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Integrated configuration and charging optimization of aggregated electric vehicles with renewable energy sources

Shuang Gao[a], Hongjie Jia[a], Jiahao Liu[a], Chunhua. Liu[b]

[a]*School of Electrical and Information Engineering, Tianjin University, Tianjin, China*
[b]*School of Energy and Environment, City University of Hong Kong, Hong Kong, China*

Abstract

The commercialization and wide application of electric vehicles (EVs) rely on the development of EV charging infrastructure and its coordinated operation in the electric power grid with renewable energy sources. As the EV aggregator is introduced as intermediate control entity to form a multi-layer control framework, the optimal configuration of EV aggregator and the charging power regulation are closely related to each other. This paper proposes an integrated optimization to solve the mixed configuration and operation problem of EV aggregator. A hybrid optimization algorithm based on partial swarm optimization (PSO) and sequential quadratic programming (SQP) is formulated to find the best solution for the location and size of EV aggregator in the distribution network and the charging scheduling of each individual EV. The master problem in the coupled optimization algorithm is to calculate the optimal configuration of the EV aggregator based on the estimation of the EV charging load, and based on the setting of EV aggregator the subproblem is to obtain the charging plan for individual EV under the day-ahead optimal dispatching of charging demand in the distribution grid. Finally, 123-bus distribution system is adopted to analyze the characteristics of the proposed model for concurrent optimization of EV aggregator and its operation in the test distribution network. The simulation results validate the hybrid optimization algorithm in integrated configuration and operation of EV charging infrastructure.

Keywords: electric vehicle aggregator; optimal configuration and operation; power quality; charging infrasturcture

1. Introduction

Energy crisis and environmental stress have brought with opportunities of developing electric automobile industry. Governments of many counties have provided corresponding strategic plan to lead the electrification of future transportation system with zero or low carbon emission. Chinese government has claimed that 120 thousand

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EV charging stations and 4.8 million charging spots will be installed in the distribution system by 2020. However, the large-scale penetration of EVs will place new challenges on the power system reliability and quality of power supply to the customers. In order to the control a large amount of EVs to fit the needs of power system, i.e. vehicle-to-grid technology, the EV aggregator is usually introduced as the intermediate control entity between EVs and distribution system operator (DSO). The rational configuration of EV aggregator can reduce the control complexity caused by scheduling EV charging power to provide ancillary services such as cost minimization, peak shaving, and power quality improvement.

There has been a lot of existing research on the optimal dispatching of EV charging power in the power system [1]. From the prospective of EV aggregator, the location and size of the aggregator needs to be found, the differential evolution and PSO algorithms are used to solve the optimization problem with objective of total cost minimization [2]. The location of the charging stations and the optimal number of charging spots were given in the optimal solution [3]. However, the power network has not been taken into account the model [4]. Other objective functions were adopted for the optimal placement and sizing of EV aggregator, typically the profit maximization of EV aggregator, but some practical issues from the side of users were not described such as the satisfaction of mobile needs and power quality deterioration caused by recharging massive EVs at peak hours [5]. The optimal dispatch by using EVs as mobile energy storage in the power grid is also studied in the recent literature [6]. The control method for this special energy storage has been reformed from centralized control to distributed control framework. Plenty of distributed control methods have been utilized to relieve the burden on computation and communication congestion when a large amount of EVs are connected and must be controlled by DSO [7].

The integrated optimization for configuration and operation of EV charging infrastructure proposed in this paper is on the basis of previous research on the EV aggregator optimal setting and the distributed control of EV charging power for day-ahead optimal dispatch in the power system. The total cost is minimized by optimal configuration of EV aggregator and the EV charging power regulation under the given aggregator configuration. The mathematical model is built with the variables of both setting and operation considering the constraints of power system installations and the EV mobile needs. A 123-bus test system is adopted to analyze the feasibility of the proposed optimization algorithm and the performance of EV infrastructure with optimized setting and charging rate.

2. Mathematical model of combined configuration and operation of EV aggregator

EV aggregator is usually defined as the control entity between power grid and EVs, which offers services to aggregate EV charging power (or discharging defined as V2G) from a group of EVs and acts towards the grid to provide considerable power regulation capacity. In the context of this paper, the V2G operation is only comprised of charging adjustment, since battery wear and tear is a serious problem and participation of EV users is still uncertain. From current practice and theory, aggregators are installed at the large charging facility such as parking lots or at feeders where plenty of EVs are scattered in the residential area. In this context, the control realm of one aggregator is modeled as a bus of the distribution grid in this paper, and EVs connected to the bus are subject to the charging plan assigned by the EV aggregator.

2.1. Objective function

The multi-period optimal dispatch with EV charging infrastructure formulated in considering network constraints is a mixed integer nonlinear programming (MINLP) problem [8-11]. It is the base for the mathematical model presented here. The characteristics of EV aggregator configuration and the operation of EV charging infrastructure for regulating charging rate of individual EV are modeled in the optimal dispatch problem. The goal considered in this work is the cost minimization. To calculate the cost, the expenditure on supplying electricity to the load including charging EVs and the total power loss are calculated as can be seen in (1):

$$\min \sum_{t=0}^{T} \sum_{i=1}^{n} \rho\left(t\right)\left(P_{Ld}\left(t\right) + P_{EVAi}\left(t\right) + P_{Ls}\left(t\right)\right)\Delta t \tag{1}$$

where $\rho(t)$ is the electricity price at time *t*; $P_{Ld}(t)$ is the net power load of the original distribution system;

$P_{EVAi}(t)$ is the accumulated EV charging power at bus *i*; $P_{Ls}(t)$ is the total power loss at time t; and Δt is the time interval which is one hour as defined in the proposed day-ahead optimal dispatch of EV charging power.

$$P_{EVAi}(t) = \sum_{m=1}^{Mi} P_{EVAi}^{m}(t) \tag{2}$$

where $\sum_{m=1}^{Mi} P_{EVAi}^{m}(t)$ is the charging rate of individual EV in the control realm of EV aggregator installed at bus *i*.

$$P_{LS}(t) = \sum_{(i,j)\in B} R_{ij} \frac{P_{ij}^2 + Q_{ij}^2}{|V_i|^2} \tag{3}$$

where P_{ij} and Q_{ij} are the active and reactive power transmitted on the branch between bus *i* and *j*; $|V_i|$ is the voltage magnitude at bus *i*, and R_{ij} is the resistance of branch *ij*.

2.2. Constraints

The mathematical model is subject to constraints from several aspects, including power flow equations, limits on reliable operation of power system, and requirements of EV aggregator and EV users.

$$I_{ij}(t)^2 = \left(G_{ij}^2 + B_{ij}^2\right)\left[U_i^2(t) + U_j^2(t) - 2U_i(t).U_j(t)\cos\theta_{ij}(t)\right] \le I_{ij\max}^2 \tag{4}$$

where $I_{ij}(t)$ is the branch current; G_{ij} and B_{ij} denote admittance matrix of the power network; U_i and U_j are the bus voltage; and $I_{ij\max}$ is the maximum current of transmission line.

$$\left(V_i^{\min}\right)^2 \le V_i^{r}(t)^2 + V_i^{im}(t)^2 \le \left(V_i^{\max}\right)^2 \tag{5}$$

where $V_i^{\min}$ and $V_i^{\max}$ are the lower and upper limits of bus voltage; $V_i^{r}(t)$ and $V_i^{im}(t)$ are the real and imaginary parts of the bus voltage.

3. Two-stage hybrid optimization algorithm

In the proposed integrated optimization model, the decision variables include the siting of EV aggregator and the charging power control under the given configuration parameters. The increased number of variables makes it even harder to solve the MINLP problem. Thus, a two-stage algorithm is formulated to separate the variables into two categories, which are EV aggregator configuration and optimal charging plan for individual EV. The original problem is converted to a master problem of optimal configuration and subproblem of optimal charging strategy so as to reduce the complexity of the nonlinear constrained optimization modeled in the above section.

3.1. Solution procedure

A two-stage hybrid optimization algorithm based on PSO and SQP is derived to accelerate the calculation speed, as depicted in Fig. 1. As shown in the flowchart, the problem solution of the hybrid optimization algorithm requires an iterative process between the master problem of optimal configuration and the subproblem of optimal charging strategy. In the master problem, the optimal locations of EV aggregators are found and the charging plans for each individual EV are ignored to limit the number of variables to aggregated power level at the bus in distribution systems and slightly expand the feasible region of the problem. The optimal solution of master problem are provided to subproblem as input parameters and the constraints from power network operation and EV mobile needs are checked to ensure the charging plan of each EV can fulfill the overall objective.

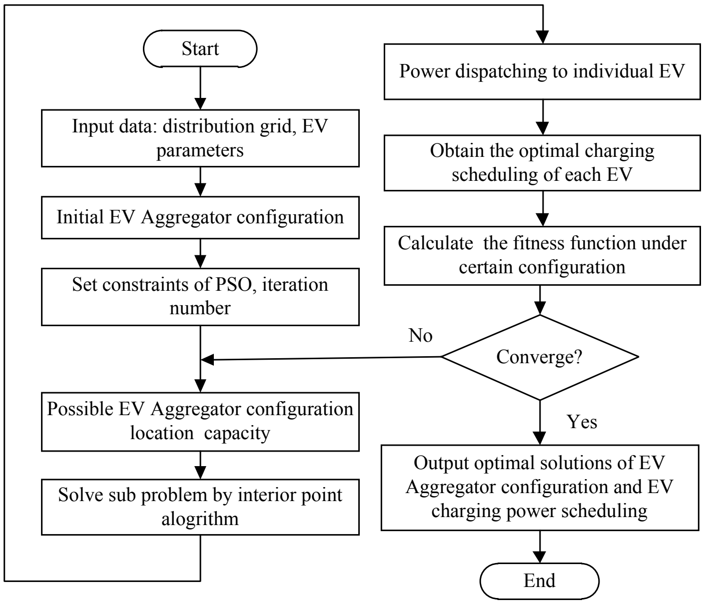

Fig. 1. Flowchart of the proposed integrated optimization algorithm

3.2. Mathematical formulation of master problem and subproblem

The objective function of master problem is described in equation (1) with the location and power capacity of EV aggregation at each bus as decision variables and subject to:

$$0 \le P_{EVAi}(t) \le P_{EVAi}^{\max}(t) \quad (6)$$

where $P_{EVAi}^{\max}(t)$ is the upper limit of the overall charging power, that is the power capacity of each EV aggregator.

$$P_{EVAi}^{\max}(t) = \sum_{m=1}^{Mi} PC_{EVAi}^{m}(t) \quad (7)$$

where $PC_{EVAi}^{m}(t)$ is the power capacity of EV aggregator.

$$LC_{EVAi} \in \{0, 1\} \quad (8)$$

where LC_{EVAi} is the location of EV aggregator, and in this algorithm is defined as binary variable.

$$N_A^{\min} \le \sum_{i=1}^{n} LC_{EVAi} \le N_A^{\max} \quad (9)$$

where $N_A^{\min}$ and $N_A^{\max}$ are the minimum and maximum number of EV aggregators that are planned to be installed in the power system depending on the construction budget of EV charging infrastructure.

The subproblem performs the optimal dispatch of EV charging power under the configuration parameters of EV aggregator given in the master problem. Accordingly, the subproblem is formulated as:

$$\min SP\left(P_{EVAi}^{m}(t)\,|_{P_{EVAi}^{\max}(t),LC_{EVAi}}\right) = \sum_{t=0}^{T}\sum_{i=1}^{n} P(t)\left(P_{Ld}(t) + P_{EVAi}^{m}(t) + P_{Ls}(t)\right)\Delta t \quad (10)$$

where $P_{EVAi}^{m}(t)\,|_{P_{EVAi}^{\max}(t),LC_{EVAi}}$ represents the charging rate of individual EV, which is the decision variable of subproblem that is to be optimized under the parameters given in the master problem.

$$\mathrm{f}_{m}\left(L\right)=\frac{1}{\sqrt{2\pi}\sigma_{\mathrm{m}}L}\exp\left(\frac{-\left(\ln L-\mu_{m}\right)^{2}}{2\sigma_{m}^{2}}\right) \tag{11}$$

where $\mathrm{f}_{m}\left(L\right)$ is the probability distribution function of the distance L travelled by each EV; σ_{m} and μ_{m} are the parameters of exponential distribution that is used to simulate the stochastic travelled distance of EV. In this paper, it can be set to $\ln L \sim N\left(3.46, 0.95^{2}\right)$.

On the basis of travel distance, the required power recharged of each EV is calculated by:

$$CB_{EV,ini}=CB_{EV,ed}-\frac{\lambda L}{CB_{EV}} \tag{12}$$

where $CB_{EV,ini}$ is the initial SOC and $CB_{EV,ed}$ is the SOC at the end of parking period; CB_{EV} is the battery storage capacity, and λ is the power consumption per unit distance.

The other commonly used constraints that describe the limits on the charging rate and required battery energy of each EV under the control EV aggregator can be found in previous research work [11-14].

Table 1. Simulation parameters for EV type and EV charging infrastructure.

	EV	Power (kW)	Battery (kWh)	SOC_End	Number of EVs	Recharge mileage (Km)
Charging station	1.Tesla Model X	13	60	0.9-0.95	40	355
	2.BMW i3	44	22	0.9-0.95	40	160
Household charger	1.Chevrolet VOLT	2.2	13.2	0.9-0.95	100	80
	2.CHANG AN YIDONG	3.75	30	0.9-0.95	100	200

Table 2. Charging scenarios in the EV aggregation.

	Charging period (Hour)	EV_in #1 μ_1 (Hour)	EV_end #1 μ_1 (Hour)	EV_in #2 μ_2 (Hour)	EV_end #2 μ_2 (Hour)
Station (Daytime)	9-18	9	15	12	18
Household (Night)	20-5	20	2	23	5

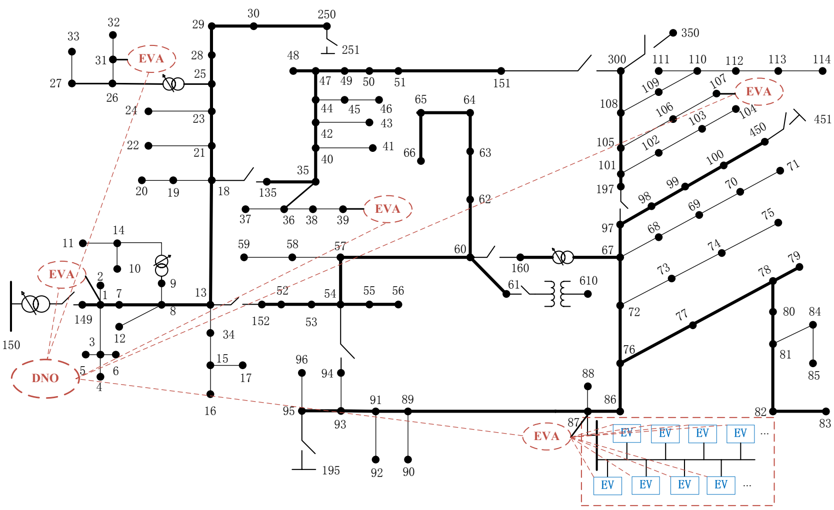

Fig. 2. Flowchart of the proposed integrated optimization algorithm

Table 3. Optimal configuration of EV aggregator.

Node	type	Phase	Proportion
1	1&2	A	55%
31	1&2	C	8%
39	1&2	B	9%
87	1&2	B	6%
107	1&2	B	22%

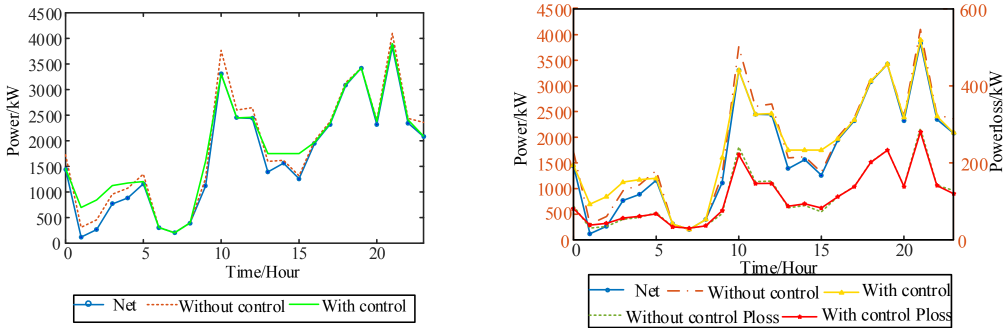

Fig. 3. Power load profile and power losses with the high penetration of EVs

4. Simulation results

4.1. Case study

The IEEE 123-bus distribution network with three-phase unbalanced load is used for simulation studies [15], as depicted in Fig. 2. For time-series simulation, the active and reactive loads are calculated by multiplying the coefficient that reflects the daily load curve as shown in Fig. 3. The original load is equivalent to the load level indicated by coefficient 0.85. The two-tariff pricing is adopted for daily electric energy price including two main periods. The minimal number and the maximal number of EV aggregators planned to be installed in the test network are set to 5 and 8 considering the budget for EV infrastructure and the operating cost of EV aggregator is assumed to be zero in the objective function.

In this paper, acceptable range of voltage domain is considered between 0.95 and 1.05 p.u. for the studied test system. The scenarios of household charging and charging station are adopted to demonstrate the performance of proposed integrated optimization based on EV aggregator where EVs are connected to low-voltage household charger and recharged for commuting. The parameters for the two scenarios and the setting of EV models and charging infrastructure are given in Table 1 and Table 2. Two types of EVs with different battery storage capacity but in the same category of sedan are selected in each scenario. The household charging is assumed to happen in the night and EVs used for commuting are recharged at the charging station when they are parking at the workplace.

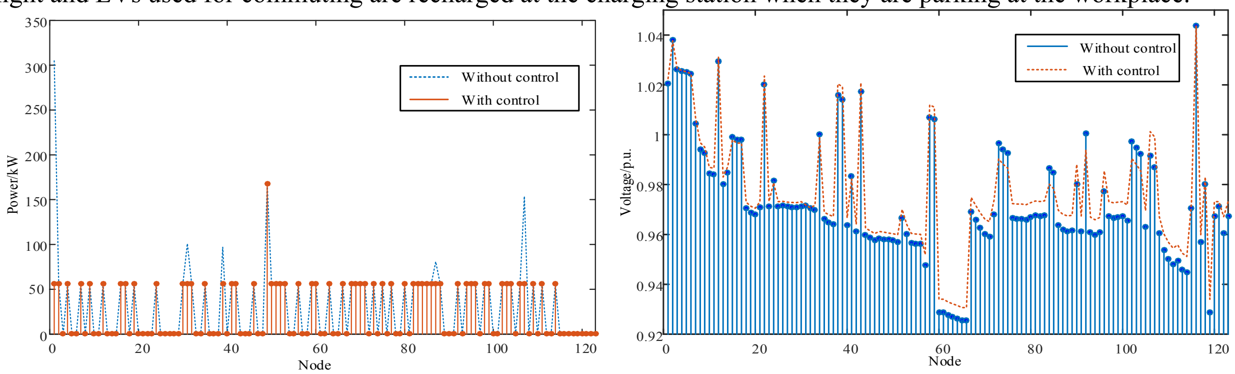

Fig. 4. Power load distribution and bus voltage of the 123-bus test system with and without optimization

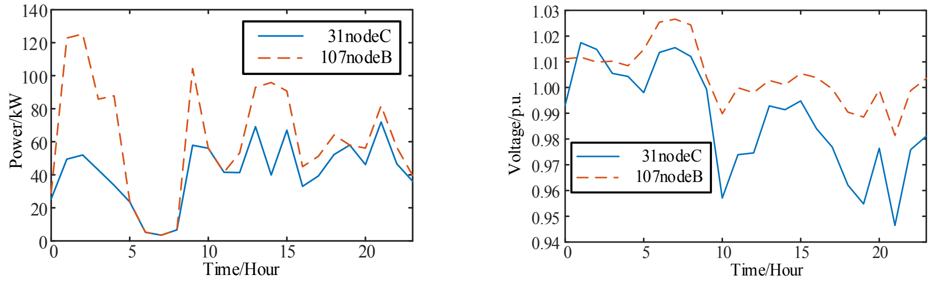

Fig. 5. Power load and voltage profiles at different bus with EV charging load connected to phase-C and phase-B

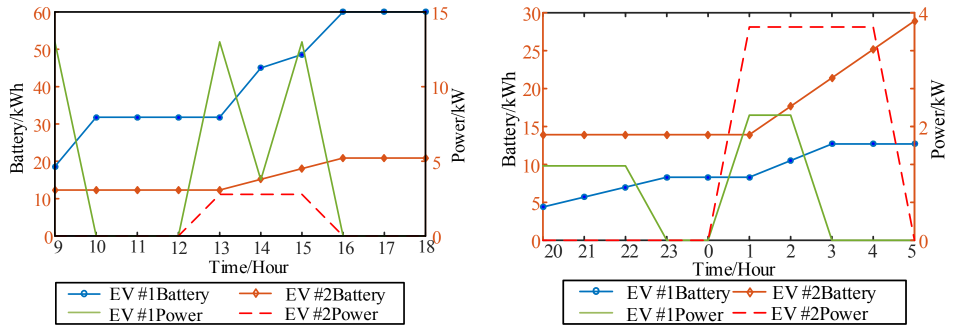

Fig. 6. Charging rate and SOC profile of individual EV in the control realm of EV aggregator at node-31 phase-C

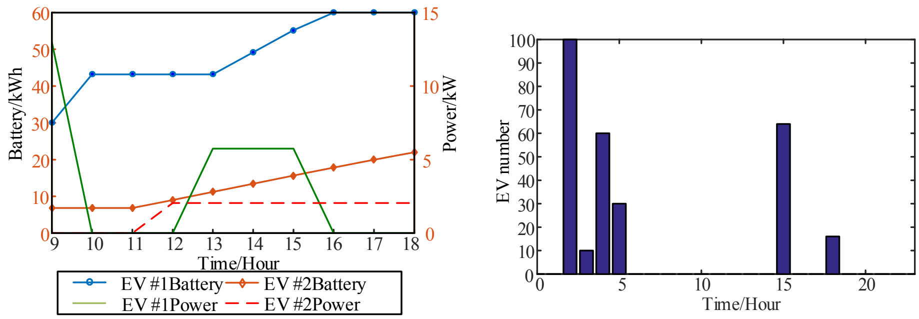

Fig. 7. Charging profiles of EVs at node-107 phase-B and the total distribution of EV reaching the target SOC

4.2. Result and discussion

The load pattern and voltage deviation of the network with EVs in uncontrolled condition and optimization scheme are compared to evaluate the efficiency of the proposed method, as shown in Fig. 3 and Fig. 4. The load and voltage profile between the uncontrolled case and optimal controlled case indicate that EV charging load is switched to the off-peak period during 23:00 to 5:00 of the next day based on Fig. 3 and Fig. 5, and the total power losses is reduced since the power losses at the peak hours are significantly curtailed. Similar results can be found in the scenario of charging station in the daytime where the two types of EVs are charged during the off-peak period as long as the required SOC can be reached at the departure time. Noted that the two-tariff pricing directs the EV charging load to off-peak hours with lower electricity price, and the reduced power loss further minimize the objective function.

The optimal locations of EV aggregator are selected from a group of candidate buses, as shown in Table 3. The capacity of the EV aggregation is the maximal total charging power at each bus. The overall charging power during the parking period is allocated to each individual EV under the realm of the aggregator. The charging plans of EVs connected at different bus are shown in Fig. 6 and Fig. 7 in which the charging profiles of two EVs in the control realm of EV aggregator at node-31 phase-C and node-107 phase-B are depicted. In Fig. 7, the distribution of EVs reaching the desired SOC over the charging period is calculated for all EVs integrated into the 123-bus distribution network in both household charging and charging station scenarios. It can be seen that EV of different type reaches the desired SOC before departure even though the charging power profile varies according to the optimal control algorithm.

5. Conclusion

Rational configuration and optimal operation of charging infrastructure can accelerate extensive application of EVs while reducing the operational cost and risks of power system. In this context, this paper studied the optimal configuration of EV aggregator and the combined optimization of configuration and operation. A two-stage hybrid optimization algorithm is proposed to efficient design the master problem and subproblem, and thus solving the optimal configuration and operation of EV aggregator with the reduced computation workload. The optimal solution including the configuration parameters and EV charging plan can improve the economic and reliable operation of the power system with EV charging load. The proposed algorithm can serve as an effective tool for the integrated optimization problem in the same scope.

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