEEE Transactions on Smart Grid, 2019, 10, 5851-5860.

[11] G. R. Chandra Mouli, M. Kefayati, R. Baldick, P. Bauer, Integrated PV Charging of EV Fleet Based on Energy Prices, V2G and Offer of Reserves, in IEEE Transactions on Smart Grid, 2019, 10, 1313-1325.

[12] S. Deb, K. Tammi, K. Kalita, P. Mahanta, Impact of Electric Vehicle Charging Station Load on Distribution Network, Energies, 2018, 11, 178.

[13] N. R. Watson, J. D. Watson, R. M. Watson, K. Sharma, A. Miller, Impact of Electric Vehicle Chargers on a Low Voltage Distribution System, In Proceedings of the EEA Conference & Exhibition, 2015, 24-26.

[14] D. Ronanki, A. Kelkar, S. S. Williamson, Extreme Fast Charging Technology-Prospects to Enhance Sustainable Electric Transportation, Energies, 2019, 12, 3721.

[15] SAE Electric Vehicle, 2010-2017. Available online: http://www.fveaa.org/fb/J177_2386.pdf (accessed on 19 February 2020).

[16] M. Yilmaz, P. H. T. Krein, Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles, IEEE Trans. Power Electron, 2013, 28, 2151-2169.

[17] M. Vasiladiotis, A. Rufer, A. Béguin, Modular converter architecture for medium voltage ultra-fast EV charging stations: Global system considerations, In Proceedings of the 2012 IEEE International Electric Vehicle Conference, 2012, 1-7.

[18] Y. Gao, X. Zhang, Q. Cheng, B. Guo, J. Yang, Classification and Review of the Charging Strategies for Commercial Lithium-Ion Batteries, IEEE Access, 2019, 7, 43511-43524.

[19] M. M. Alam, S. Mekhilef, M. Seyedmahmoudian, B. Horan, Dynamic Charging of Electric Vehicle with Negligible Power Transfer Fluctuation, Energies, 2017, 10, 701.

[20] X. Fang, S. Misra, G. Xue, D. Yang, Smart grid-The new and improved power grid: A survey, IEEE Commun. Surv. Tutor, 2011, 14, 944-980.

[21] A. Dubey, S. Santoso, Electric Vehicle Charging on Residential Distribution Systems: Impacts and Mitigations, IEEE Access, 2015, 3, 1871-1893.

[22] C. Li, C. Liu, K. Deng, X. Yu, T. Huang, Data-driven charging strategy of pevs under transformer aging risk, IEEE Transactions on Control Systems Technology, 2018, 26, 1386-1399.

[23] M. R. Khaldi, Sensitivity matrices for reactive power dispatch and voltage control of large-scale power systems, WSEAS Trans. Circuits Syst, 2004, 3, 1918–1923.